Inversion of extensional basins parallel and oblique to their boundaries: Inferences from analogue models and field observations from the Dolomites Indenter, eastern Southern Alps

Anna-Katharina Sieberer[1], Ernst Willingshofer[2], Thomas Klotz[1], Hugo Ortner[1], Hannah Pomella[1]

[1]Department of Geology, University of Innsbruck, Innsbruck, 6020, Austria
[2]Department of Earth Sciences, Utrecht University, Utrecht, 3584 CB, Netherlands

Correspondence to: Anna-Katharina Sieberer (anna-katharina.sieberer@uibk.ac.at)

Abstract. Polyphase deformation of continental crust is analysed through physical analogue models for settings where platform-basin geometries at passive continental margins are subject to subsequent shortening and orogenesis. In a first stage, segmentation of the brittle and brittle-ductile models into basins and platforms is achieved by extension. Basins are partly filled with brittle material to allow for a strength ~~differences~~difference between basin and platform realms, simulating relatively weaker, incompetent deposits of grabens surrounded by competent pre-rift basement or carbonate platform rock, respectively. In a second stage of deformation, contraction parallel ~~to~~and oblique (10 to 20 degrees) ~~with respect~~ to the basin axes has been applied leading to the inversion of earlier formed basins. The experiments show that ~~the simple presence of an inherited~~strength contrasts across platform-basin ~~configuration~~transitions controls the localisation and overall style of compressional deformation, ~~no matter~~irrespective of the nature of ~~including~~ the basal décollement (frictional ~~or~~versus viscous ~~basal décollements, of varying~~), the rheology of the basin fill, or ~~of~~ changing platform-basin thickness ratios. Orientations of thrust faults change laterally across inherited platform-basin transitions throughout all experiments; higher obliquity of basin inversion ~~leading~~leads to stronger alignment of thrust curvature ~~of thrusts with respect~~ to the orientation of pre-existing rift axes. ~~Variations~~At individual thrust faults, variations in the strike of thrust fronts are accompanied ~~by~~with changes of the shortening direction ~~along one single fault and time step. Furthermore, our models support localisation~~during incremental phases of deformation ~~in areas of lateral strength contrasts, as platform basin transitions represent~~. Reactivation of normal faults occurs in oblique basin inversion settings only, favourably at platform-basin transitions where the normal faults face the shortening direction. The amount and style of fault reactivation depend on the material used. ~~Both parallel and oblique inversion~~ Our experiments ~~can be applied to polyphase deformed continental crust,~~are relevant for natural cases such as ~~e.g.,~~ the Dolomites Indenter of the eastern Southern Alps. ~~Our models involving two phases of deformation, suggest that~~underlining the ~~whole tectonic evolution of the Dolomites Indenter is controlled by~~importance of inherited geologic features. ~~Fault slip data and~~ for the subsequent shortening ~~directions from fold axes from our field case study along~~geometries. Field structural data from the western segment of the Belluno thrust of the Valsugana fault system support predicted variations of thrust fault orientation and a lateral change in shortening direction (from SSW to SSE along strike) along one single fault. Based on our modelling results, we ~~infer~~suggest that this variability of thrust fault orientation and shortening directions ~~depends on,~~

controlled by inherited structures ~~and do~~, is consistent with strain partitioning during a single phase of deformation and does not necessarily reflect different deformation phases.

Keywords. Crustal-scale analogue modelling, parallel to oblique basin inversion, polyphase deformation, lateral strength contrasts, eastern Southern Alps, Dolomites Indenter.

1 Introduction

Shortening of passive continental margins is ~~typically~~often associated with the reactivation of inherited normal faults, inversion of sedimentary basins, and their incorporation in fold- and thrust belts (e.g., Turner and Williams, 2004; Cooper and Warren, 2020). Inverted sedimentary basins are known from numerous orogenic settings worldwide, from, e.g., the European Alps (Boutoux et al., 2014; Gillcrist et al., 2015; Granado et al., 2016; Oswald et al., 2018; Héja et al., 2022), the Apennines (Scisciani et al., 2001; Pace et al., 2014), the Pyrenees (Tavani et al., 2011; Mencos et al., 2015), Iberia (Ramos et al., 2017), the Atlas Mountains of Morocco (Beauchamp et al., 1999) and Algeria (Bracène and Froizon De Lamotte, 2002), and from the South American Andes (Kley and Monaldi, 2002; Giambiagi et al., 2003; Kley et al., 2005; Carrera et al., 2006). ~~For understanding~~Analogue modelling is frequently used for studying complex and large-scale 3D ~~tectonic~~deformation patterns resulting from superposed ~~extension~~extensional and ~~compression~~compressional deformation phases~~, tectonic inversion was already long studied through analogue~~ (e.g., Buchanan and Mcclay, 1991; Sassi et al., 1993; Brun and Nalpas, 1996; Amiliba et al., 2005; Panien et al., 2005; Mattioni et al., 2007; Yagupsky et al., 2008; Cerca et al., 2010; Yamada and Mcclay, 2010; Bonini et al., 2012; Di Domenica et al., 2014; Granado et al., 2017; Deng et al., 2020; Zwaan et al., 2022) ~~and~~. Together with numerical modelling (Buiter et al., 2006; Panien et al., 2006; Buiter et al., 2009; Granado and Ruh, 2019; Ruh, 2019) ~~modelling.~~fundamental insights are obtained allowing to infer favourable mechanic and kinematic conditions for basin inversion. These studies confirm conceptual ideas (e.g., Sibson, 1985) and demonstrate that fault reactivation in inversion settings indeed strongly depends on the orientation and the dip angle of pre-existing faults or crustal discontinuities and on the rheology of rocks in foot- and hanging walls. Additionally, a combination of lateral, stratigraphically controlled, mechanical ~~differences~~variations and pre-existing structures in basement or cover sequences often controls the location of ~~so-called transverse or~~ transfer zones, which connect ~~differing~~different styles of deformation along strike of thrust belts (Thomas, 1990). Within the European Alps, a prominent example of inverted sedimentary basins, which are now part of a fold- and thrust belt ~~is the polyphase deformation history of~~, is the eastern Southern Alps. The relationship between Mesozoic extension, resulting in laterally distinct stratigraphic successions related to the structuration of the Adriatic crust into basins and platforms (Bernoulli and Jenkyns, 1974; Winterer and Bosellini, 1981; Sarti et al., 1992; Bertotti et al., 1993), and Cenozoic compression was intensively discussed by Doglioni (1987, 1991, 1992), as their interaction is crucial to understand the tectonic evolution of the eastern Southern Alps. Based on field evidences from the Dolomites (eastern Southern Alps ~~E~~east of Bozen/Bolzano, ~~W~~west of the Cadore region and N of Valsugana fault system) and the Venetian Pre-Alps (eastern Southern Alps ~~S~~south of Valsugana fault system towards the Venetian plain) (Doglioni, 1991, 1992; Schönborn, 1999), and from the Friuli-Alps

(eastern Southern Alps ~~E~~east of Cadore region, W of the Italian-Slovenian border) (Nussbaum, 2000), contrasting ideas for the evolution of inversion structures were proposed.

Through a series of crustal scale analogue ~~models~~experiments, we investigate the effect of an early extensional phase leading to differentiation of the crust in platforms and basins on a later compressional phase, which is relevant for the discussion of inversion tectonics in settings such as the eastern Southern Alps. In particular, we test the hypothesis that pre-existing NNE-SSW trending normal faults are of paramount importance for understanding and explaining Paleogene to Neogene crustal deformation of the Dolomites Indenter. More precisely, we aim at demonstrating causal relationships between lateral changes of thrust fault orientations and the inherited fault-bound basin to platform transitions in extended crust. We substantiate our findings by comparison with field observations, e.g., with the Belluno area, where the western (i.e., Trento) platform merges into the eastern (i.e., Belluno) basin.

2 Geological setting of the Dolomites Indenter

~~In the evolution of the European Alps, the Adriatic plate is traditionally considered as rigid indenter (i.e., Adriatic indenter) (Schmid et al., 2004) and research mainly focused along its confining fault system, e.g., the Periadriatic fault system, the Giudicarie belt, and the Valsugana and Montello fault systems (Fig. 1) and areas to the north elucidating collision and extrusion tectonics (Ratschbacher et al., 1991; Scharf et al., 2013; Favaro et al., 2017; Rosenberg et al., 2018). An indenter is known as a piece of rigid continental crust which, after collision, moves into weaker parts of an orogen (Tapponnier et al., 1986; Reiter et al., 2018)~~In continent-continent collision settings, an indenter is defined as a piece of relatively rigid continental lithosphere which, upon collision, deforms weaker lithosphere in front (Tapponnier et al., 1986). In the evolution of the European Alps, the Adriatic plate is traditionally considered as rigid tectonic element often referred to as Adriatic Indenter (e.g., Schmid et al., 2004) and research mainly focused along its confining fault system, e.g., the Periadriatic fault system, the Giudicarie belt, and the Valsugana and Montello fault systems (Fig. 1) and areas to the north elucidating collision and extrusion tectonics (Ratschbacher et al., 1991; Scharf et al., 2013; Favaro et al., 2017; Rosenberg et al., 2018). Following Schmid et al. (2004), we use the term Adriatic (micro)plate as part of greater Apulia which is located south of the Periadriatic fault system; Apulia being paleogeographically understood as consisting of all continental realms between the Neotethys in the south and the Alpine Tethys in the north. However, the structure of the northernmost part of the Adriatic microplate within the eastern Southern Alps of Italy and Slovenia, referred to as Dolomites Indenter (Rosenberg et al., 2007), demonstrates significant internal deformation. This continental indenter contains the structural memory of Permian and Late Triassic to Early Jurassic extensional phases, which possibly controls thrust fault orientations related to Neogene to recent fold-and-thrust belt formation (Bosellini, 1965; Doglioni, 1992) in the eastern Southern Alps, with mainly in-sequence deformation towards its external southern parts (Selli, 1998; Castellarin et al., 2006).

The eastern Southern Alps are bordered by the Pustertal-Gailtal fault (a part of the Periadriatic fault system) to the north, the Venetian plain to the south and the Giudicarie fault system and the Giudicarie belt to the west (Fig. 1a). The term "eastern

Southern Alps ~~equals the term~~ " is used synonymously to "Dolomites Indenter~~, which in turn equals~~" and refers to the eastern part of the Adriatic ~~indenter. The~~ Indenter. Therefore, the Dolomites Indenter ~~therefore~~ represents the front of the Neogene to ongoing N(W)-directed continental indentation of Adria into Europe. The indentation leads to the offset of the Periadriatic fault system along the Giudicarie fault system (Pomella et al., 2011), to the doming of the Tauern Window (Scharf et al., 2013; Schmid et al., 2013; Favaro et al., 2017; Rosenberg et al., 2018), to eastward lateral extrusion of crustal fragments of the Eastern Alps (Ratschbacher et al., 1991; Rosenberg et al., 2007), and to overall S-directed folding and thrusting of the eastern Southern Alps (Doglioni and Bosellini, 1987). ~~In order to asses whether and how inherited platform basin geometries affect younger, Alpine deformation, it is of importance to~~In the following sections we characterise the Permian to Jurassic extension and Paleogene to Neogene shortening of the Dolomites Indenter~~.~~ in order to asses whether and how inherited platform-basin geometries affect younger, Alpine deformation.

[Figure 1]

2.1 Permian to Jurassic extensional phases

A first rifting event affecting the Adriatic crust started during the ~~Lower Permian and was related to the opening of the Neotethys (i.e., Meliata-Hallstatt Ocean)~~Early Permian and was related to large-scale intracontinental dextral transform shear (Muttoni et al., 2003) (or to the opening of the Neotethys (i.e., Meliata-Hallstatt Ocean) according to, e.g., Stampfli and Borel, 2002; Stampfli et al., 2002; Schmid et al., 2004). ~~Extension lead to the formation of N-S trending normal faults and ENE trending.~~ Late Permian to Upper Triassic (Carnian) extension (Bertotti et al., 1993) lead to the formation of N-S striking normal faults and ENE striking transfer faults (Doglioni, 1991), accompanied by the deposition of the up to ~2 km thick Athesian Volcanic Complex (Bosellini et al., 2007; Morelli et al., 2007; Marocchi et al., 2008; Brandner et al., 2016) (Figs. 1b, 2a). A second rifting event during the Late Triassic to Early Jurassic, associated with the opening of the Alpine Tethys (Sarti et al., 1992; Schönborn, 1999; Nussbaum, 2000; Masetti et al., 2012; Picotti and Cobianchi, 2017) ~~(or to the opening of the Neotethys Ocean according to, e.g., Vrabec et al. (2009)),~~(or to the opening of the Neotethys Ocean according to, e.g., Vrabec et al., 2009), segmented the Adriatic passive continental margin into submarine carbonate platforms and basins, which are bordered by N(NE)-S(SW) ~~trending~~striking, crustal-scale normal faults (Winterer and Bosellini, 1981; Doglioni, 1991; Sarti et al., 1992; Bertotti et al., 1993; Selli, 1998; Busetti et al., 2010; Picotti and Cobianchi, 2017; Le Breton et al., 2021) (Figs. 1b, 2b). These normal faults reach into the ~~upper and~~middle crust to depths of about 10 ~~km (Martinelli et al., 2017) or~~to 20 km ~~(Masetti et al., 2012)~~(e.g., Pogallo fault in Handy, 1987; Lugano fault in Bertotti, 1990), and are associated with minor normal faults reaching down to about 4 to 7 km depth (~~Pieri and Groppi, 1981~~Bertotti et al., 1993).

From west to east, four major domains, bounded by N-S striking rift faults, were formed: the Lombardian basin, the Trento platform, the Belluno basin, and the Friuli platform (Winterer and Bosellini, 1981) (Figs. 1b, 2). The Lombardian basin has the Ballino-Garda line, which is part of the Giudicarie belt, at its eastern border towards the Trento platform and therefore belongs to the western Southern Alps. The Trento platform is located east of the Ballino-Garda line and is split into a northern

and a southern part by the SW-NE trending Valsugana fault system. The northern Trento platform shows differential syn-sedimentary subsidence (Sarti et al., 1992; Martinelli et al., 2017) (Figs. 1b, 2) and its location approximately coincides with the extent of the Permian Athesian Volcanic Complex (Fig. 1b). The southern Trento platform (i.e., Venetian Pre-Alps) shows a thicker and more continuous sedimentary cover than the northern Trento platform (Fig. 2a). The Belluno basin is narrower ~~in its W-E extent~~ and shows a more complex geometry compared to basins west of the Ballino-Garda line as it is N-trending in its central part, but NE-trending towards the Carnia region (Sarti et al., 1992). Whether and how the Belluno basin merges into the Slovenian basin, located north of the Friuli platform and NE of the Belluno basin (Fig. 1b), is topic of ~~discussion~~discussions (Smuc and Goričan, 2005; Van Gelder et al., 2015). The Friuli platform ~~(i.e., Dinaric carbonate platform (Smuc, 2005))~~(i.e., Dinaric carbonate platform in Smuc, 2005) shows stable shallow water sedimentation during most of the Jurassic and Cretaceous (Nussbaum, 2000; Merlini et al., 2002; Kastelic et al., 2008; Picotti and Cobianchi, 2017; Moulin and Benedetti, 2018) and ~~merges into~~transitions to the vast Adriatic carbonate platform (Vlahović et al., 2005) to the southeast.

[Figure 2]

2.2 Paleogene to Neogene shortening

Continental collision between Adria and Europe resulted in a first compressional phase (i.e., Pre-Adamello phase) within the western Southern Alps ~~(i.e., Insubric Indenter west of the Giudicarie belt; Rosenberg et al. (2007))~~(i.e., Insubric Indenter west of the Giudicarie belt; Rosenberg et al., 2007) which is mostly S-directed (Schönborn, 1990; Carminati et al., 1997), preceding the Adamello intrusion and therefore pre-middle Eocene in age (Zanchi et al., 2012; Zanchetta et al., 2013) and not documented within the eastern Southern Alps (Castellarin et al., 1992). During the Paleogene, the eastern Southern Alps were in a foreland, pro-wedge position to Dinaric post-collisional shortening (Ustaszewski et al., 2010). Especially the eastern part of the eastern Southern Alps, from Gadertal/Val Badia eastward, shows mainly thin-skinned (Doglioni, 1987), WSW- to SW-directed Dinaric shortening (Doglioni and Bosellini, 1987; Caputo, 1996; Keim and Stingl, 2000; Nussbaum, 2000) of about 10-15 km (Doglioni, 1992), whereas the western Venetian plain and the western Dolomites were representing the foreland to the external Dinarides (Poli et al., 2021). ~~After a short phase of extension and transtension accompanied by volcanism (i.e., Veneto Volcanic Province, Zampieri (1995); Beccaluva et al. (2007)) within the southern Trento platform NE of Verona (Fig. 1b), SSE directed shortening in the eastern Southern Alps starts in Late Oligocene (Fantoni and Franciosi, 2010; Vignaroli et al., 2020) to Miocene (Venzo, 1940; Castellarin and Cantelli, 2000) times.~~After a short phase of extension and transtension accompanied by volcanism (i.e., Veneto Volcanic Province, Zampieri, 1995; Beccaluva et al., 2007) within the southern Trento platform, NE of Verona (Fig. 1b), SSW-directed shortening in the eastern Southern Alps starts in Late Oligocene and SSE-directed shortening in Miocene (Venzo, 1940; Castellarin et al., 1992; Castellarin and Cantelli, 2000) times. From the Late Oligocene onwards, the eastern Southern Alps represent the retro-wedge of the Alpine orogen (Castellarin and Cantelli, 2000). The Late Triassic to Jurassic platform-basin configuration was shortened and inverted; the Dinaric fold-and-thrust belt got

overprinted by overall SSE-directed deformation (Mellere et al., 2000; Placer et al., 2010). From north to south, the major Neogene faults within the eastern Southern Alps are (i) the Valsugana fault system, including Valsugana and Belluno thrusts and its N-directed back-thrusts, the Villnöss/Funes and Würzjoch/Passo delle Erbe faults (ii) the blind Bassano-Valdobbiadene thrust with the Bassano anticline in its hanging wall and its N-directed back-thrust, the Val di Sella back-thrust (Selli, 1998), and (iii) the blind Montello thrust with the Montello anticline in its hanging wall, representing the most external structural feature of the eastern Southern Alps (Picotti et al., 2022).

The main shortening phase within the Dolomites Indenter (i.e., Valsugana phase) takes place during the Miocene (17-9 Ma), ~~according to the available but~~and is constrained by scarce thermochronological ~~dataset~~data (Zattin et al., 2006; Pomella et al., 2012; Heberer et al., 2017). Crystalline basement in the hanging wall of the Valsugana thrust clearly shows Neogene thick-skinned thrusting in the western part of the eastern Southern Alps (i.e., western Dolomites), but does not crop out in eastern part of the eastern Southern Alps (Friuli region) above the main thrust. Serravallian to Tortonian sediments are deformed by the Valsugana thrust (Doglioni, 1992), representing the final push along the Valsugana fault system. ~~Pliocene sediments are folded above the frontal triangle zone of the Montello thrust (Doglioni, 1992; Ortner et al., 2016).~~Further south, Pliocene sediments are folded above the frontal triangle zone of the Montello thrust (Venzo, 1977). According to recent studies of Anderlini et al. (2020), Jozi Najafabadi et al. (2021), and Picotti et al. (2022), the Bassano-Valdobbiadene and the frontal Montello thrusts are seismically active at present.

Mesozoic structures are frequently reactivated during the Neogene, as, e.g., the Permian normal Calisio and Schio-Vicenza faults as strike-slip faults or cross-cut in shallower angles as, e.g., the dextral Paleo-Valsugana fault (Selli, 1998). Normal faults related to platform-basin transitions are reactivated according to their dip angle and dip direction and lead to lateral ramps for Neogene thrusts. According to Doglioni (1992), E-dipping Mesozoic normal faults have predominantly been cut and involved in the ~~alpine~~Alpine fold-and-thrust belt without major reactivations, whereas W-dipping Mesozoic normal faults seem ~~to~~ often to be strongly deformed and reused as thrust planes or by sinistral transpression, as it is the case for, e.g., the Giudicarie belt. In the eastward prolongation of the Bassano-Valdobbiadene thrust, at the transition of Belluno basin and Friuli platform, the Caneva line (i.e., Cansiglio line) represents a lateral ramp (Doglioni, 1991; Schönborn, 1999; Picotti et al., 2022). Neogene structures stack platform regions onto basin regions, as, e.g., the Belluno thrust, which brings competent successions of the Trento platform onto more incompetent stratigraphy of the Belluno basin~~.~~ (Doglioni, 1991, 1992).

The amount of shortening along the Valsugana fault system is approximately 15 km (Selli, 1998). However, recent studies show 6 to 8 km of shortening along the Belluno fault only (Zuccari et al., 2021), leading potentially to more shortening along the whole Valsugana fault system. According to Verwater et al. (2021), the amount of shortening across the eastern Southern Alps depends on competence contrasts and on thickness variations of sedimentary successions due to laterally heterogeneous paleogeographic domains. Therefore, competent platform successions show less shortening compared to basinal regions as, e.g., the Belluno basin, where the spacing of thrusts is especially narrow and the southern thrust front is located remarkable far north (Doglioni, 1992).

2.3 Sedimentary succession and mechanical significance

In general, the stratigraphy of the eastern Southern Alps is characterised by a ~~Variscian~~Variscan metamorphic basement, Permian volcanic rocks (Athesian Volcanic Complex, limited to the northern Trento platform), and a Late Permian to Neogene sedimentary succession (Winterer and Bosellini, 1981) (Fig. 2). The sedimentary succession shows minor differences in W-E extent across Adria during the ~~Upper~~Late Permian and Triassic, except stronger subsidence in the Lombardian basin (Sarti et al., 1992; Bertotti et al., 1993; Picotti et al., 1995) and stronger Ladinian volcanism in the western part of the eastern Southern Alps, but becomes strongly heterogeneous during Late Triassic to Jurassic extension (syn-rift sediments). Lateral and vertical facies changes known from several places within the eastern Southern Alps are~~, aside to normal faults, are other~~ expressions of the platform-basin configuration of the Mesozoic passive continental margin (Abbots, 1989; Doglioni, 1992; Picotti and Cobianchi, 1996; Selli, 1998; Franceschi et al., 2014; Picotti and Cobianchi, 2017).

Especially the northern Trento platform shows remarkable unconformities from the Jurassic onwards with, e.g., a fully eroded Mesozoic cover on top of the Athesian Volcanic Complex or a strongly reduced Jurassic (Winterer and Bosellini, 1981; Beccaro et al., 2002) to Cretaceous (Lukeneder, 2010) succession overlying the Athesian Volcanic Complex north of the Valsugana fault system (Fig. 2a). Within the southern Trento platform, the stratigraphic succession reaches into the Paleogene to Miocene (Fig. 2a) with ~~bioclastic to marly sediments~~limestone and marls (Doglioni and Carminati, 2008; Vignaroli et al., 2020). During the lower Jurassic, at the footwall of the ~~rifted margins~~major normal faults of the Trento and Friuli platforms, massive shallow water carbonates were deposited, whereas deep-water sediments occurred in the Belluno basin; oolitic limestone, shed from the platforms, transitions both realms (Masetti et al., 2012; Franceschi et al., 2014; Masetti et al., 2017; Picotti and Cobianchi, 2017) (Fig. 2b). The Slovenian basin shows a sediment thickness comparable to the Belluno basin (Fig. 2), but developed earlier (Ladinian) and is deeper marine (Goričan et al., 2012; Rožič et al., 2018).

The main detachment horizon for thick-skinned deformation in the eastern Southern Alps is located at depth between 15 and 20 km, supported by recent local earthquake data (Jozi Najafabadi et al., 2021). For thin-skinned deformation, the two main detachment horizon are (i) evaporite-bearing ~~facies associations~~shales of the Late Permian to Early Triassic Bellerophon Formation (Doglioni and Bosellini, 1987; Nussbaum, 2000), which thickens from W (no Bellerophon Formation west of Val d'Adige/Etschtal) to E, reaching a maximum thickness of approximately 400 m in the E (Noé, 1987; Massari and Neri, 1997), and therefore the main detachment for SW-directed Dinaric structures and (ii) the alternate succession of evaporite, shales, and marls of the Carnian Raibl Group (Nussbaum, 2000) with a maximum thickness of about 250 m (De Zanche et al., 2000).

3 Analogue modelling approach

~~A~~Inspired by the case of the Dolomites Indenter (section 2), a series of 12 crustal-scale brittle and brittle-ductile analogue experiments provide insights in the structural evolution of continental upper to middle crust subject to extension followed by contraction. The experiments are designed such to allow for the opening of multiple extensional basins separated by platform-type areas, a structural configuration that is frequently observed in passive margin settings where the continental shelf is

dissected by graben structures and where the shelf transitions to ~~the deeper basin~~deep basins (Mandl, 2000; Berra et al., 2009; Sapin et al., 2021). ~~Subsequent contraction~~Contraction of ~~the~~ earlier formed graben structures of variable width allows for testing the influence of inherited structures and basin geometries on the style of a younger contractional deformation phase, as well as timing and localisation of uplift of the inverted graben structures and their transition to platform areas. Key parameters of this study include ~~the thickness differences between platforms and basins, the rheological stratification of the model crust, and the angle of obliquity between extensional and compressional deformation phases.~~(i) the angle of obliquity (0°, 10° or 20°) of shortening with respect to the strike of the first phase rift structures, (ii) the basal décollement rheology, and (iii) the basin fill rheology, and form the basis for grouping the experiments in three major sets (Table 1). The experiments have been designed to allow comparison with the Dolomites Indenter of the eastern Southern Alps, but are ~~from a conceptional point of view~~ also ~~applicable to~~relevant for other regions ~~affected by multiple deformation phases.~~where rift structures are inverted at low angle to the rift axes.

[Table 1]

3.1 Set-up and geometries of analogue models

Model setups and the modelling results are described within a geographic frame where the north direction is aligned with the strike of the velocity ~~discontinuity (VD~~discontinuities (VD1 and VD2) and thus the strike of the basin axes (Fig. 3a-c). All experiments are built on a table and on top of one fixed and two mobile plastic sheets of 1,0 mm thickness. ~~Pre-deformation rotation of~~Positioning the ~~fixed sheet by 10 and 20 degrees~~ VDs obliquely with respect to the ~~extension direction~~ backstop allows for the formation of graben structures, ~~which are~~ at ~~high angle~~angles of 10 and 20 degrees to the shortening ~~phase~~direction (Fig. 3a-c). The mobile plastic sheets are attached to two ~~separated~~individual engines which simulate extension by pulling the mobile sheets in opposite directions from underneath the fixed sheet at constant velocity ~~but opposite directions (~~of 5 cm/h or 2.5 cm/h for brittle or brittle-ductile experiments, respectively (Table 1, Fig. 3a-c). Lower velocities yield differential stresses for the ductile layers, that allow for mechanical decoupling at the transition from brittle to ductile layers, ensuring that the ductile layer acts as a décollement. As such the transition from the fixed to the mobile plastic sheets predefines VDs along the western and eastern margins of the fixed plastic sheet. This kinematic boundary condition leads to asymmetric extension on either side of the fixed sheet comparable to proposed extensional geometries of the northern Adriatic plate margin (Sarti et al., 1992; Masetti et al., 2012). The extensional phase was terminated after 5,0 cm of displacement of the eastern mobile sheet, whereas it continued to 9,0 cm of displacement at the western mobile sheet, ~~producing~~ (Fig. 3a-c), leading to sedimentary basins of different size comparable to the relatively narrow Belluno and wide Lombardian basins in the Southern Alps (Winterer and Bosellini, 1981; Bertotti et al., 1993; Picotti and Cobianchi, 2017).

[Figure 3]

Additional to pre-existing discontinuities and obliquity in basin inversion we apply lateral ~~changes in mechanical stratigraphy to our experiments. Lateral~~ strength contrasts ~~result~~resulting from (i) pre-existing deformation due to the ~~first~~ extensional phase, (ii) syn-extensional basin fill material, and (iii) lower thickness of the basinal succession compared to the platform succession. ~~Regarding (ii), using~~Using different material for the basin fill than for platforms simulates relatively weaker, incompetent graben deposits ~~of grabens~~ compared to surrounding competent pre-rift basement or carbonate platform rock, respectively. In our analogue models we tackle this by using, e.g., homogeneous layers of quartz sand for the initial, non-stretched model, simulating competent crust, which was extended in a first phase of deformation. Syn- to post-extensional sedimentation has been applied ~~to~~in the resulting grabens by manually ~~by~~ sieving either quartz sand, feldspar sand or glass beads into the graben structures after approximately each cm of extension (Fig. 4a). The resulting grabens were filled up to a platform-basin thickness ratio of (i) 0.7 to 0.8 for underfilled basins using quartz sand only (models 1-7) or (ii) 1.0 for filled basins using either quartz sand (model ~~4), glass beads (model 11) or~~ 8), feldspar sand (model 9), or glass beads (models 10-12), simulating relatively incompetent rock compared to the platforms (Fig. 4a). ~~The~~Minor thickness variation of underfilled basins (models 1-~~3 and 5-8) of (i~~7) is a consequence of the handling technique. For ~~(ii) we chose a~~ platform-basin ~~ratio~~ratios of 1.0 ~~for modelling the~~ lateral strength ~~difference~~differences between platforms and basins ~~only in terms of~~ are achieved by varying the material properties~~, not in terms of varying material thickness.~~ of the basin fill.

Once the extensional phase is finished, the mobile plastic sheets are detached from their engines and fixed to the table. Subsequent contraction of the extensional basins is achieved by pushing the rigid backstop at constant velocity into the experiment. The velocity of the moving wall is 3.0 cm/h or 2.5 cm/h for brittle or brittle-ductile experiments, respectively ~~.~~(Table 1). The compressional phase was terminated after 9.0 cm of shortening. Experiments consisting of brittle material only are confined by a rigid backstop in the north, aluminum bars in the east and west and have an open boundary in the south, whereas brittle-ductile models also have their southern boundary confined with aluminium bars to prevent the outflow of ductile material. ~~A wider backstop was used in experiments 4 and 8 to model the evolution of the western basin in an oblique inversion setting with straight outlines only. All~~Most other oblique inversion models show a kink in the transition from the western basin to the western platform, because of limited space of setup arrangements~~, which is not of influence for the modelling results.~~. This simplification does not influence the modelling results, because shortening is stopped prior to deformation reaching this kink. However, a wider backstop was used in experiments 7 and 8 to test the sensitivity of modelling results on model size. An overview of modelling setups is provided in Table 1.

[Figure 4]

3.2 Model material and scaling

The analogue experiments presented in this study consist of brittle or a combination of brittle-ductile layers representing continental upper crust, which is either entirely brittle or brittle with a ductile layer at the base (Fig. 4a). The latter simulates crustal layers below the brittle-ductile transition (models 6 and ~~8~~7). Layers of colored, dry quartz sand represent the brittle pre-rift crust in all models, whereas the ductile layer consists of polydimethylsiloxane (PDMS silicon polymer), mixed with Rhodorsil gomme~~.~~, representing the ductile crust below the brittle-ductile transition. The ductile material has a density of 1500 kg/m³, a viscosity of 3~~.~~8 x 10⁴ Pas, and shows slightly non-Newtonian behaviour (n = 1~~.~~15) (Table 2). The properties of the ductile material have been determined with a pycnometer and a coni-cylindrical viscometer, respectively. Variations to these setups entail a layer of glass beads at the base of the brittle crust simulating a weak, frictional décollement comparable to what has been used by Cotton and Koyi (2000). The influence of sediment strength on subsequent deformation geometries during the inversion phase is accounted for by varying the granular material representing the syn-extensional sediments. These include quartz sand (model ~~4~~8), feldspar sand (model ~~12~~9) and glass microbeads (models ~~9 and 11~~10-12). The mechanical properties of all brittle and ductile materials used in this study are summarized in Table 2 and are described in detail in ~~Willingshofer et al. (2018)~~Klinkmüller et al. (2016) and ~~Klinkmüller~~Willingshofer et al. (~~2016~~2018).

[Table 2]

Scaling of all models follows ~~standard~~ scaling procedures described in the pioneering works of Hubbert (1937) and Weijermaars and Schmeling (1987). With a length-scale ratio of L* (Lmodel/Lnature) = 1~~.~~25 x 10⁻⁶, 1~~.0~~ cm in the model represents 8~~.0~~ km in nature (1:800.000). As such the initial and final model widths (after extension) scale to 352 and 464 km in nature, respectively. For modelling contraction of oblique rift structures, models ~~4~~7 and 8 have been increased in ~~size~~width to minimize boundary effects; a larger backstop ~~of 85~~leading to a final model width of 73 cm, scaling to ~~680~~584 km in nature, was used. For the adopted length scaling, the brittle-ductile transition of our analogue models is at a depth of 16 km in nature, which agrees with earlier published estimates of the brittle-ductile transition in the eastern Southern Alps (Willingshofer and Cloetingh, 2003; Viganò and Martin, 2007; Laubscher, 2010). At this depth the vertical stress (i.e., lithostatic stress) in, e.g., the platform regions of our experiments, is 590 Pa, corresponding to 880 MPa in nature, which results in a stress-scale ratio of 6~~.~~7 x 10⁻⁷. Strength profiles (Fig. 4b) are representative for the initial conditions and have been calculated following ~~Brun (2002). The density scale ratio ρ* (ρmodel/ρnature) yields 0,~~Weijermars (1997); Brun (2002). The density-scale ratio ρ* (ρmodel/ρnature) yields 0.54 as the density of our model material, e.g., quartz sand, is 1500 kg/m³, representing densities of 2800 kg/m³ of natural upper to middle crust (e.g., Ebbing, 2004; Faccenda et al., 2007; Šumanovac et al., 2009). The velocity for our brittle-ductile models is scaled after a time-scale ratio t* = 1~~.~~93 x 10⁻¹¹ calculated as:

$$t^* = \frac{1}{\varepsilon^*} \tag{1}$$

with ε* referring to the shear strain rate ratio equaling:

$$\varepsilon^* = \frac{v^*}{L^*}$$

(2)

where the velocity ratio v* is 6.49 x 10^4 and scales 2.5 cm/h of model velocity rate to 0.33 cm/a to nature, representing 50 km of shortening within a period of 15 Ma. This shortening rate correlates well with estimates form orogenic belts such as the eastern Southern Alps (Doglioni, 1987, 1991; Nussbaum, 2000). The velocity of the moving wall for brittle-ductile experiments simulates a compressional model strain rate of 1.13 x 10^{-3}, corresponding to 2.18 x 10^{-14} in nature. The viscosity of the ductile model material of 3.8 x 10^4 Pas scales to natural viscosities of approximately 10^{21} Pas, representing, ~~according to, e.g., Hirth et al. (2001),~~ quartz dominated ductile middle curst below the brittle-ductile transition~~.~~ (Hirth et al., 2001).

3.3 Monitoring and analysis of experiments

During the experimental runs, the model surface is monitored by top-view photographs (using a Panasonic Lumix DC-G9 with 20.3 megapixels) and a 3D surface scanner in order to trace changes in surface deformation. Top-view pictures and 3D surface scans have been taken at regular time intervals. For brittle and brittle-ductile experiments, the translation displacement between two successive top-view photographs is 0.15 cm and 0.125 cm, between two surface scans 0.75 cm and 0.625 cm, respectively. Adding coffee grains as tracers on the model surfaces facilitated calculating incremental particle displacements using particle image velocimetry (PIV) analysis (PIVlab, Thielicke and Stamhuis, 2004) and PIV-derived strain analysis (strainmap, Broerse et al., 2021). The strainmap tool of Broerse et al. (2021) further enables to determine strain types (e.g., extension, strike-slip, shortening and transitions) occurring during the respective model runs from the ratio of the largest to the smallest principal strain. The conversion of 3D surface scan data into digital elevation models enables tracing of the topographic evolution during the compressional deformation phase. After the model run, layers of black and natural coloured quartz sand are implemented as post-kinematic covers in order to preserve topography. Water sprinkled on the sand increases cohesion and enables sectioning the experiments for studying internal deformation in 2D. Photographs of 2D cross-sections (using Panasonic Lumix DC-G9 with 20.3 megapixels) are then put back together to a quasi 3D model using Midland Valley's MOVE software, in order to follow fault geometries laterally throughout the model.

3.4 Limitations and simplifications of analogue models

Potential influences leading to strain localisation like (i) surface processes (e.g., erosion, or sediment transport ~~or deposition of sediments~~), (ii) isostasy or (iii) temperature dependence ~~through depth~~of materials are absent in our physical analogue ~~modelling techniques and hence mark major limitations~~models. The viscosity of the ductile layer is therefore invariant to depth, what is widely accepted in analogue modelling studies (Davy and Cobbold, 1991), but can be adapted through implementing appropriate uniform viscosities. ~~Regarding (ii), the~~The absence of an asthenospheric layer excludes isostatic compensation of the model ~~layers~~ and therefore leads~~, in brittle~~ to an overestimation of the evolving topography. Shortening is mainly accommodated by (ductile ~~models, to)~~ thickening ~~of the ductile base layer. Ductile thickening accommodates~~

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355 ~~deformation during the shortening phase mainly in uplift, localising the~~close to the moving wall where strain ~~in systems of~~localises to form symmetric fore- and back-thrusts~~, which develop close to the moving wall~~. Despite those simplifications, the presented experiments resemble first-order deformation processes of a polyphase deformed continental crust and possible influences of erosion and sedimentation on the localisation of faults or on fault geometries in general are acknowledged (Graveleau et al., 2012) ~~are acknowledged.~~.

4 Modelling results

In the following sections, the results of our analogue modelling study are described, starting with a detailed description of the "reference model" (model 1, Fig. 5). Thereafter we comparatively describe the models based on interpreted top-view photographs, interpreted cross-sections of the final stage of the specific experiment, PIV analyses, and PIV-derived strain analyses~~, and by the use of topographic profiles extracted from digital elevation models.~~. Note that the transpressional

365 deformation at the western side of the western basin of model 4~~7~~ and model 8 is a result of the modelling setup with a wider backstop and not relevant for comparison with the natural prototype. The term thrust system (i.e., thrust sheet) is used in the following for a combination of fore-thrust and accompanying back-thrust(s).

4.1 Reference model, model 1

Model 1 (Fig. 5) ~~is an entirely~~ consists only of brittle ~~model (i.e.,~~material (quartz sand for ~~both~~ ~~for,~~ platforms and basin

370 ~~fillings) where~~fill) and basin inversion is parallel to the strike of the rift structures. The strength difference between platforms and basins is simulated by a variation in thickness of the sand layers (i.e., underfilled basins) (Table 1, ~~Fig~~Figs. 3a~~).~~ and 4a). Model 1 serves as reference model as it is the relatively simplest experiment of our study and allows for comparison to all other experiments, which represent variations to the reference model.

During extension, two asymmetric ~~grabens~~graben structures, separated by one platform, form, each with a major, high-angle

375 normal fault above the basal VDs (i.e., west and east of the western platform~~)~~ ~~(~~; see interpreted top-view ~~picture~~photograph in Fig. 5a, cross-section c-c' in Fig. 5g). As the basal kinematic boundary condition is opposite for both graben structures, the major normal faults dip in opposite directions. ~~Accompanying the major normal faults with large~~Large offset (~~e.g.,~~ ~~1,~~2 cm ~~offset along major normal faults of model 1~~ in cross-section c-c' in Fig. 5g) normal faulting on the stationary ~~(i.e., referring to the fixed plastic sheet beneath the deformable parts of the model)~~ side of the evolving graben~~, this first extensional phase also~~

380 ~~creates~~ is coeval with the formation of a large number of small-offset normal faults ~~with smaller offsets~~ on the ~~moving (i.e., referring to the~~mobile ~~plastic sheet beneath the deformable parts of the model)~~ side. All normal faults evolve perpendicular to the extension direction ~~of extension~~, are parallel to each other, appear straight, and dip towards the center of the main graben with an average dip angle of 63°. At the end of extension, model 1 consists of two basins and two platforms, which are perpendicular to the backstop (Fig. 5a, cross-section c-c' in Fig. 5g). The crust was thinner at the locations of the basins (1~~,~~4

385 cm average thickness) compared to the platforms (2~~,0~~ cm), leading to a platform-basin thickness ratio of 0~~,~~7 representing

lateral mechanical strength differences (Fig. 4b, cross-section c-c' in Fig. 5g), which~~,~~ simulates overall weaker basin domains (e.g., ~~alternation~~equivalent to alternations of limestone, marl, clay) compared to non-stretched platform areas (e.g., basement rock, carbonate platforms). Note that the strike-slip fault north of the eastern platform (Fig. 5a-d) is a result of the modelling setup, which bears no major implication for the modelling result during contraction.

390 Early stages of ~~parallel~~ basin inversion (Fig. 5b) already show curved thrust faults forming at platform-basin transitions (thrusts 1 of thrust sheet I in Fig. 5b), where the relatively weaker basins ~~transitions~~transition to the stronger platforms. The evolving thrust faults ~~clearly~~ show anastomosing ~~patterns~~orientations at their fronts and cross-cut pre-existing normal faults without reactivation of the latter.

395   **[Figure 5]**

After 4~~,~~.5 cm of shortening (Fig. 5c), a second, in-sequence thrust system II evolves, showing a curved thrust front, which is more distinct at the transition from the central western platform to the western basin than into the eastern basin. The cumulative strain map after 4~~,~~.5 cm of shortening (Fig. 5d) shows shortening close to the backstop especially in and close to basinal areas
400 (grey arrows in Fig. 5d), extension in the hanging wall of thrust system I within platform areas, and shortening at the fronts of both thrust systems I and II. ~~Parallel basin inversion is here most probably compensated by back-thrusting, as fault reactivation in such a high angle is not the favoured mechanism. Cross-sections of the final shortening stage of model 1 (sections a-a' and b-b' in Fig. 5g) reveal the platform hosted back thrusts 2, 4, 5 (section a-a' in Fig. 5g) and basin hosted back-thrusts 2, 3, 6 (section b-b' in Fig. 5g) which were active at 4,5 cm of shortening. The prominent back-thrust 6 of the eastern basin (section~~
405 ~~b-b' in Fig. 5g) is traceable on the model surface from 4,5 cm of shortening onwards (Fig. 5e-f).~~Basin inversion is here most probably compensated by back-thrusting, as the orientation of early formed normal faults is not favourable for reactivation.
By the end of ~~shortening~~the contractional phase (Fig. 5e-f, cross-sections a-a' and b-b' in Fig. 5g), the thrust front of the third and most external thrust system III is located further towards the foreland on platforms than in basinal areas (Fig. 5e-f, cross-sections a-a' and b-b' in Fig. 5g). ~~Pre-existing normal faults are cross-cut and transported piggy back as shown in Fig. 5e. The~~
410 ~~localisation of deformation~~Deformation in basinal areas is represented by backstepping of oblique thrust fronts towards the hinterland~~.~~ (Fig. 5e-f, cross-sections a-a' and b-b' in Fig. 5g). Backstepping follows the orientation of the platform-basin boundary. In model 1, where platform-basin boundaries are parallel (0° obliquity) to the shortening direction, the orientation of the thrust front at the transition from platform to basin is at high angle (~55°) to the overall strike of the mountain belt. Platform thrusts link with basin thrusts in the center of the respective basins (Fig. 5e-f).
415 Pre-existing normal faults are cross-cut by contractional faults and transported piggy back as shown in Fig. 5b-f. The extensional cumulative strain type which dominates the hanging walls of thrust systems I and II in platform areas (Fig. 5f), is a result of the passive uplift of thrust systems in the hinterland of the model orogen with in-sequence character. Passive uplift occurs along reactivated fore- and accompanying back-thrusts of the specific thrust systems. Fault reactivation is shown by two separate back-thrusts (back-thrusts 4 and 5 in cross-section a-a' in Fig. 5g), which root in one single fore-thrust 3 (cross-

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section a-a' in Fig. 5g). Both back-thrusts 4 and 5 cross-cut fore-thrust 1 and therefore indicate a younger age. ~~Due to this reactivation~~Reactivation of fore-thrust 3 ~~and the cross-cutting~~leads to steepening of ~~fore-thrust 1,~~earlier formed thrusts and uplift of thrust system I ~~with its initial fore-thrust 1 and back-thrust 2 (section a-a' in Fig. 5g) steepens along fore-thrust 1 and gets uplifted passively by younger thrusts 3 to 5 ((~~cross-section a-a' in Fig. 5g).

Overall, the style of thrusting documented in model 1 is a combination of foreland vergent pop-up systems, with in-sequence thrusting. Back-thrusts are either reactivated several times or formed new, meaning existing foreland-directed thrust faults being cross-cut by younger back-thrusts (e.g., fore-thrust 1 being cut by back-thrusts 4 and 5 in cross-section a-a' in Fig. 5g). The style of thrusting varies laterally, across platforms and basins, as both ramps and flats are longer on platforms (e.g., 4 cm ramp length of thrust 3 in cross-section a-a' in Fig. 5g) compared to those of basinal areas (e.g., 1~~.~~4 cm ramp length of thrusts 5 and 7 in cross-section b-b' in Fig. 5g), what is in accordance with the undulating surface expression of the thrust systems in map-view (Fig. 5e-f). The wavelengths of thrusts (i.e., the distance between the transition of lower flat to ramp of two adjacent thrusts) are longer on platforms compared to basin realms in parallel inversion models, e.g., 8~~.~~6 cm for platform hosted thrusts 3 to 6 (western platform, Fig. 5e-f, cross-section a-a' in Fig. 5g) and 6~~.0~~ cm for basin hosted thrusts 7 to 8 (eastern basin, Fig. 5e-f, cross-section b-b' in Fig. 5g). As normal faults are cut rather than reactivated during shortening, the basins are inverted and uplifted by closer spaced thrust imbrication compared to platforms (e.g., thrusts 4 and 7 in cross-section b-b' in Fig. 5g). This difference is related to thickness variations of the crust at the onset of shortening.

4.2 Parametrical study

In the following, we describe and compare ~~modelling results with variations in~~three sets of experiments, which focus on (i) the obliquity of inversion (Fig. 6), (ii) the basal décollement rheology ~~at base of the model~~ (Fig. 8), ~~and~~ (iii) the strength of the basin fill (Fig. ~~10) with respect~~10), and compare the results to the reference model (model 1, Fig. 5).

4.2.1 Influence of obliquity of inversion

Models 2 (Fig. 6a-c) and 3 (Fig. 6d-f) represent models where the inversion has taken place at angles of 10 and 20 degrees with respect to the rift axes (Table 1, Fig. 3b-c), respectively. Similar to model 1, both models are brittle only, have a platform-basin thickness ratio of 0~~.~~7 to 0~~.~~8 (i.e., underfilled basin) (Table 1) and a syn-extensional basin fill consisting of quartz sand (Fig. 4a). ~~. Overall~~Therefore, models ~~2~~1-3 represent set 1 of our experiments ~~and 3 produced close to similar basin platform geometries by~~aim at studying the ~~end of the extensional phase (compare Fig. 5~~influence of obliquity (0, 10 and ~~Fig. 6).~~20 degrees, respectively) of inversion on fault-reactivation and the kinematics and structural style of the evolving fold and thrust belt (Table 1).

~~The analysis of oblique~~Overall, models 2 and 3 produced close to similar basin ~~inversion models shows that~~platform geometries by the end of the extensional phase (Fig. 6a-b and 6d-e) and the curvature of the thrust fronts in map-view ~~increases with~~aligns to the orientation of the platform-basin boundary between western platform and eastern basin when increasing obliquity (compare Fig. 6a-b for 10° obliquity with Fig. 6d-e for 20° obliquity). ~~In models 2 and 3, this curvature is maximum~~

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~~at platform~~Compared to model 1, the deviation of the strike of contractional faults across platform-basin transitions ~~where~~from the overall strike of the ~~trusts~~model orogen is ~~at angles of 50 to 60 degrees with respect to the shortening direction~~~40° for model 2 and ~30° for model 3 (e.g., thrusts 5 of model 2 and 3 shown in Fig. 6a-b and Fig. 6d-e, respectively). ~~We note that angles of maximum 45° are obtained for models with parallel basin inversion.~~Thus, higher angles between basin axes and shortening direction, lead to less curvature of the thrust front relative to the overall strike of the mountain belt (e.g., ~30° for model 3 versus ~55° for model 1).

~~Platform thrusts~~Different to model 1, platform thrusts of models 2 and 3 preferentially link with basin thrusts ~~preferred~~at the eastern border of the grabens~~, e.g., at the transition from the eastern basin to the eastern platform (Fig.~~ (Fig. 6a-b, d-e~~), whereas in model 1, thrusts connect in the center of the respective basin (Fig. 5e-f)~~). Therefore, the location of lateral ramps and transfer zones shifts in oblique basin inversion models further towards the platform-basin transition. Additionally, the difference of wavelengths of thrusts between platform and basinal areas is more pronounced in experiments with oblique basin inversion (compare Fig. ~~6c, f) compared to models~~5g ~~with parallel basin inversion (Fig. 5g~~6c, f). The wavelength of thrusts is, e.g., for platform hosted thrusts 5 to 7 of model 2 (western platform, Fig. 6a-b, cross-section a-a' in Fig. 6c) is 12 cm, whereas it is only 0~~,~~.8 cm for basin hosted thrusts 6 to 7 (eastern basin, cross-section b-b' in Fig. 6c). ~~Comparable~~Model 3 shows comparable differences in wavelength of thrusts from platforms ~~to~~and basins~~ shows model 3~~, e.g., 7 cm for platform hosted thrusts 3 to 5 (western platform, Fig. 6d-e, cross-section a-a' in Fig. 6f) and 1 cm for basin hosted thrusts 4 to 5 (eastern basin, cross-section f-f' in Fig. 6f). ~~Both in~~In model 2 and model 3, ramps and especially flats of thrusts on platforms are ~~particularly~~longer (e.g., 5 cm ramp length of thrust 5 of model 2 in cross-section a-a' in Fig. 6c and 4 cm ramp length of thrust 5 of model 3 in cross-section e-e' n Fig. 6f) compared to thrusts within basins (e.g., 4 cm ramp length of thrust 7 of model 2 in cross-section b-b' in Fig. 6c and 3 cm ramp length of thrust 8 of model 3 in cross-section f-f' in Fig. 6f).

[Figure 6]

Models with oblique basin inversion seem to favour the development of laterally shorter (thrust sheets III and IV in model 2 in Fig. 6a-b and thrust sheets III and IV in model 3 in Fig. 6d-e) and isolated thrust systems (thrust sheet II in model 2 in Fig. 6a-b and thrust sheet II in model 3 in Fig. 6d-e). Model 2 (Fig. 6a-c) and model 3 (Fig. 6d-f) both show an initial thrust system I, which was laterally continuous over the entire model width, comparable to ~~parallel basin inversion~~model 1 (Fig. 5). However, thrust system II of models 2 and 3 is limited to the transition of the eastern basin to the western platform only. ~~Thrust system III in model 2 (Fig. 6a-c) shows, although~~Although very narrow in N-S direction within the eastern basin~~ (Fig. 6a-b, sections b-b' and c-c' in Fig. 6c), a W-E extent~~, thrust system III in model 2 extents over the entire width of the model~~,~~ (Fig. 6a-c), whereas thrust system IV in model 3 ~~(Fig. 6d-f, with increased obliquity compared to model 2,~~terminates within the eastern basin and does not reach the eastern platform~~. Thrust~~ (Fig. 6d-f). Also, thrust sheets IV and V in model 2 (Fig. ~~6a-c) both~~6a-c) and thrust sheet III in model 3 (Fig. 6d-f) terminate within the eastern basin, either as western or eastern termination. ~~Thrust sheet III in model 3 (Fig. 6d-f) is isolated and only present within the eastern platform and the eastern basin.~~This is in contrast

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with parallel basin inversion, where thrust systems I to III ~~can be found with a~~are laterally continuous ~~development of the deformation front all over the model's W-E extent (model 1, Fig. 5).~~along the entire model width.

In the case of oblique basin inversion, parts of platform sequences get thrusted over basinal sequences as shown at the transition of the western platform to the eastern basin along thrust 7 of model 2 (Fig. 6a-b) or thrust 5 of model 3 (Fig. 6d-e). Additionally, parts of basinal sequences get thrust over platform sequences (thrust 4 in cross-section c-c' in Fig. 6c, thrust 8 in cross-section f-f' and thrust 5 in cross-section g-g' in Fig. 6f). Otherwise, thrust faults cross-cut pre-existing normal faults and either overthrust them and/or transport them piggy back. In model 2, pre-existing normal faults are mostly cross-cut by younger thrust faults throughout the experiment, with an exception within the imbricated stack of thrusts of the eastern basin ~~(thrusts 4-7 in section b-b' in Fig. 6c),~~, where pre-existing normal faults get reactivated in oblique slip mode (thrusts 4, 6-7 in cross-section b-b' and thrusts 5 and 7 in cross-section c-c' in Fig. 6c). Thrusts 4, 6 and 7 of cross-section b-b' (Fig. 6c) and thrusts 5 and 7 of cross-section c-c' (Fig. 6c) of model 2 ~~(Fig. 6a-c)~~ incorporate fully reactivated normal faults up to their initial termination at the boundary between syn- and post-rift sediments (cross-section d-d' in Fig. 6c) and cut through post-rift sediments to the model surface. Thrusts 6 and 7 ~~of~~ in cross-section c-c' (Fig. 6c) are, together with non-reactivated normal faults, passively steepened by the younger in-sequence fore-thrust 8 (cross-section c-c' in Fig. 6c). ~~In~~Compared to model ~~3~~2, oblique reactivation of pre-existing normal faults as thrust faults is more common further in the hinterland of the model 3 orogen (thrusts 5-6 in cross-section f-f' and thrust 5 in cross-section g-g' in Fig. 6f) ~~compared to model 2 where fault reactivation is located further towards the foreland (thrusts 4, 6-7)~~. Furthermore, in ~~section b-b' and thrusts 6-7 in section c-c' in Fig. 6c). In~~model 3, normal faults are ~~(i)~~ if reactivated, fully reactivated as compressional faults (e.g., thrusts 5-6, 8 in cross-section f-f' and thrusts 4 and 7 in cross-section g-g' in Fig. 6f), ~~comparable to those in model 2, (ii)~~and cross-cut by younger back-thrusts (e.g., thrust 9 in cross-section g-g' in Fig. 6f) ~~and (iii)~~). Overall, in oblique inversion models, pre-existing normal faults are favoured areas ~~of~~where deformation ~~re-localisation~~localises (e.g., thrust 7 in cross-section g-g' in Fig. 6f grows towards the pre-existing normal fault and reactivates it~~.~~), compared to parallel inversion models.

~~Regarding the obliquity of~~For inferring oblique slip ~~along~~on thrust faults, zoom-ins on the strain type and time evolution diagrams of the incremental and cumulative strain types of selected points of models 2 and 3 are provided in Fig. 7. For model 2, points (a) and (b) (upper left-hand panel in Fig. ~~9~~7) are positioned in the footwall of the thrust fronts of thrust systems II and III within the eastern basin, respectively. The evolution of the two principal stretches λ (Hencky strains) shows increasing shortening at the thrust front after 50 min in model time for point (a) and slightly later (80 min) for point (b) (middle column in Fig. 7a-b). The dominant strain type for both points (a) and (b) is shortening (dilatation < 1, see right column in Fig. 7a-b), but the incremental strain type plots in between strike-slip and shortening/extension (right column in Fig. 7a-b), indicating transpressive to transtensive motion along the thrusts. For point (a), the temporal evolution of the incremental strain type deciphers a change from thrusting to strike-slip to extension (right column of Fig. 7a); for point (b) transpression until approximately 140 min in model time, leading into pure shortening. ~~Comparable~~Compared to model 2, points (c) and (d) of model 3 (middle left-hand panel in Fig. 7), which are positioned at the thrust fronts of thrust systems II and IV within the

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eastern basin, respectively, show shortening as dominant strain type with increased oblique slip motion of point (c) towards
the end of the model run.

[Figure 7]

4.2.2 Influence of basal décollement rheology

~~When combining~~Models 4-7 comprise set 2 of our experiments and focus on the influence of basal décollement rheology (Table 1) for conditions of parallel (models 4 and 6) and oblique (models 5 and 7) inversion. Variations of basal décollement strengths for parallel inversion setups (models 4 and 6, Table 1) have been included for completeness but will not be discussed in detail because of less relevance for the natural example. Instead, we focus on models with an obliquity of 20° between pre-existing structures and the shortening direction, and a variation of basal décollement strength and behaviour~~,~~.

The modelling results highlight major differences ~~in (i)~~related to the number of thrust sheets forming and ~~(ii)~~the style of fault reactivation ~~are observable.~~. Model ~~7~~5 (Fig. 8a-c) ~~shows oblique (20°) basin inversion of an entirely brittle model where a 0,6 cm thick layer of glass beads below the brittle crust of quartz sand simulates the presence of~~is characterized by a frictional ~~décollement (Table 1, ~~and model 7 (~~Fig. 4a). Model 8 (Fig. ~~8d-~~f) represents oblique (20°) basin inversion of a brittle ductile model with a 0,6 cm thick ~~e) by a viscous ~~layer~~décollement below the brittle crust. The latter has the same thickness as set 1 experiments (Table 1~~, brittle/ductile setup in Fig. ~~). In both~~4a). Both~~ models ~~7~~the thickness of the décollement is 0.6 cm and ~~8 have a~~the platform-basin thickness ratio ranges between 0~~,~~.7 and 0~~,~~.8 (i.e., underfilled basin) (Table 1, Fig. 4). Notably, ~~the~~phase 1 extensional basins are wider and more normal faults developed in case of a viscous décollement (compare ~~cross-section c-c' of ~~Fig. 8c with ~~7f).~~cross-section f-f' of Fig. 8f). As such, normal faults reach ~~farther~~further into the platforms (e.g., western platform in Fig. 8d~~-e) and~~), are mostly parallel~~ but~~, in some instances curved, and offset across strike through relay ramps (Fig. 8d-e).

~~In map view~~Upon shortening, model ~~7~~5 (Fig. 8a-b) and model ~~8~~7 (Fig. 8d-e) ~~both ~~show curved thrust fronts in map-view. At an early stage of deformation (i.e., thrust sheet I of model ~~7~~5 and ~~8~~7, Fig. 8a-b, d-e), the thrust front undulates but is approximately at the same distance from the backstop, ~~for~~at the platform as well as basin areas. At the final stage of deformation ~~(i.e., 9 cm of shortening, Fig. 8a-b, d-e),~~ the thrust front steps back in basinal areas and is located further towards the foreland on platforms~~. Comparable to oblique inversion models 2 and 3, the strike of the thrusts where ~~(Fig. 8a-b, d-e). Thrust curvature ~~is~~shows maximum ~~is~~alignment to the orientation of basin boundaries at angles of ~~55 to 60 degrees~~~30° with respect to the overall strike of the orogen (Fig. 8a-b, d-e). ~~shortening direction (e.g., transition of platform hosted thrust 4 to basin hosted thrust 5 of model 7 within the eastern basin in Fig. 8a-b). ~~Deformation is consistently concentrated at eastern borders of the respective basins, independent of ~~variations in ~~basal décollement material ~~at the base of the model ~~(Fig. 8a-b, d-e). This is shown by obliquely striking thrusts evolving on the eastern platform ~~and connecting~~which connect with ~~basin hosted ~~thrusts

~~at~~in the ~~eastern border~~basin through lateral ramps as indicated in the cumulative strain maps, which show predominance of ~~the eastern basin~~compressional deformation (Fig. 8b and 8e).~~8a-b, d-e).~~

[Figure 8]

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~~Lateral ramps and transfer zones of platform thrusts to basin thrusts strike oblique, the setting being mostly compressional (red colours in cumulative strain maps in Fig. 8b, e).~~ However, ~~the compressional domain is accompanied by slight~~ we also find indications for incremental oblique slip movements~~, as~~ in zoom-ins ~~on~~of the strain type and time evolution diagrams ~~of the incremental and cumulative strain types for~~ for selected points of models 5 and 7 ~~and 8 show~~ (Fig. 9). For model ~~7~~5, points (a)

560   and (b) (upper left-hand panel in Fig. 9) are positioned in the footwall of the thrust front of thrust system II. The actual thrust front location is shown through areas of strongest convergence of black material lines in the zoom-in panels of the strain type (left column in Fig. 9a-b). The evolution of the two principal stretches shows increasing shortening at the thrust front after 115 min in model time for point (a) and slightly earlier (105 min) for point (b) (middle column in Fig. 9a-b), ~~the latter~~which is located ~~(i)~~closer to the moving wall and ~~(ii)~~ within the eastern basin where the model crust is thinner compared to the platform.

565   The dominant strain type for both points (a) and (b) is shortening (dilatation < 1, see right column in Fig. 9a-b), but the incremental strain type for point (b) plots in between strike-slip and shortening (right column in Fig. 9b), ~~referring to~~suggesting lateral variations in oblique slip along the thrust front of thrust system II and slightly higher oblique slip within the eastern basin (towards the eastern platform~~) than on the western platform. The difference~~). Differences in ~~the amount of lateral oblique slip applies to the~~fault kinematics are also observed at the thrust front of model ~~8~~7 (points (c) and (d) in the middle left-hand

570   panel in Fig. 9~~), where~~). There, point (d), located at the footwall of the frontal thrust of thrust system II ~~within the eastern basin, shows~~, describes most of the time ~~purely~~pure strike-slip motion (right column in Fig. ~~9d), underlined by an equal deformation magnitude of the two principal stretches (middle column in Fig. 9d).~~9d). Instead, point (c), located on the western platform, shows mostly shortening, ~~but an~~with incremental strain ~~type plotting between~~types characterised by strike-slip and shortening~~, referring to slight oblique slip strongly overprinted by shortening (middle and right columns in Fig.~~ (Fig. 9c)~~. The~~

575   ~~onset of deformation in brittle-ductile model 8 is, for points (c) and (d), right at the model start (middle column in Fig. 9c-d).~~ When using glass beads or a viscous layer as basal décollement ~~instead of quartz sand only~~, two major thrust systems (Fig. 8) instead of three (model 1, Fig. 5) or four to five thrust systems (model 2 and model 3, Fig. 6) form. Both~~,~~ model ~~7~~5 and model ~~8,~~7 show an initial thrust system I with a W-E strike covering the entire width of the models. Thrust system II of model ~~7~~5 has its eastern termination within the eastern basin, whereas thrust system II of model ~~8~~7 extends from the western basin towards

580   the eastern platform. In map view, the style of deformation and thrust system evolution of model 7 is comparable to that of model 3 (Fig. 6d-e), but with longer (by ca. 1 cm) ramps and flats (compare cross-sections in Figs. 6 and ~~7~~8).
In cross-sectional view, normal faults dip shallower and are slightly more listric ~~in style of the normal faults compared to using quartz sand only (compare Fig. 5 and Fig. 6) or a viscous layer below quartz sand (Fig. 8d-f). Therefore, decreasing dip angles towards lower parts of the faults in combination with 20° of obliquity between inherited structures and shortening direction~~

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585 ~~lead to~~favouring their reactivation ~~of normal faults~~particularly at very low ~~dip~~ angle, ~~most likely~~mostly along W-~~-~~dipping ~~normal~~ faults, and in fault segments close to the backstop where the orogen is at maximum height (thrusts 1-5, 7 in cross-section b-b' in Fig. 8c). ~~Due to the initial phase~~Examples of ~~extension, the layer of glass beads (model 7, Fig. 8a-c) and silicon putty (model 8, Fig. 8d.f) thins out in basinal areas (sections b-b' and c-c' in Fig. 8c, sections e-e' and f-f' in Fig. 8f) and normal faults steepen and show a decrease in listric behaviour towards areas of lower glass beads and silicon putty thickness,~~

590 ~~respectively (sections b-b' and c-c' in Fig. 8c, sections e-e' and f-f' in Fig.~~ fault reactivation include ~~8f). This is directly related to a limited amount of reactivated normal faults as thrust faults in models 7 and 8. In model 7 only~~ the lowest fault segment of thrusts 1 and 3-5 ~~represents reactivation of an inherited normal fault;~~ in model ~~8 only~~5 (cross-section b-b' in Fig. 8c) and the lowest fault segment of thrust 5 in model 7 (cross-section e-e' in Fig. 8f). ~~Instead, both in~~ Compared to brittle-only models, in basin areas of models ~~7~~5 and ~~8,~~7, where the décollements are thinned most, less listric faults are observed opposing their

595 reactivation. Often normal faults ~~mostly~~ get folded and cross-cut by thrust faults as their dip angle mostly exceeds 45° and their dip direction varies between W- and E-dipping (cross-section b-b' in Fig. 8c and cross-section e-e' in Fig. 8f).

[Figure 9]

600 For model ~~8~~7, the area of deformation affected by shortening is comparable to brittle-only models, but the viscous layer facilitates transfer of deformation to the external part of the thrust system where inversion of normal faults takes place (e.g., in the footwall of ~~for~~fore-thrust 5 in cross-section e-e' in Fig. 8f). Other than in brittle-only models, where deformation jumps towards the foreland when a specific thickness of the thrust sheet is reached, in model ~~8~~7 shear zones close to the backstop within the ductile layer lead to ~~polyphase~~repeated reactivation of thrust sheet I (thrust 1 in cross-section d-d' in Fig. 8f, thrusts

605 1-4 in cross-section e-e' in Fig. 8f). ~~Because of imbrication~~Imbrication within the thrust sheet I and simultaneous growth of the orogen~~, the~~ yields extensional cumulative strain ~~type of thrust sheet I is strongly dominated by extension~~at the surface (Fig. 8e). In general, thrusts of set 2 experiments evolved in-sequence, with a vergence varying from mostly pop-up structures using a ductile layer (cross-sections d-d', e-e' in Fig. 8f) to foreland-directed using glass beads as basal detachment (cross-sections a-a', b-b' in Fig. 8c).

610 ~~In general, the thrusts evolved in both experiments in-sequence, with a vergence varying from mostly pop-up structures using a ductile layer (sections d-d', e-e' in Fig. 8f) to foreland-directed using glass beads as basal detachment (sections a-a', b-b' in Fig. 8c).~~

4.2.3 Influence of basin fill rheology

In models ~~11 and 12, glass beads and feldspar sand represent~~8-10 of set 3, the basin fill~~, respectively, instead~~ consists of either

615 quartz sand ~~(model 4).~~, feldspar sand or glass beads (Table 1), and oblique shortening conditions apply. Models ~~4, 11,~~11 and 12 of set 3, with glass beads as basin fill and ~~12~~parallel inversion, will not be discussed in detail. Models 8-10 show that a platform-basin thickness ratio of 1 basically leads to smaller differences in wavelengths of ~~thrusts~~deformation on platforms

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and in basins compared to experiments with platform-basin thickness ratios of 0~~.~~7 to 0~~.~~8 (Table 1, model 1 in Fig. 5, models 2 and 3 in Fig. 6, models ~~7~~5 and ~~8~~7 in Fig. 8).

620 For models ~~11~~9 and ~~12~~10, lateral differences in thrust orientations (e.g., curved fore-thrust ~~4 in model 11 in Fig. 5d e and~~ 5 in model ~~12~~9 in Fig. ~~5g~~10d-e and 4 in model 10 in Fig. 5g10g-h) are similar to other oblique inversion models ~~shown in this study (e.g., models 2 and 3 in Fig. 6, models 7 and 8 in Fig. 8), with~~yet the ~~strike of the thrusts where~~ maximum curvature ~~is maximum~~ at platform-basin transitions being at slightly ~~higher~~lower angles ~~of 70°(~25°)~~ with respect to the ~~shortening direction (e.g., transition of platform hosted thrust 4 to eastern basin of~~ overall strike of the mountain belt (e.g., model ~~11 in~~

625 ~~Fig. 10d e). Instead, in model 4,~~10, Fig. 10g-h). In contrast, in models where the basin fill has the same properties as the platform and is of equal thickness (model 8, Fig. 10a-b) thrusts do not change their orientation ~~laterally~~ across platform boundaries~~.~~ (Fig. 10a-c). This suggests that~~, when using the same thickness of quartz sand both for platforms and basins,~~ the strength ~~difference~~drop along the normal faults is not sufficient to produce changes in thrust orientation~~,~~ but ~~you also need~~additional lateral strength contrasts are needed as provided by a weaker basin fill~~, as glass beads of~~. In model ~~11 or feldspar~~

630 ~~sand of model 12 as basin fill simulate.~~

~~Ramps~~8, ramps of thrust faults show similar ~~extents~~ length-scales of ca. 4 cm on platforms and in basins (~~e.g., 4 cm ramp length of platform hosted~~ thrust 8 ~~of model 4~~ in cross-section a-a' ~~in~~of Fig.~~9c compared to 4 cm ramp length of basin hosted 10c or~~ thrust 10 ~~of model 4~~ in cross-section b-b' in Fig. 10c), whereas flat parts of thrust faults are slightly shorter (by ca. 1 cm) in basinal realms~~(e.g., 3 cm flat length for platform hosted thrust 5 of model 12 in section i i' in Fig. 10i compared to 2~~

635 ~~cm of flat length of basin hosted thrust 8 of model 12 in section k k' in Fig. 10i) or are partly not properly visible due to stronger imbrication in basinal realms. Exceptions are long flats in basinal realms of models 4 and 11 above sets of non-reactivated normal faults (e.g., 5 cm of flat length of thrust 8 of model 4 in section c c' in Fig. 10c and 4 cm of flat length of thrust 8 of model 11 in section g g' in Fig. 10f).~~.

640 **[Figure 10]**

~~Deformation~~In set 3 experiments, deformation localises at the position of pre-existing normal faults and contractional faults grow from there (e.g., thrusts 1-6 in cross-section b-b' in Fig. 10c, thrusts 1-~~9~~8 in cross-section f-f' in Fig. 10f, thrusts 1-~~8~~9 in cross-section j-j' in Fig. 10i). Concentration of deformation appears again preferred at eastern borders of basins, i.e., where

645 thrust faults of the younger deformation phase interact with and partly reactivate pre-existing, mostly W-dipping, normal faults (e.g., ~~fully reactivated normal faults as~~ thrust faults 4, 6, ~~5~~8, 10 in cross-section f-f' in Fig. 10f or thrust faults ~~5~~4, 6, 8, 10 in cross-section j-j' in Fig. 10i). Normal faults of model ~~4~~8 dip slightly steeper and are mostly cross-cut by thrusts (e.g., by fore-thrusts 1 to 6 in cross-section b-b' or by fore-thrusts 7-8 in cross-section c-c' in Fig. 10c~~), as normal faults dip slightly steeper in model 4 (quartz sand basin fill; section d d' in Fig. 10c) compared to model 11 (glass beads basin fill; section h h' in Fig.~~

650 ~~10f) and model 12 (feldspar sand basin fill; section l l' in Fig. 10i).~~). The lower friction coefficient of glass beads ~~compared to quartz sand and feldspar sand lead to~~leads to shallower (average of 55°) dipping ~~faults (normal and reverse faults) (model~~

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11; sections f-f', g-g', and h-h' in Fig. 10f). However, normal faults get reactivated most in model 12 (normal faults (model 10; cross-sections j-j' and, i-i', k-k' in Fig. 10i10i). However, this does not lead to more reactivation of normal faults. In contrast, fault reactivation is most prominent in model 9 (cross-sections f-f' and g-g' in Fig. 10f), where fully reactivated normal faults as compressional faults reach the model surface within thrust system II (thrusts 6-8 in cross-section k-k'g-g' in Fig. 10i10f).

Fault reactivation and moreOverall, pronounced foreland transport along major thrust faults (i.e., a wider orogen in N-S direction) are, compare cross-section i-i' in Fig. 10i with cross-sections e-e' in Fig. 10f and a-a' in Fig. 10c) is the characteristic mechanismsmechanism for models incorporating glass beads as basin fill (model 11; Fig. 10d-f10g-i), where the growth of the orogen in height is lower compared to models 48 and 129. Fault reactivation and orogen growth in height are the dominating mechanisms when using feldspar sand as basin fill (model 129; Fig. 10g-i10d-f). The overall deformation style is in-sequence for all experiments with a platform-basin thickness ratio of 1,and mostly foreland directed when using glass beads and feldspar sand; but using quartz sand as basin fill leads to a combination of foreland directed thrusts and pop-up structures.

5 Discussion of modelling results

In the following sections, we summarise (Fig. 11) and discuss the experimental results and compare them with previous studies.

5.1 Summary of modelling results

Our experiments show that the style and orientation of contractional structures isare strongly affected by the inherited rift geometry and the rheology of the basin fill. In particular, orientations of thrust fronts vary laterally across the inherited structures in all models, except for model 48 (Fig. 10a-b), where the there is effectively no strength difference of the materials used forbetween platforms and basins (i.e., quartz sand) was too low.at the onset of shortening. A reduction of strength along first phase normal faults is in these cases insufficient to influence the orientation of the evolving thrust structures. The oblique strike of thrusts across platform boundaries is accompanied by slightanalysis of incremental strain shows that oblique slip along thrust faults and reactivated normal faults as thrust faults in oblique inversion models, shown by temporal evolution of incremental strain at key locations in selected modelspredominantly occurs across platform boundaries where the strike of contractional faults deviates from the overall strike of the mountain belt by ca. ~30° (e.g., Figs. 7 and 9).

Models where shortening was oblique to the rift axes (10 and 20 degrees) and the platform-basin thickness ratios were less than 1 lead toshow (i) a shift of the transfer zone of thrust faults connecting platformplatforms with basin realms from basin centers (e.g., parallel inversion of model 1 in Fig. 5) to platform-basin transitions, and (ii) a marked variability of thrust strikes of updown to 70°~25° with respect to the shortening directionoverall strike of the mountain belt (compared to an average of 3755° for parallel inversion models). Additionally, such kinematic boundary conditions favouroblique shortening favours the reactivation of W-dipping normal faults (e.g., normal faults 4, 6-7 in cross-section b-b' in Fig. 6c, normal faults 4 and 7 in cross-section g-g' in Fig. 6f) whereas E-dipping normal faults are preferentially cut by contractional structures leading to

thrusting of platforms on top of basin sequences and an increase of ramp lengths. Ramps and flats are especially shorter in basins in parallel inversion models as basins consist initially of thinner crust (e.g., compare cross-section b-b' of parallel

685 inversion model 1 in Fig. 5g with cross-section b-b' of oblique (10°) inversion model 2 in Fig. 6c).

Models including a frictional basal décollement result in (i) shallower dipping normal faults with an average dip of 55° compared to models without (average dip of 63°), (ii) fewer thrust systems (two instead of three or more in models without basal décollement), (iii) longer ramps and flats especially on platforms, and (iv) fewer back-thrusts. Models with a viscous basal décollement show (i) curved ~~and through relay ramps offset~~ normal faults with relay ramps in between fault segments,

690 (ii) deformation ~~spreading~~being distributed over larger areas ~~due to distribution of deformation within the ductile layer~~, (iii) ~~normal faults not incorporated in the fold-and-thrust belt experiencing~~fault reactivation ~~as thrust faults~~at distance to the model orogen (e.g., reactivated normal fault in the footwall of fore-thrust 5 in cross-section e-e' in Fig. 8f), and (iv) fewer thrust systems similar to models with a frictional basal décollement.

Models with ~~higher~~ platform-basin thickness ratios of 1 and variable material for the basin fill (i.e., other than quartz sand)

695 result in (i) more thrusts (~~e.g., up to 10 thrust faults in the eastern basins of model 4~~Fig. 10f and ~~11 in section b-b' of Fig. 10c and section f-f' in~~Fig. 10c, respectively~~10i), (ii) ~~even narrower spacing of thrusts~~more fault reactivation within basins ~~compared to basins of other~~during oblique (20°) inversion ~~models presented in this study~~ (e.g., model 3 in Fig. 5d6d-f and models 5 and ~~models~~7-~~8~~ in Fig. 8), and (iii) less lateral ~~variations of~~variation in thrust ~~orientations~~orientation across platform-basin boundaries.

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[Figure 11]

5.2 Do inherited extensional structures trigger strain localisation during contraction?

Basins in general, as well as normal faults at platform borders, represent natural weakness zones in which deformation

705 ~~concentrates~~localises during parallel to oblique basin inversion (Doglioni, 1992; Munteanu et al., 2013). Results of all models presented in this study confirm that deformation localises in areas of lateral strength contrasts in the crust such as transitions from platforms to basins, which are characterised by intense faulting and a change from basement or platform to basin sequences (Figs. 5, 6, 8, 10, 11). ~~With respect to the former, friction is decreased by about 17% for the quartz sand wherein the normal faults developed as shown by ring-shear experiments inferring frictional properties for peak- and reactivation~~

710 ~~conditions~~Upon faulting, friction decreases within the quartz sand by about 17 % (Willingshofer et al., 2018). ~~A~~ Furthermore, ring shear tests constrain fault reactivation for the analogue material for friction ~~coefficient~~coefficients of ca. 0.52~~for fault zone material falls thus within the possible range of friction~~. For such values ~~for reactivating~~reactivation of normal faults dipping at 60° is expected (Sibson, 1995)~~. In contrast, analogue modelling studies using materials with higher reactivation friction reported less evidence of fault reactivation (Panien et al., 2005)~~, leading to localisation of deformation at the position

715 of the normal faults. However, we do not find a correlation between strain localisation and the position of the normal faults in

cases where there is no strength contrast from platform to basin fill, suggesting that the reduction of strength along the normal faults in our experiments is insufficient to trigger strain localisation. Instead, our modelling results suggest that lateral strength variations related to the transition from rigid platforms to the weak basin fill are required for strain to localise at platform-basin transitions. These results are consistent with earlier modelling studies demonstrating the importance of strength variations in the crust for the localisation of deformation (Brun and Nalpas, 1996; Sokoutis and Willingshofer, 2011; Bonini et al., 2012; Calignano et al., 2015; Auzemery et al., 2020).

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Previous studies have furthermore shown that localizationlocalisation of deformation through the reactivation of pre-existing faults, is favoured when the shortening direction is at angles smaller than 45° with respect to the strike of the inherited discontinuities (e.g., Nalpas et al., 1995; Brun and Nalpas, 1996; Amiliba et al., 2005; Panien et al., 2005; Del Ventisette et al., 2006; Yagupsky et al., 2008; Deng et al., 2020) or the fault is substantially weakened by clay smearing (e.g., Marques and Nogueira, 2008) or elevated pore-fluid pressure (Sibson, 1995). Yet the latter is not part of our experimental work, our modelling results support these earlier findings as demonstrated by the fact that inherited normal faults are more often reactivated upon oblique inversion. Additionally, we note that normal faults dipping against the direction of shortening (W-dipping normal faults in our models) seem to be better oriented for reactivation than E-dipping normal faults (Figs. 6, 8, 10).

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Consequently, E-dipping normal faults are preferentially cut by newly formed thrust faults. A similar relationship has been described by Panien et al. (2005).

Lateral strength variations caused by the transition from rigid platforms to the weak basin fill is supported through tighter spacing and therefore a higher number of in-sequence thrusts (e.g., compare platform section e-e' and basin sections f f' and g g' of model 11 in Fig. 10f). These results are consistent with earlier modelling studies demonstrating the importance of strength variations in the crust for the localisation of deformation (Brun and Nalpas, 1996; Sokoutis and Willingshofer, 2011; Bonini et al., 2012; Calignano et al., 2015; Auzemery et al., 2020).

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5.3 Are the vertical motions at platforms different to basins?controlled by the inherited platform-basin configuration?

The style of thrust faulting is overall comparable on platforms and in basins and mostly in-sequence, the latter is shown as the preferred deformation style in many previous analogue modelling studies (e.g., Ellis et al., 2004; Panien et al., 2005; Deng et al., 2020). Tighter spacing of thrusts in basinal areas, is mostly depending on the difference of initial crustal thickness (Mulugeta, 1988) (i.e., platform-basin thickness ratio of 0,7-0,8 in all but models 4, 11, and 12 where it is 1),. Yet accompanied with shorter and steeper ramps, this does not lead to enhanced vertical motions within basinal areas. Instead, longer ramps and flats on platforms result in higher topography, also at the final stage of the inversion models.. The rheology of the basal décollement ishowever, seems to be of importance regardingfor differences in vertical motion across basin boundaries. Using, e.g., a viscous basal décollement leads to shearing within the ductile layer close to the backstop within the eastern basin of model 8 (7 (cross-section e-e' in Fig. 8f) and therefore to strong uplift of thrust sheet I. Overall, models including a basal décollement (i.e., frictional or viscous) show lower vertical motionsless topography than models without (Liu et al., 1992; Ravaglia et al., 2006), independent of platforms or basins.

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Regarding basins, we modelled different basin sizes to conceptually test variations in fault localisations. LargeOur modelling setup produces large (western) and small (eastern) rift basins with ranges of basin sizes between 11,0-14,0 cm, average widths of 12,.2 cm (i.e., western basin) and 8,2-9,5 cm, average 8,.6 cm (i.e., eastern basin), . respectively (Fig. 12a). The style and number of thrust faults (e.g., 6 major fore-thrusts within both the western and eastern basins of model 11 in Fig. 10d-e) are very similar in large and small basins. Comparing vertical motions in large and small basins, parallel inversion models (e.g., model 1 in Fig. 5) show similar vertical motions in both basins, whereas oblique inversion leads to enlarged vertical motions within the eastern basin. Due to oblique inversion, western (Fig. 10g-h) but topography evolutions differ, particularly in cases where the western platforms get thrusted onto basin successions of eastern basins (e.g., models 2 and 3 in Fig. 6,6, models 5 and 7 in Fig. 8, models 7 and 8-10 in Fig. 8, models 4, 11, and 12 in Fig. 10), resulting in successive gain of crustal thickness compared to the western basin.10). In these cases, more pronounced thickening of the crust results in high topography.

[Figure 12]

5.4 What controls the variation in strike directions of the major thrust faults?

Our analogue models emphasize strong lateral variability in thrust fault orientation across platform-basin transitions (i.e., pre-existing rheological discontinuities),. which has also been observed by Ravaglia et al. (2004); Di Domenica et al. (2014). The lateral variability of thrust fault strikes can be up to 70° with respect to the shortening directionsoverall strike of the model orogens varies between ~55° for parallel inversion models to ~25° for oblique inversion setups. The close correlation of these variations with the platform-basin transitions suggest causal relationships with the orientation of inherited strength variations. We also note that this feature is a robust model outcome and not applicable for the exceptional case where the basin is completely filled with material of the same strength as the platforms are made of.

Quantitative differences of thrust front positions from the backstop in both western and eastern basins are presented in Fig. 12b. From a conceptual point of view, deformationDeformation localises in both, large and small basins, but backstepping of the thrust front is more profound in larger basins (Fig. 12b) due to more space for lateral ramps. This appliesleading to stronger undulationsvariations of thrust faults in experiments where the thrust front is located further towards the hinterland within the large basin (i.e., western basin)fault orientations (Fig. 11, Fig. 12b). In other cases, where the thrust front in the large and small basin are located at equivalent distances from the backstop (e.g., models 4, 7, 115, 8, 10 in Fig. 12b), the thrust front is either continuous from the western to the eastern basin or an additional fore-thrust formed separately in the western basin without connection towards the eastern basin (e.g., model 7 in Fig. 11m-n). In model 4, the location of the thrust front within the western basin is even further in the foreland of the orogen compared to the western platform (Fig. 11g-h, Fig. 12b), what could be (i) influenced from the presence of another platform to the west, as a wider backstop was used in this experiment in order to conceptually test basin inversion in large basins with straight graben borders or (ii) due to the use of the same material for platforms and basins (i.e., quartz sand) additional to a platform-basin thickness ratio of 1, resulting in a too low strength

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~~contrast between platforms and basins.~~model 5 in Fig. 11i-j). Thrust fronts are at approximately the same position in basins and platforms and show little variation in orientation when the platform-basin thickness ratio is 1 and no rheologic contrasts exists between basins and platforms (e.g., model 8).

785 Earlier studies including strength contrasts between basins and surrounding areas by variations in crustal thickness and in basin fill material yielded similar results (Nalpas et al., 1995; Panien et al., 2005) suggesting that pre-existing lateral heterogeneities within the model ~~already prior to the shortening phase and~~ are a major controlling factor for the ~~undulation~~orientation of the thrust faults. As such, their nature is different to variations of thrust orientations related to lateral variation of décollement strength (Cotton and Koyi, 2000; Nieuwland et al., 2000). ~~Similar to Nalpas et al. (1995); Panien et al. (2005) we tested the~~
790 ~~influence of basin fill rheology on the evolution of shortening structures. The results consistently indicate the mechanical stratification of the basin fill exerts a strong control on the style of deformation and the orientation of the shortening structures. On the scale of the lithosphere, Calignano et al. (2017) show that pre-existing heterogeneities that are oblique to the shortening direction can lead to the formation of oroclines.~~

Surprisingly, ~~the above described transfer zones, the~~cumulative strain on oblique thrust segments that connect basins and
795 platforms~~, show little evidence for strike-slip movement~~ is of thrust-type (Figs. 7 and 9~~).~~) and strike-slip dominated phases of motions are transient features during incremental stages of thrust formation and displacement. We suggest, that this can be explained by strain partitioning as described in complex fault systems (Krstekanić et al., 2021; Krstekanić et al., 2022).

6 Application to polyphase deformation within the Dolomites Indenter of the eastern Southern Alps

The model outcomes show that the presence of an inherited platform-basin configuration controls the localisation and overall
800 style of deformation during the subsequent shortening phase. These first-order results of our crustal-scale analogue modelling study agree with previous studies of the Dolomites Indenter of the eastern Southern Alps, highlighting the importance of inherited Mesozoic structures on Alpine deformation (Doglioni, 1992; Schönborn, 1999; Verwater et al., 2021). Other than in previous analogue modelling studies where indenters were assumed rigid (Tapponnier et al., 1982; Ratschbacher et al., 1991; Luth et al., 2013a; Luth et al., 2013b; Krstekanić et al., 2021; Krstekanić et al., 2022), we focus on indenter internal deformation
805 and therefore follow Sokoutis et al. (2000); Willingshofer and Cloetingh (2003); Van Gelder et al. (2017)~~, stating indenters are never completely rigid.~~, by using a deformable indenter. Kinematically, the model configuration of oblique (20°) basin inversion comes closest to SSE-directed inversion of approximately N-S striking inherited discontinuities within the Dolomites Indenter of the eastern Southern Alps. As such model 7, which also resembles the natural example of the Dolomites Indenter best on aspects of structural style of extensional structures, the overall style and kinematics of deformation related to the
810 subsequent shortening phase, and shortening within basinal areas, has been chosen as our "best fit model" which will be used for the comparison with the natural example. We remark that our crustal-scale analogue models do not account for strength variations with the platforms (e.g., mechanically stronger northern part of the Trento platform, related to the presence of the up to 2 km thick Athesian Volcanic Complex; Bosellini et al., 2007) or the evolution

815 Evaluating all conducted experiments (Fig. 11), the outcome of model 8 (Table 1, Fig. 8d-f) resembles most closely the natural example of the Dolomites Indenter, particularly on aspects of (i) style of extensional structures, (ii) overall style of the subsequent shortening phase and (iii) shortening within basinal areas. Not included in any of our crustal-scale analogue models and therefore also not in the best-fit model are (i) a mechanically stronger northern part of the Trento platform, related to the presence of the up to 2 km thick Athesian Volcanic Complex (Bosellini et al., 2007) and (ii) the presence of the sinistral

820 transpressive Giudicarie fault system delimiting the Dolomites Indenter to the NW (Castellarin and Cantelli, 2000; Viola et al., 2001; Pomella et al., 2012; Verwater et al., 2021), which strikes slightly oblique to parallel to Late Triassic/Jurassic extensional structures and oblique to Neogene compressional structures.is beyond the scope of this study.

6.1 Best fit model for the Dolomites Indenter

825 Extensional structures of the best-fit model (model 7, Fig. 8d-f) are characterised by curved fault segments, which are connected via relay ramps. In this model, normal faulting also affected parts of the Trentino platform resulting in tilted fault geometries and half-grabens (Fig. 8d-f). These structures are in accordance with local to regional scale graben structures within the platforms of the Dolomites Indenter, e.g., the Seren graben (Doglioni, 1992; Doglioni and Carminati, 2008; Sauro et al., 2013) located within the hanging wall of the Bassano-Valdobbiadene thrust and probably controlled by inherited Jurassic

830 geometries. During subsequent shortening those graben structures partly get reactivated and inverted, both in analogue models (cross-section e-e' in Fig. 8f) as in the natural analogue (Sauro et al., 2013).

The in-sequence deformation style of the shortening phase fits well towith the documented in-sequence thrust sequence of the Southern Alps (Doglioni, 1992; Castellarin and Cantelli, 2000). The pop-up structure of thrust system II on the western platform of the best-fit model (7 (cross-section d-d' in Fig. 8f) is in line with, e.g., the so called Asiago (i.e., Sette Comuni)

835 pop-up structure between the Bassano-Valdobbiadene fore-thrust and the Val di Sella back-thrust (Fig. 1b) (Barbieri, 1987; Barbieri and Grandesso, 2007) of the natural analogueTrento platform. The Asiago pop-up is documented as wide box-fold becoming narrower when entering the Belluno basin and ending in a transpressive waystructure at the transition of the Belluno basin to the Friuli platform (Doglioni, 1990, 1992). A decrease in size of the pop-up structure from the Trento platform towards the Belluno basin is also documented in the best-fit model (compare cross-sections d-d' and e-e' in Fig. 8f). Comparing the

840 style of thrusting on the platform (cross-section d-d' in Fig. 8f) and in the basin (cross-section e-e' in Fig. 8f), ramps show shallower dips in basinal compared to platform successions, resulting in longer ramps on platforms and shorter ramps in basins, taking thicker model crust on platforms compared to basins into account.. Flats in basins show different positions compared to flats on platforms (lower height and closer to the backstop). This observation is in accordance with models of Doglioni (1992), where, e.g., the anticline in the hanging wall of the Bassano-Valdobbiadene thrust (Fig. 1b) is located further external

845 on the Friuli platform (i.e., Maniago thrust in Doglioni (1992)) than within the Belluno basin (i.e., Bassano thrust in Doglioni

(1992)), across the W-dipping normal fault transition zone at the transition from Friuli platform to Belluno basin. 1b) is located further external on the Friuli platform (i.e., Maniago thrust in Doglioni, 1992) than within the Belluno basin (i.e., Bassano thrust in Doglioni, 1992), across the W-dipping normal fault transition zone at the transition from Friuli platform to Belluno basin. W-dipping normal faults show, according to Doglioni (1992), especial strong sinistral reactivation (e.g., W-oriented

850   faults within the sinistral transpressive Giudicarie belt at the margin of the Trento platform towards the Lombardian basin). In contrast, our models suggest strike-slip movement (mostly transpression) of (reactivated normal) faults at western boundaries of basins (i.e., along E-dipping normal faults) (Fig. 9c-d). This is in accordance with strike-slip transpressive reactivation of paleostructures pre-existing structures oriented oblique to the shortening direction along lateral ramps (Schönborn, 1999), like, e.g., the Cimolais-Longarone or Tagliamento zones (Nussbaum, 2000). The Cimolais-Longarone zone (Nussbaum, 2000), e.g.,

855   is located within the Belluno basin, in the hanging wall of the Belluno thrust, directly north of the transfer zone of the Bassano-Valdobbiadane thrust from Belluno basin to Friuli platform (Fig 1b).

In terms of normal fault reactivation, Our best-fit model 8 shows stronger inversion of shallow W-dipping normal faults (e.g., thrust 5 in cross-section e-e' in Fig. 8f), whereas E-dipping normal faults have more likely been folded and/or cut by compressional structures (e.g., folded and cut normal fault in the hanging wall of fore-thrust 4 in cross-section d-d' and in the

860   hanging wall of fore-thrust 1 in cross-section e-e' in Fig. 8f). Lateral changes in fault reactivation are common at platform-basin transitions, e.g., thrust 7 in cross-section e-e' in Fig. f, which is independent from the normal fault in its immediate footwall; the latter getting reactivated as thrust fault straight E of cross-section e-e' (Fig. 8d-e).

The overall style of compressional deformation documents undulations variations of the (frontal) thrust orientations and of the fold axes of frontal growth folds across lateral discontinuities (e.g., platform hosted thrust 2 in Fig. 8d-e and cross-section d-

865   d' in Fig. 8f stepping back towards the eastern basin), the latter representing anisotropies, like lateral ramps of transfer zones in, e.g., the upper to middle crust. Similar effects have been shown by Ravaglia et al. (2004), where growth folds in transfer zones produce lateral culminations in the folded structures. The style of deformation within the basinal areas of the best-fit model 8 is especially well in line with the natural analogue when comparing the model cross-section to geological cross-sections through (i) the Venetian Alps, where platform (i.e., Trento platform) get thrusted over basinal (i.e., Belluno)

870   successions (Doglioni, 1992; Schönborn, 1999) or (ii) the Friuli Alps, where basinal (i.e., Belluno and/or Slovenian basin) sediments are located north of platform (i.e., Friuli platform) successions and get thrusted over the latter (Kastelic et al., 2008; Ponton, 2010). Characteristic for the Friuli Alps is that the steep to the S dipping backthrust is steeply dipping to the S (Fella fault), which is cut by several N-verging thrust faults (Merlini et al., 2002; Galadini et al., 2005; Kastelic et al., 2008; Ponton, 2010; Poli and Zanferrari, 2018). In our best-fit model 8, the position of the fore-thrusts 1-4 (cross-section e-e' in Fig. 8f)

875   indicates polyphase shearing within the ductile layer close to the backstop (cross-section e-e' in Fig. 8f), supporting the crustal-scale (Poli et al., 2021) high-angle backthrust in, e.g., the model of Venturini (1990). As this shear zone (section e-e' in Fig. 8f) does not reach the model surface, discussion about the amount of lateral (dextral referring to Merlini et al. (2002)) movement along the fault is not possible. As this shear zone (cross-section e-e' in Fig. 8f) does not reach the model surface, discussion about the amount of lateral (dextral referring to Merlini et al., 2002) movement along the fault is not possible.

6.2 Structural observations along the western Belluno fault of the Valsugana fault system

Polyphase deformation within the Dolomites Indenter of the eastern Southern Alps is well known ~~throughout its extent from W to E~~ through regional paleostress studies with plenty of studied sites along the whole Southern Alps, dated with a tectonic stratigraphic approach (Doglioni, 1991; Carulli and Ponton, 1992; Castellarin et al., 1992; Doglioni, 1992; Polinski and Eisbacher, 1992; Caputo, 1996; Castellarin et al., 1998; Castellarin and Cantelli, 2000; Mellere et al., 2000; Venturini and Carulli, 2002; Kastelic et al., 2008; Caputo et al., 2010; Abbà et al., 2018; Poli et al., 2021). Additionally, a detailed reconstruction of the Adria-Europe convergence path, based on the magnetic anomalies of the Atlantic Ocean by Dewey et al. (1989), presented by Mazzoli and Helman (1994), suggests similar timing and direction of convergence as observed in the paleostress reconstructions of the Southern Alps and other Mediterranean areas (e.g., Fellin et al., 2005; Caputo et al., 2010).

To compare analogue modelling results with internal deformation of the Dolomites Indenter, fault slip data from existing ~~studies~~ regional studies (e.g., Caputo, 1996; Castellarin and Cantelli, 2000; Caputo et al., 2010) were compiled and supplemented with new local fault slip data and shortening directions referred from strongly folded strata from the field (Fig. 13~~). Overall,~~), leading to the following main deformational phases within the Dolomites Indenter since the Late Triassic ~~are~~: (i) ~~D0~~D1 – Late Triassic to Jurassic W-E extension, (ii) ~~D1 – the ?Cretaceous to Paleogene top S-directed pre-Adamello phase is mentioned for completeness, but until today only suspected within the eastern Southern Alps, while detected within the western Southern Alps west of the Giudicarie belt (Castellarin et al., 1992), (iii)~~ D2 – Paleogene top SW-directed shortening, mostly thin-skinned (i.e., Dinaric phase), (~~iv~~iii) D3 – Miocene top S(SE)-directed shortening, mostly thick-skinned (i.e., Valsugana phase), ~~(v) Miocene to Pliocene top S-directed shortening,~~ which undulates from top ~~SSW directed~~S- to top SSE-directed and (~~vi) D5~~iv) D4 – Pliocene to Pleistocene top E(SE)-directed shortening, mostly transpressive, and with an increasing prominence towards the east (Fig. ~~13).~~13). A common problem within the polyphase deformed Southern Alps is, when cross-cutting relationships can not be found in the field. As this is the case for D3 in our study, shortening directions changing from top SSW- via top S- to top SSE-directed were combined. Deformation phase D4 clearly cross-cuts previous, top S-directed deformation.

[Figure 13]

Variations in structural style along strike of thrusts within the Dolomites Indenter were studied by collecting measurements of planar (bedding, fault planes, S-C fabrics) and linear (fault striation, fold axes) structural elements along ~~several major faults. Here we~~major fault zones between Adige Valley in the west (for location see label Bozen in Fig. 1b) to the Friuli Alps in the east (for location see label FriR in Fig. 1b). Here we zoom in and present structural observations along the western segment of the Belluno thrust as a case study (Fig. ~~14a-b~~14a-b). Our spatially distributed data along major faults across the Dolomites Indenter were integrated in the compilation of the main deformational phases (Fig. 13).

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The Belluno thrust belongs to the Valsugana fault system and represents a southern thrust splay of the Valsugana thrust, merging into the Valsugana thrust slightly east of Borgo Valsugana (location 1 in Fig. 14b). The Belluno thrust is part of the Valsugana fault system and represents a southern thrust splay merging with the Valsugana thrust slightly east of Borgo Valsugana (location I in Fig. 14b). The Belluno thrust was mainly active during the Miocene or later (deformation phase D3, Fig. 13) with an eventual initiation in the Late Oligocene (Vignaroli et al., 2023), has been reactivated several times (Vignaroli et al., 2020), and shows seismic activity at present (Areggi et al., 2023). The overall strike of the approximately 20 km long and approximately 30° to the N dipping Belluno thrust is WSW-ESE-trending (Vignaroli et al., 2020; Zuccari et al., 2021). The hanging wall of the Belluno thrust shows a prime example of is a S-verging fault-propagation fold (Mt. Coppolo anticline) with a sub-vertical forelimb (Vignaroli et al., 2020). The Mt. Coppolo anticline exposes Upper Triassic to Lower Jurassic shallow water carbonates (Dolomia Principale, Calcari Grigi Group), which are thrusted onto Cretaceous to Paleogene strata (Maiolica Formation, Scaglia Variegata Formation, Scaglia Rossa Formation) (D'alberto et al., 1995). (D'Alberto et al., 1995). In the western segment of the Belluno thrust, close to where it merges into the Valsugana thrust (Fig. 14b), fault slip data from within the footwall of the Belluno thrust shows top SSW-directed shortening, accompanied by strongly folded strata with a mean fold axis of 301/14 (1I in Fig. 14a, for location of 1I see Fig. 14b), suggesting SSW-NNE directed shortening. Further towards the east (location 2II in Fig. 14b), fault slip data from within the footwall of the Belluno thrust mainly shows top S-directed thrusting, with undulations towards the SSW and the SSE (2II in Fig. 14a, for location of 2II see Fig. 14b). Top S-directed thrusting is supported by shallow plunging mean fold axes of 265/05 and 091/07 within Jurassic to Cretaceous strata in the footwall of the Belluno thrust (2II in Fig. 14a, for location of 2II see Fig. 14b). Data from location 2II origin from west of major pre-existing Mesozoic discontinuities within the Trento platform and towards the western boundary of the Belluno basin, e.g., the Seren graben and the Cismon valley alignment (Sauro et al., 2013). Our data of location II (Fig. 14b) support top S-directed thrusting, although mixing of directions can not be excluded totally, as cross-cutting criteria are partly hard to discover within the polyphase deformed eastern Southern Alps. Even further towards the east, where the Belluno thrust crosses the boundary from the Trento platform towards the Belluno basin (location 3III in Fig. 14b), fault slip data from its footwall provides thrusting directions towards SSE, accompanied by a mean fold axis of 250/22 (3III in Fig. 14a, for location of 3III see Fig. 14b). The along strike change of shortening kinematics from top SSW- via top S- to top SSE-directed in our data can be explained by strain partitioning along the Belluno thrust.

[Figure 14]

6.3 Variability of deformation styles and thrust fault orientations: Implications of modelling results for the eastern Southern Alps

Fault geometries in map-view of the conducted physical analogue experiments (Fig. 11) show strong resemblance with the fault geometries in map-view of the natural prototype (Figs. 1b, 14b). Especially striking are the (i) tighter spacing of thrusts

945 in basinal areas (e.g., Belluno basin), and ~~(ii)~~ curved thrust fronts at platform-basin transitions~~, e.g.,~~. Examples of the latter include the Belluno thrust both at the transition from Trento platform to Belluno basin (Zampieri and Grandesso, 2003) as from Belluno basin to Friuli platform or the Bassano-Valdobbiadene thrust at the transition from Belluno basin to Friuli platform (Picotti et al., 2022). ~~Observation from (i) match with field descriptions~~Field observations from the eastern Southern Alps~~, where~~ also show that the spacing of thrusts is tighter within the Belluno basin than on the Trento platform (Doglioni,

950 1991; Doglioni and Carminati, 2008). According to Doglioni (1991), both folds and thrusts show reduced wavelengths in basinal areas in the natural prototype, supporting the tighter spacing of thrusts in basins. Our analogue models support longer wavelengths of thrusts on platforms in contrast to shorter wavelengths in basins (Figs. 5, 6, 8, 10). Transitions between variations in wavelengths of thrusts appear at platform-basin boundaries, at so called transfer zones. Our models indicate that the size of the basin (Fig. 12a) ~~rules~~controls the width of the transfer zone and the lengths of oblique lateral ramps between

955 platform and basin domains. Backstepping of the most external thrust front in basins compared to platforms ~~is, in most of the analogue experiments presented in this study (Fig. 11),~~(Fig. 11) is more distinct in the western (i.e., Lombardian) basin than in the eastern (i.e., Belluno) basin (e.g., Fig. 5c-f). The increasing amount of thrusts in basins compared to platforms is not influenced by the basin size. Our study therefore emphasises that the presence of basins representing lateral mechanical strength variations (Fig. 4b) is most important for lateral variations of the deformational styles.

960 ~~According to field~~Field observations~~, the~~ suggest an along strike change of shortening ~~direction along~~directions at several of the studied faults~~, e.g. the overall SSE-directed Belluno thrust of the Valsugana fault system~~ (Figs. 1b, 14b~~), changes along strike.~~). In the case of the Belluno thrust, the shortening direction changes from top SSW to top SSE along strike (Fig. 14a-b). ~~Field data therefore clearly show varying shortening directions along strike of a single fault.~~ In map-view (Figs. 1b, 14b), this variation in shortening direction can be noticed by means of an anastomosing strike of the thrust front. ~~Focusing on this~~This

965 is particularly evident at the western segment of the Belluno thrust (locations ~~1~~I to ~~3~~III in Fig. 14b~~), especially along the sector between locations 2 and 3,~~) where the Belluno thrust follows the ~~platform boundary of the~~ Trento platform ~~towards the~~ Belluno basin boundary. West of location ~~2 (between locations 1 and 2),~~II the Belluno thrust is located further towards the foreland, ~~further towards the S,~~ whereas east of location ~~3~~III, the Belluno thrust is located further towards the hinterland~~, further towards the N~~.

970 ~~Field data are supported by PIV-analysed top-view pictures of different time steps during the run of various~~ The incremental particle path in analogue ~~modelling experiments of this study (~~models (e.g., time step between 15 and 20 % of bulk shortening of model 1 in Fig. 14c; time step between 10 and 15 % of bulk shortening of model ~~7~~5 in Fig. 14d)~~, showing trajectories of particles (black arrows in Fig. 14c-d) which indicate~~captured by detailed PIV-analysis is consistent with the field observations and indicates temporal variations in ~~moving~~movement directions (between SW to SE~~) at one particular time step of the model~~

975 ~~run. This~~). The associated change in orientation of the thrust front~~,~~ which coincides with platform-basin transitions, is a feature we ~~see~~observe in most of our parallel to oblique basin inversion models (Fig. ~~11), as a result of different styles of faulting~~11) and highlight the role of pre-existing discontinuities or lateral facies juxtaposition, which are visible in ~~laterally varying domains of mechanical strengths, as platforms and basins represent~~the inversion strain pattern.

980 ~~Taking this information from the field and the~~Field data and crustal-scale analogue ~~models into account, our study~~modelling results strongly ~~supports~~support previous studies by, e.g., Masetti and Bianchin (1987); Doglioni (1991, 1992); Schönborn (1999) and suggest that inherited structures, ~~e.g., pre-existing normal faults leading to~~ together with lateral strength variations controlled by the platform-basin ~~geometries, control~~configuration, regulate the style of subsequent compressional deformation and are the cause of variations in shortening directions along strike of thrust faults. Our study does not question the importance of large-scale paleostress analysis of previous authors (e.g., Caputo, 1996; Castellarin and Cantelli, 2000; Caputo et al., 2010),
985 but emphasises the role of pre-existing structures on strain partitioning along regional fault systems.

7 Conclusions

A series of crustal-scale physical analogue models was performed to investigate the effect of inherited extensional structures and lateral strength variations on the style and kinematics of younger compressional deformation, ~~the latter~~associated with parallel to oblique ~~to the pre-existing structures~~basin inversion. Based on our modelling results, we infer the following:

990   1. ~~Modelling results of parallel to oblique basin~~During inversion ~~confirm the localisation of deformation~~, strain predominantly localises in areas of lateral strength contrasts~~,~~ such as transitions from platforms to basins~~represent~~.

   2. Curved thrust fronts and lateral ramps coincide with the transition from platforms to basins and are therefore controlled by rheological changes including the weakness of inherited extensional faults and the transition to the weaker basin fill. These areas, referred to as transfer zones, are the surface expression of thrust connections from platform to basin realms. Transfer zones also involve lateral changes in shortening direction along strike of ~~particular~~individual thrust faults.

   3. Reactivation of inherited normal faults is favoured for oblique shortening and predominantly occurs on fault planes dipping towards the shortening direction (i.e., the moving backstop).

   4. Although compressive strain dominates, ~~undulating~~variations in thrust ~~fronts~~front orientations across platform-basin boundaries are accompanied by ~~minor~~transient incremental oblique slip movements~~, ranging from transtension to predominantly transpression~~.

   5. Spacing of in-sequence thrusts is larger on platforms and smaller in basins, which is, together with the overall style of deformation, less dependent on (i) the material used for the basal décollement, (ii) the style of graben borders, or (iii) the size of the basin, but is controlled by the presence of inherited platform-basin configuration.

1005 ~~Transferred~~With reference to the ~~natural analogue, the~~Dolomites Indenter of the eastern Southern Alps, our modelling results ~~strongly~~suggest that ~~the whole tectonic evolution~~along strike variations ~~of the Dolomites Indenter with variabilities of~~thrust orientations and associated shortening directions ~~along strike of several thrust faults (e.g.,~~ as among others documented for the Belluno thrust of the Valsugana fault system~~) is~~, are the consequence of strain partitioning controlled by inherited structures and does not necessarily reflect different regional deformation phases. ~~As such the number~~This shows that local and temporal

1010 variabilities in thrust kinematics constrained by the rock record can be explained by strain partitioning within a stable stress field and within a single progressive phase of deformation ~~phases in the Southern Alps may have been overestimated so far.~~.

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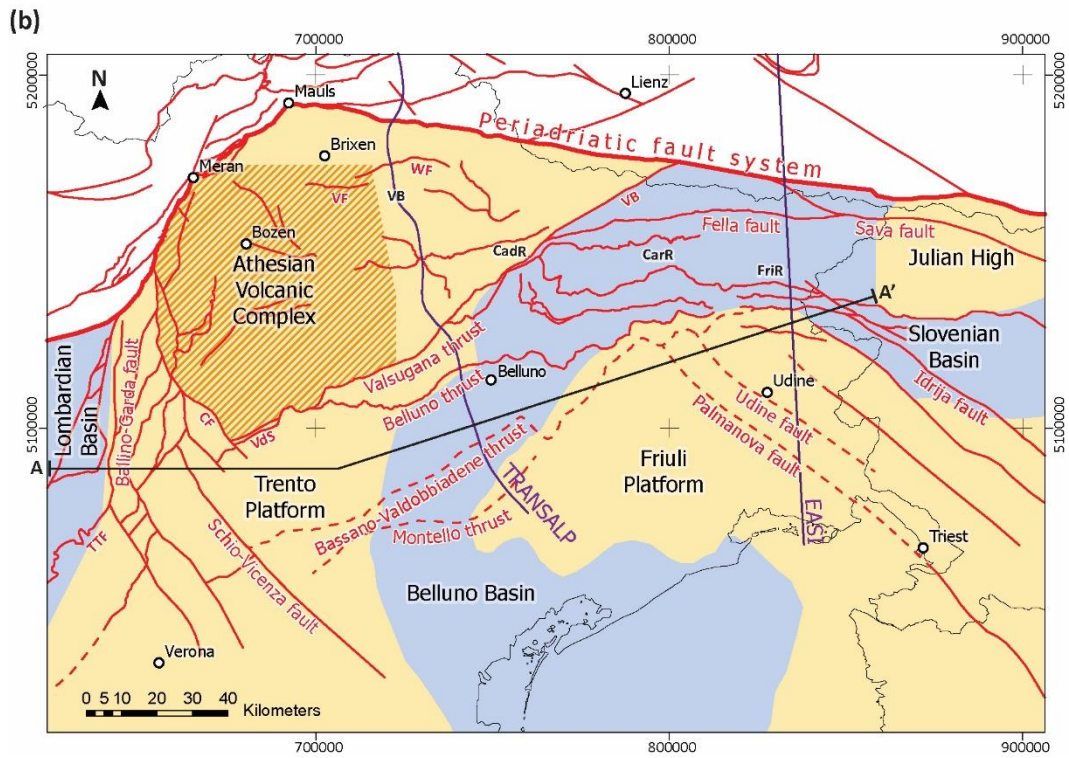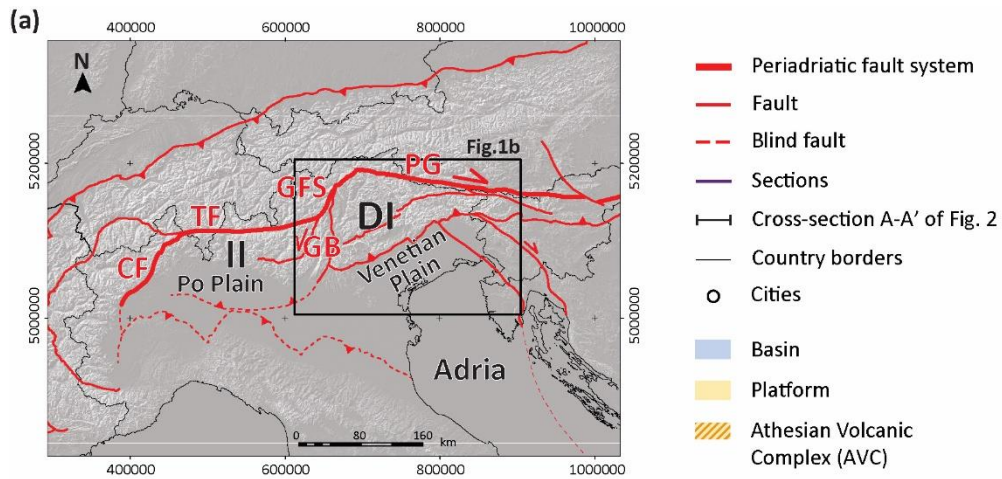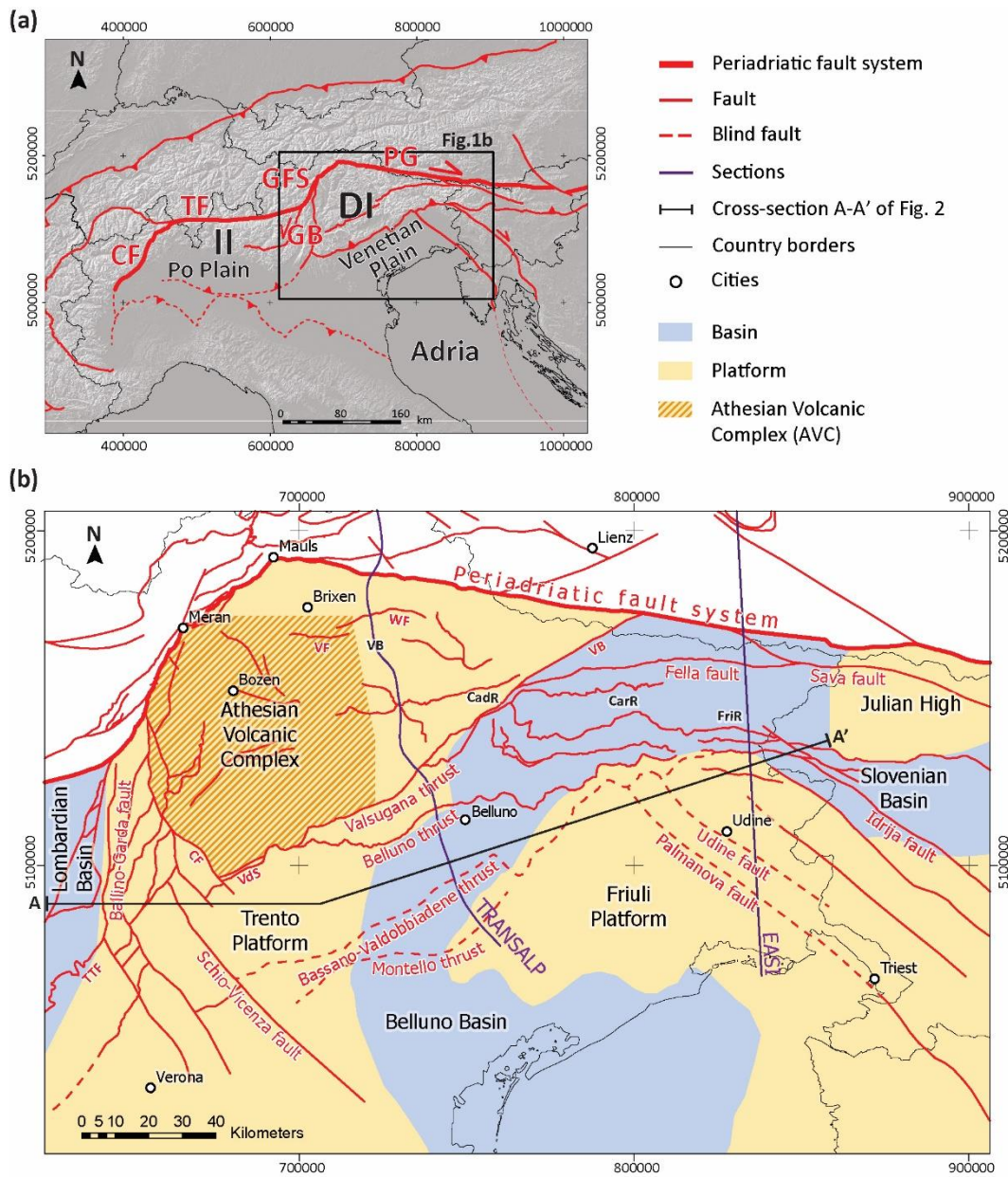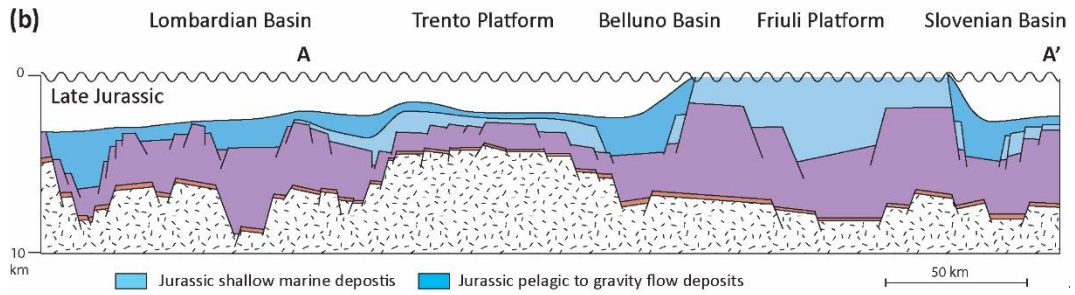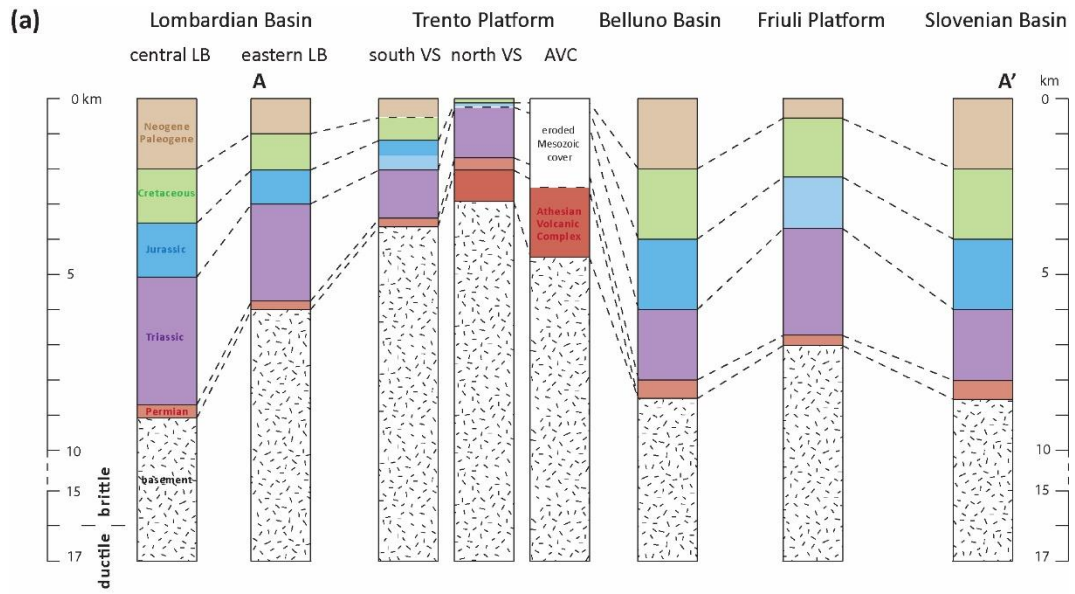
Figure 1. (a) ~~Topographic map~~Hillshaded digital elevation model (DEM) **of the Alpine Arc of western Austria, Switzerland, northern Italy and Slovenia overlain by first-order structures of the Alpine orogen** ~~(modified from~~ (modified from **Schmid et al.** ~~(., 2004); (;~~ **2020))~~.~~. The DEM was taken from the European Commission (EU-DEM). Coordinates here and in Fig. 1b are in WGS 84/UTM zones 32T and 33T. Abbreviations: PG – Pustertal-Gailtal fault, GFS – Giudicarie fault system, GB – Giudicarie belt, TF – Tonale fault, CF – Calisio fault, DI – Dolomites Indenter, II – Insubric indenter. (b) Late Triassic/Jurassic platform-basin configuration** ~~(modified from~~ (modified from **Winterer and Bosellini** ~~(, 1981);~~: **Busetti et al.** ~~(., 2010);~~: **Masetti et al.** ~~., (., 2012);~~: **Martinelli et al.** ~~(., 2017);~~: **Picotti and Cobianchi** ~~(, 2017);~~: **Picotti et al.** ~~(. 2022)~~ **projected over the present day geography and overlain by the tectonic map of the Dolomites Indenter** ~~(modified from~~ (modified from **Schönborn** ~~(, 1999);~~: **Castellarin and Cantelli** ~~(, 2000);~~: **Schmid et al.** ~~(., 2004~~; Ponton, 2010; Viscolani et al., 2020))~~.~~. Abbreviation red: VF – Villnöss/Funes fault, WF – Würzjoch/Passo delle Erbe fault,

41

1440   **TTF – Tremosine-Tignale fault, VB – Val Bordaglia fault, CF – Calisio fault, VdS – Val di Sella back-thrust. Abbreviation black: CadR – Cadore region, CarR – Carnia region, FriR – Friuli region, VB – Val Badia/Gadertal.**
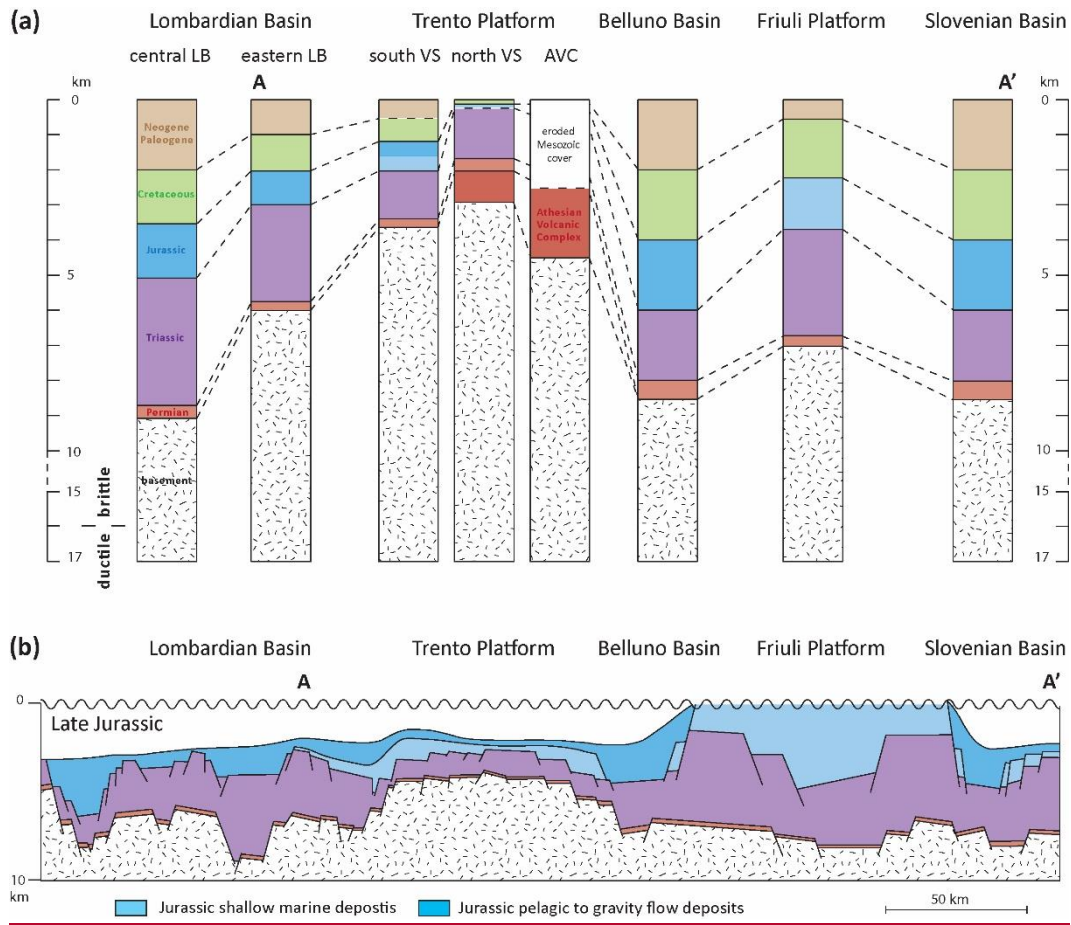
(a)

| Lombardian Basin | Trento Platform | Belluno Basin | Friuli Platform | Slovenian Basin |

central LB eastern LB south VS north VS AVC

Neogene Paleogene
Cretaceous
Jurassic
Triassic
Permian
basement

eroded Mesozoic cover

Athesian Volcanic Complex

ductile | brittle

(b)

| Lombardian Basin | Trento Platform | Belluno Basin | Friuli Platform | Slovenian Basin |

Late Jurassic

Jurassic shallow marine depostis   Jurassic pelagic to gravity flow deposits

50 km

43

Figure 2. Paleogeographic domains of the Dolomites Indenter. The location of cross-section A-A' is indicated in Fig. 1b. (a) Simplified stratigraphic columns for each paleogeographic domain ~~(modified from~~ (modified from Bertotti et al. ~~(.,~~ 1993)~~;~~; Picotti et al. ~~(.,~~ 1995)~~;~~; Picotti and Cobianchi ~~(.,~~ 2017)~~;~~; Verwater et al. ~~(.,~~ 2021)). ~~(b) Cross-section (vertically exaggerated!) through the Jurassic platform-basin configuration (modified from Winterer and Bosellini (1981); Smuc and Goričan (2005)).~~

44
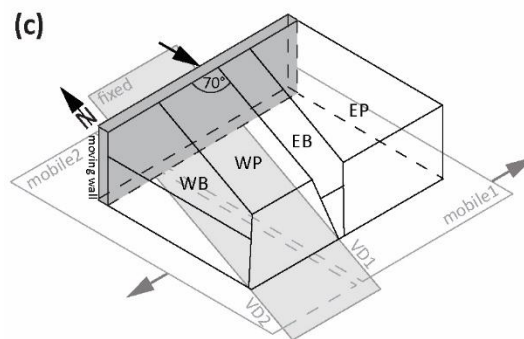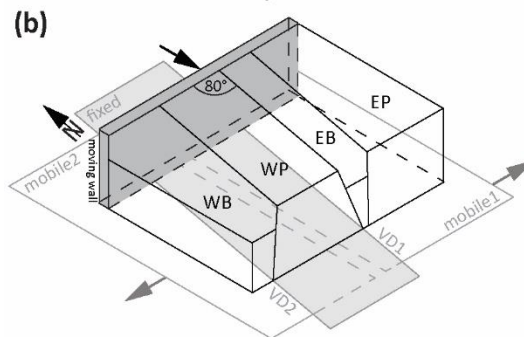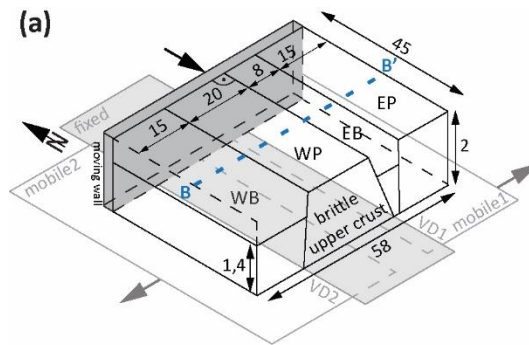
WB   Western basin   EB   Eastern basin
WP   Western platform   EP   Eastern platform

. (b) Cross-section (vertically exaggerated!) through the Jurassic platform-basin configuration (modified from Winterer and
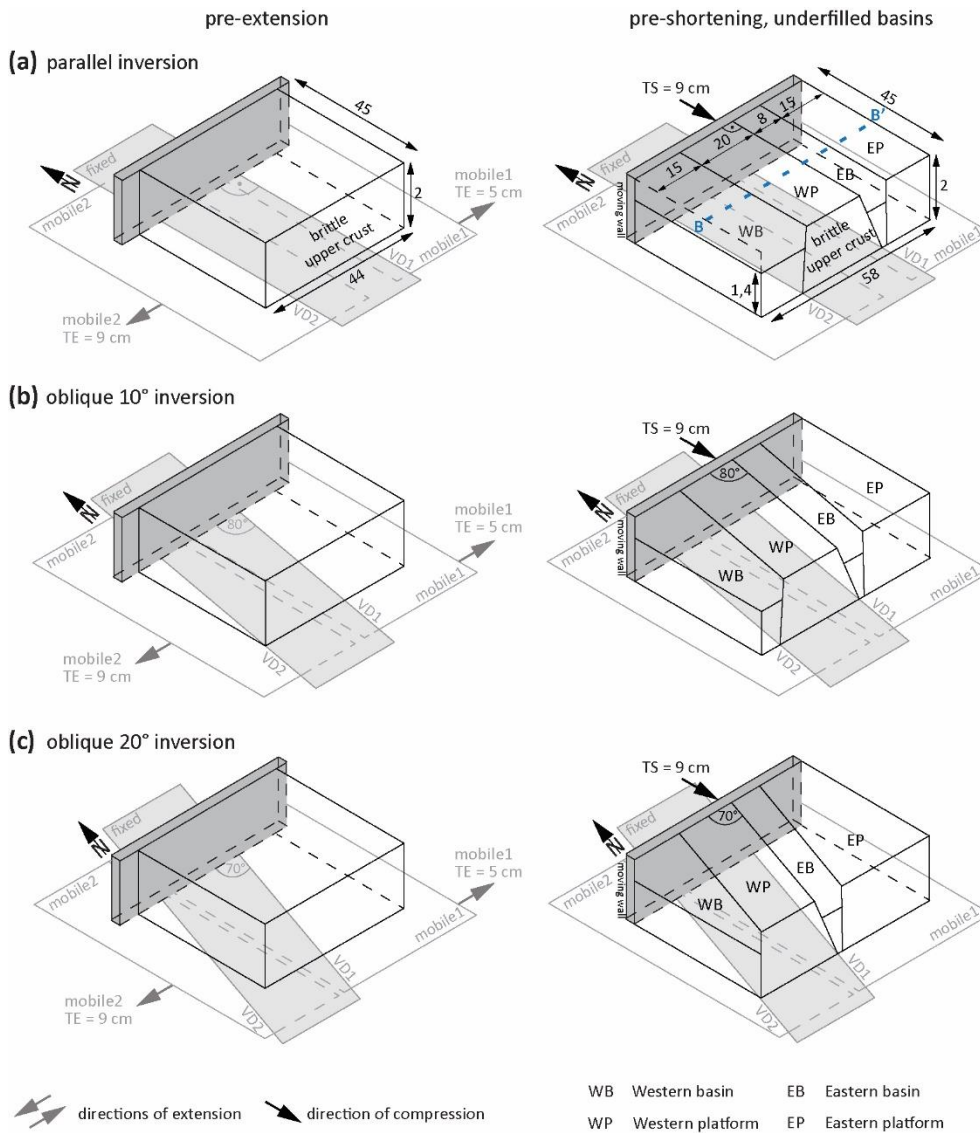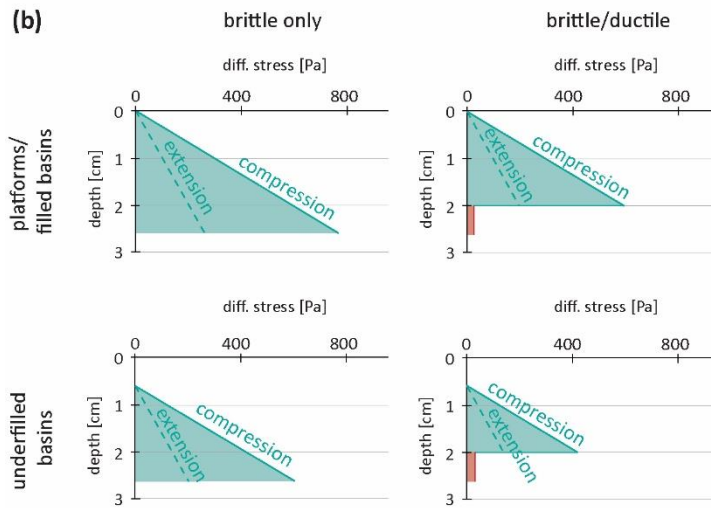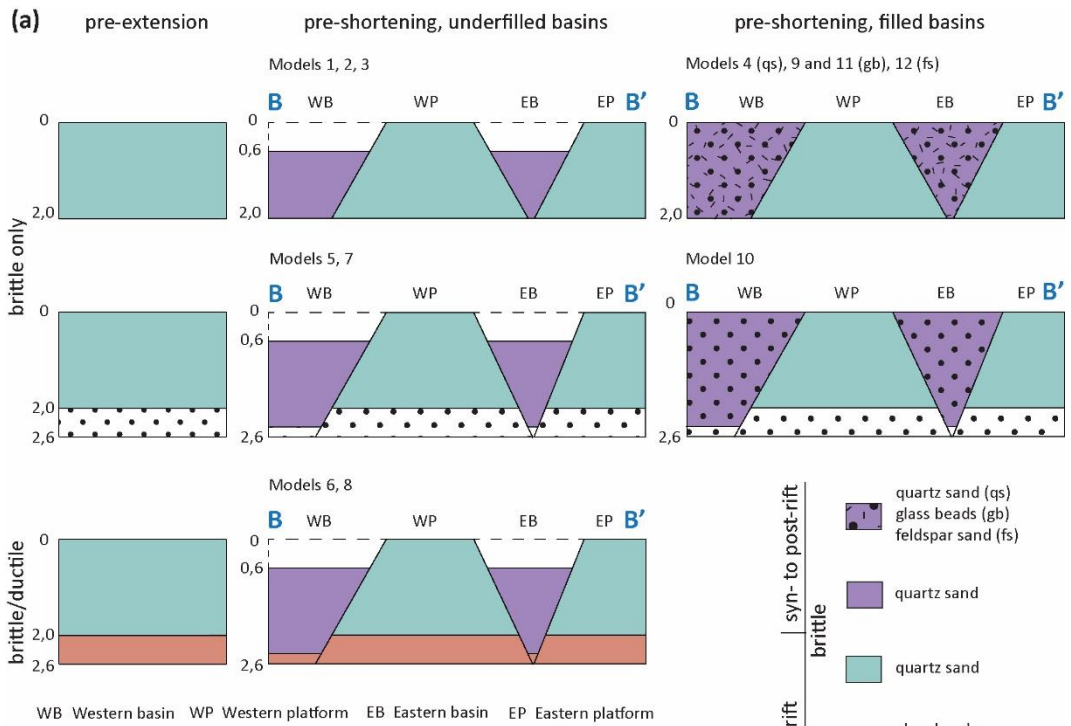Bosellini, 1981; Smuc and Goričan, 2005).

45

Figure 3. Simplified ~~sketch~~sketches **of the** ~~analogue~~geometric and kinematic **modelling setup** ~~post~~ for brittle only models with underfilled basins (set 1, Table 1) depicting pre-**extension (left panel) and pre-shortening** ~~for (a)~~(right panel) experimental conditions for inversion where the shortening direction is **parallel** ~~inversion, (b) oblique inversion with an angle~~to the strike **of** ~~80° between~~ ~~backstop and~~the **pre-**~~existing~~defined velocity **discontinuities**~~, (e)~~ (a), or **oblique** ~~inversion~~ with ~~an angle~~angles of ~~70° between~~ ~~backstop~~10° (b) or 20° (c). The eastern basin (EB) localises at VD1 due to pulling of the mobile sheet 1 below the fixed plastic sheet, whereas the western basin (WB) localises at VD2 due to pulling of mobile sheet 2. Mobile sheets 1 **and** ~~pre-existing discontinuities.~~2 are pulled in a direction indicated by the grey arrows. **All numbers in Fig. 3a-c without units are in centimeters.**

46

1460 **Dimensions are the same for all setups in Fig. 3a-c. Abbreviations: VD – velocity discontinuity, TE – total extension, TS – total shortening.**

(a)

| pre-extension | pre-shortening, underfilled basins | pre-shortening, filled basins |

Models 1, 2, 3

Models 4 (qs), 9 and 11 (gb), 12 (fs)

Models 5, 7

Model 10

Models 6, 8

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

syn- to post-rift — brittle
- quartz sand (qs)
- glass beads (gb)
- feldspar sand (fs)
- quartz sand
- quartz sand

pre-rift — brittle
- glass beads (frictional décollement)

ductile
- silicon putty (viscous décollement)

(b)

| | brittle only | brittle/ductile |

platforms/ filled basins

underfilled basins

diff. stress [Pa]

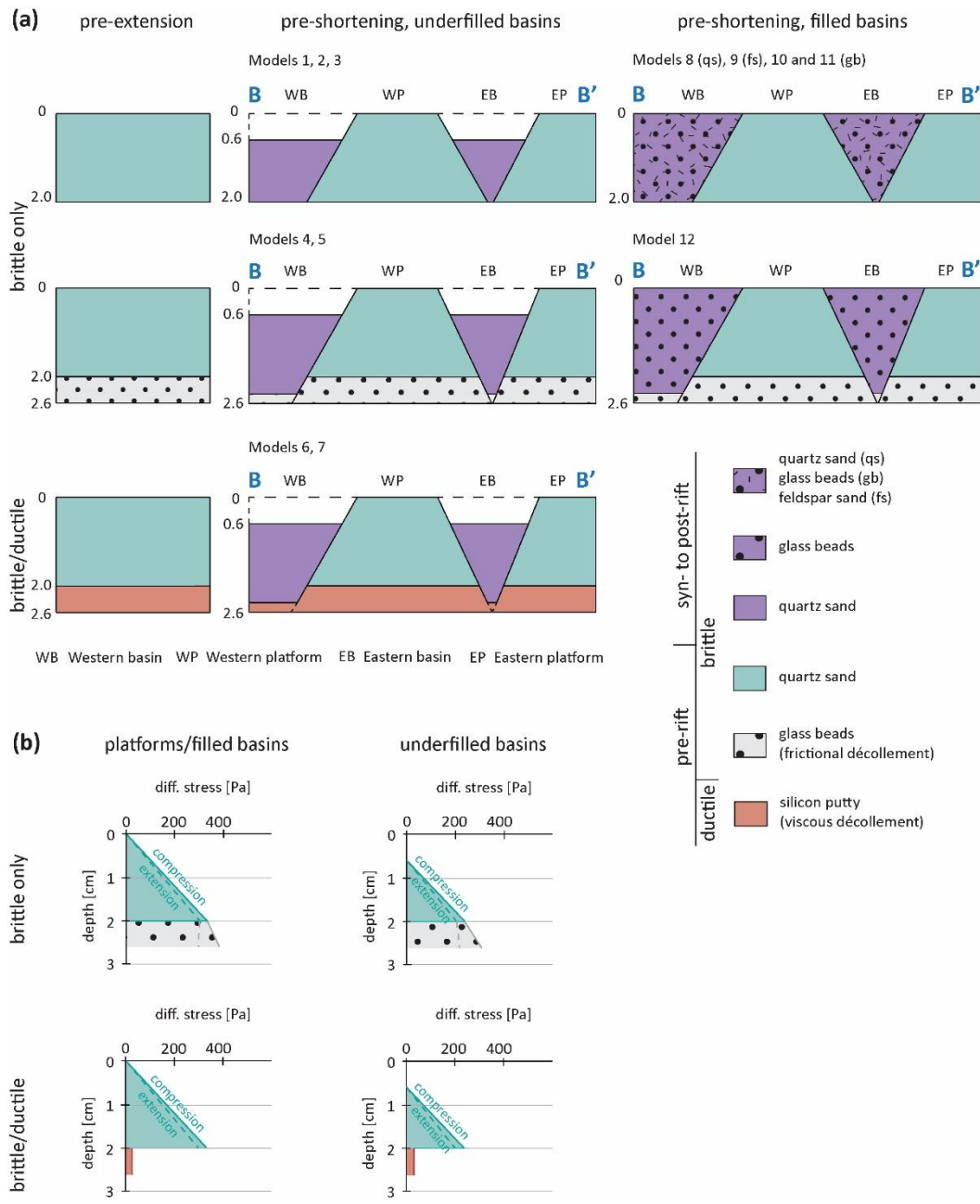extension / compression

depth [cm]

48

Figure 4. Modelling setup. (a) Simplified sketches of setup cross-sections for brittle only and brittle/ductile experiments. Cross-section location is indicated in Fig. 3a. **(b)** Strength profiles for brittle only and for brittle/ductile experiments for platforms/filled basins (platform-basin thickness ratio of 1) and for underfilled basins (platform-basin thickness ratio of 0.7 to 0.8). All numbers in Fig. 4a without units are in centimeters.

Model 1 - Reference Model
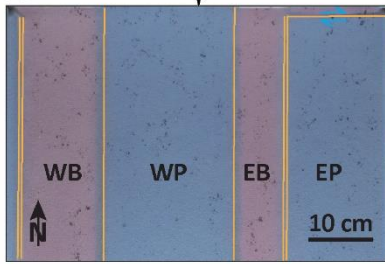
(a) post-extension/pre-shortening (0% BS)

(b) 2,25 cm of shortening (5% BS)

WB Western basin
WP Western platform
EB Eastern basin
EP Eastern platform

(c) 4,5 cm of shortening (10% BS)

(d) 4,5 cm of shortening (10% BS)

no strain

Extension

Strike-Slip
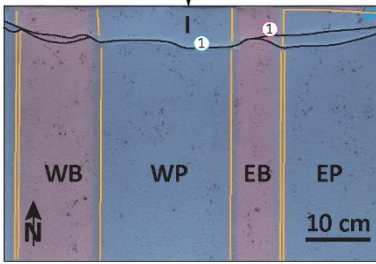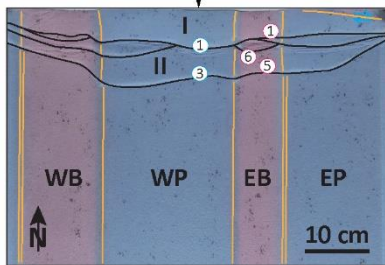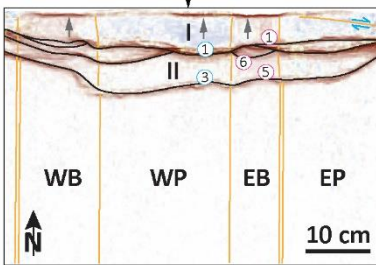
Shortening

(e) 9,0 cm of shortening (20% BS)

(f) 9,0 cm of shortening (20% BS)
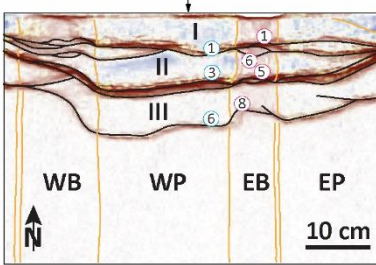
I-III thrust systems
① thrust on platform
① thrust in basin

(g)

thrust fault
normal fault
strike-slip fault
model topography
boundary between syn-
and post-rift sediments
boundary between pre-
and syn-rift sediments
section

50

Model 1 - Reference Model

(a) post-extension/pre-shortening (0 % BS)

(b) 2.25 cm of shortening (5 % BS)

WB   Western basin
WP   Western platform
EB   Eastern basin
EP   Eastern platform

WB   WP   EB   EP

N   10 cm

(c) 4.5 cm of shortening (10 % BS)

(d) 4.5 cm of shortening (10 % BS)

no strain

Extension

Strike-Slip

Shortening

WB   WP   EB   EP

N   10 cm
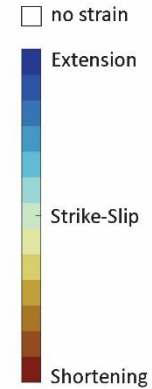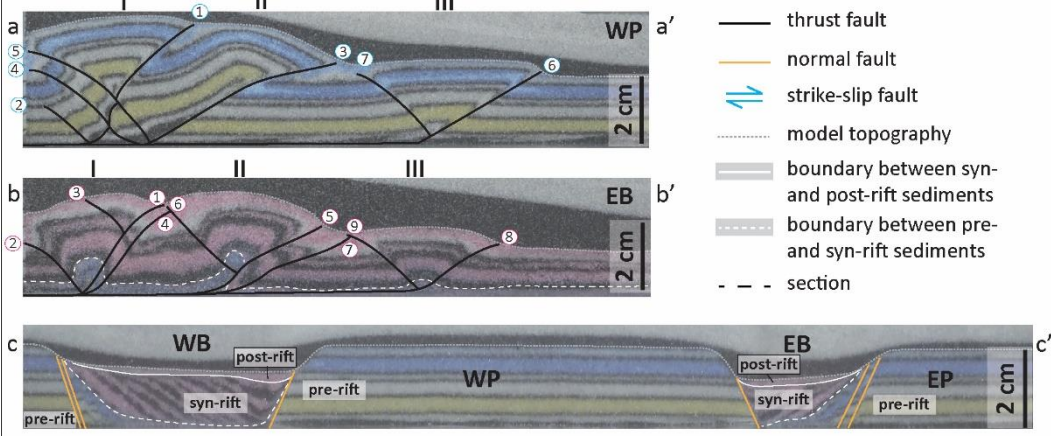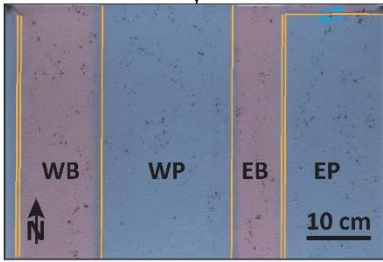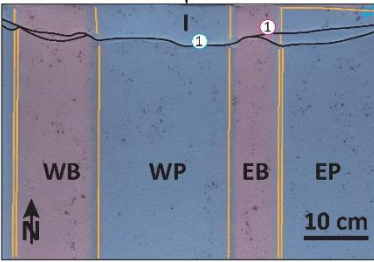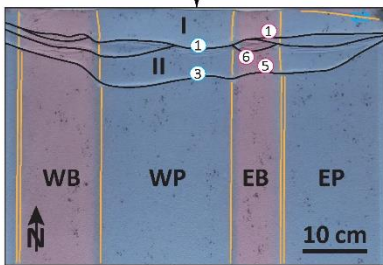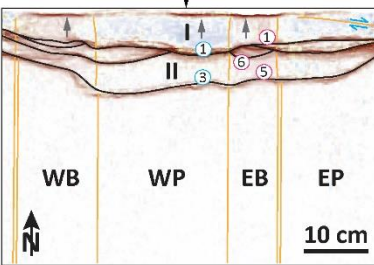
(e) 9 cm of shortening (20 % BS)

(f) 9 cm of shortening (20 % BS)
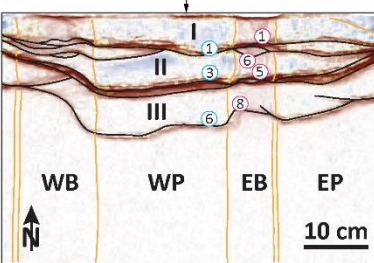
I-III thrust systems
① thrust on platform
① thrust in basin

WB   WP   EB   EP

N   10 cm

(g)

I   II   III

WP   a'

thrust fault
normal fault
strike-slip fault
model topography
boundary between syn-and post-rift sediments
boundary between pre-and syn-rift sediments
section

2 cm

I   II   III

EB   b'

2 cm

c   WB   EB   c'
post-rift   post-rift
WP
syn-rift   pre-rift   syn-rift   EP
pre-rift   pre-rift

2 cm

51
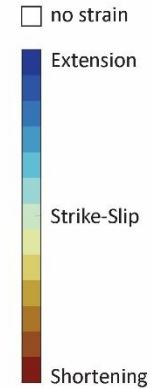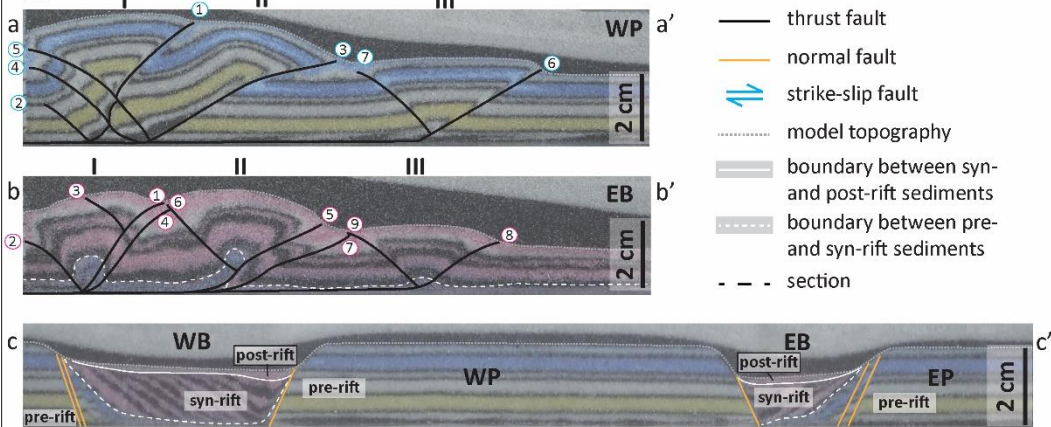
Figure 5. Model 1 – reference model, parallel basin inversion, quartz sand only. (a) Interpreted top-view picture after the first phase of extension and before shortening (0 % of bulk shortening). (b) Interpreted top-view picture after 2.25 cm of shortening (5 % of bulk shortening). (c) Interpreted top-view picture after 4.5 cm of shortening (10 % of bulk shortening). (d) Map of cumulative strain type after 4.5 cm of shortening (10 % of bulk shortening). (e) Interpreted top-view picture after 9.0 cm of shortening (20 % of bulk shortening), (f) Map of cumulative strain type after 9.0 cm of shortening (20 % of bulk shortening). Visually interpreted structures of Fig. 5c, e overlay strain type plots in Fig. 5d, f. Strain colour legend corresponds to Fig. 5d, f. The transparency of areas with a strain magnitude below the 90 percentile is increased for supressing areas without significant deformation. (g) Cross-sections of the reference model at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line marks the post-kinematic sand cover. Cross-section locations are shown in Fig. 5e.

Model 2

(a) ... (b) ... (c)

Model 3

(d) ... (e) ... (f)

Legend:
— thrust fault
— normal fault
- - reactivated normal fault
- - section

boundary between syn- and post-rift sediments
boundary between pre- and syn-rift sediments
model topography

I-V thrust systems

① thrust on platform
① thrust in basin

Extension   Strike-Slip   Shortening

no strain

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

Model 2

(a) (b) (c) a — a' WP; b — b' EB; c — c' EB/EP; d — d' WB / EB / EP

Model 3

(d) (e) (f) e — e' WP; f — f' EB/EP; g — g' EB/EP; h — h' WB / EB / EP

Legend:
— thrust fault
— normal fault
- - - reactivated normal fault
– – – section

boundary between syn- and post-rift sediments
boundary between pre- and syn-rift sediments
model topography

I-V thrust systems
① thrust on platform
① thrust in basin

Extension — Strike-Slip — Shortening — no strain

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

Figure 6. Model 2 and model 3 – oblique (10°, 20°, respectively) basin inversion; quartz sand only. (a) Interpreted top-view picture of model 2 after 9,0 cm of shortening (20_% of bulk shortening). (b) Map of cumulative strain type of model 2 after 9,0 cm of shortening (20_% of bulk shortening). (c) Cross-sections of model 2 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line marks the post-kinematic sand cover. Cross-section locations are shown in Fig. 6a. Note that cross-sections a-a', b-b' and c-c' are oriented oblique (10°) to the main structures. (d) Interpreted top-view picture of model 3 after 9,0 cm of shortening (20_% of bulk shortening). (e) Map of cumulative strain type of model 3 after 9,0 cm of shortening (20_% of bulk shortening). Visually interpreted structures of Fig. 6a, d overlay strain type plots in Fig. 6b, e. Strain colour legend corresponds to Fig. Fig. 6b, e. The transparency of areas with a strain magnitude below the 90 percentile is increased for supressing areas without significant deformation. (f) Cross-sections of model 3 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line marks the post-kinematic sand cover. Cross-section locations are shown in Fig. 6d. Note that cross-sections e-e', f-f' and g-g' are oriented oblique (20°) to the main structures.
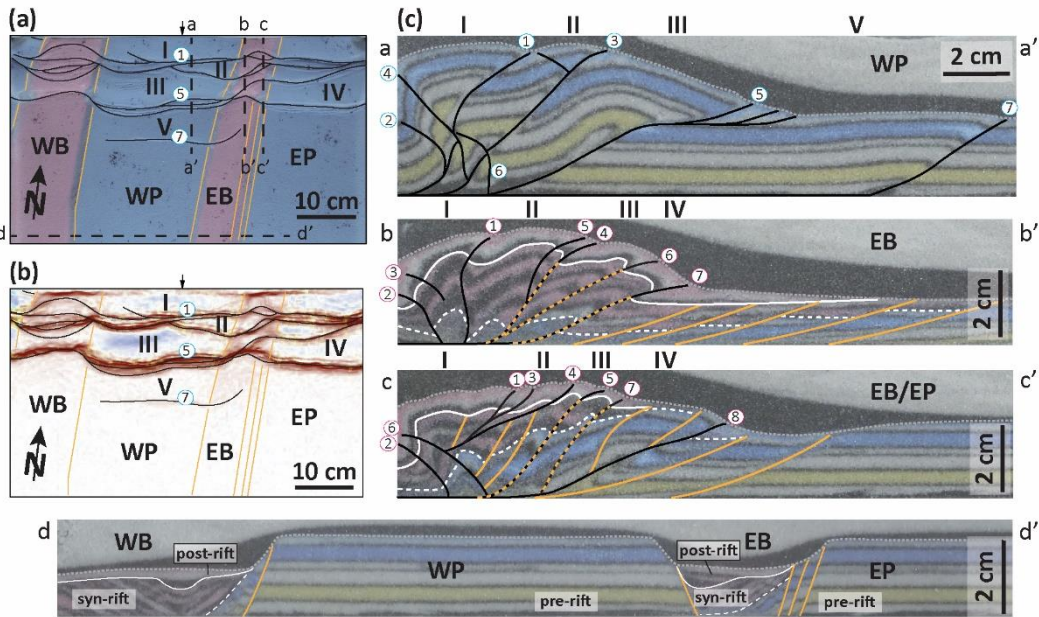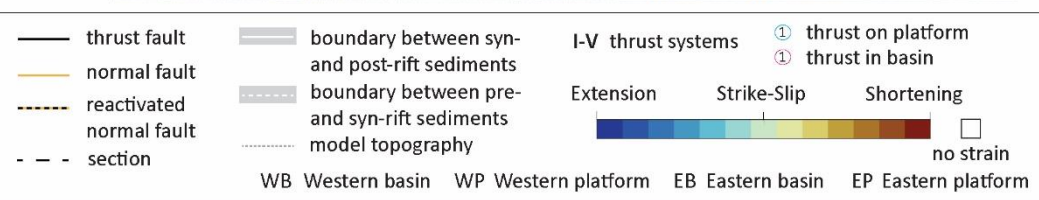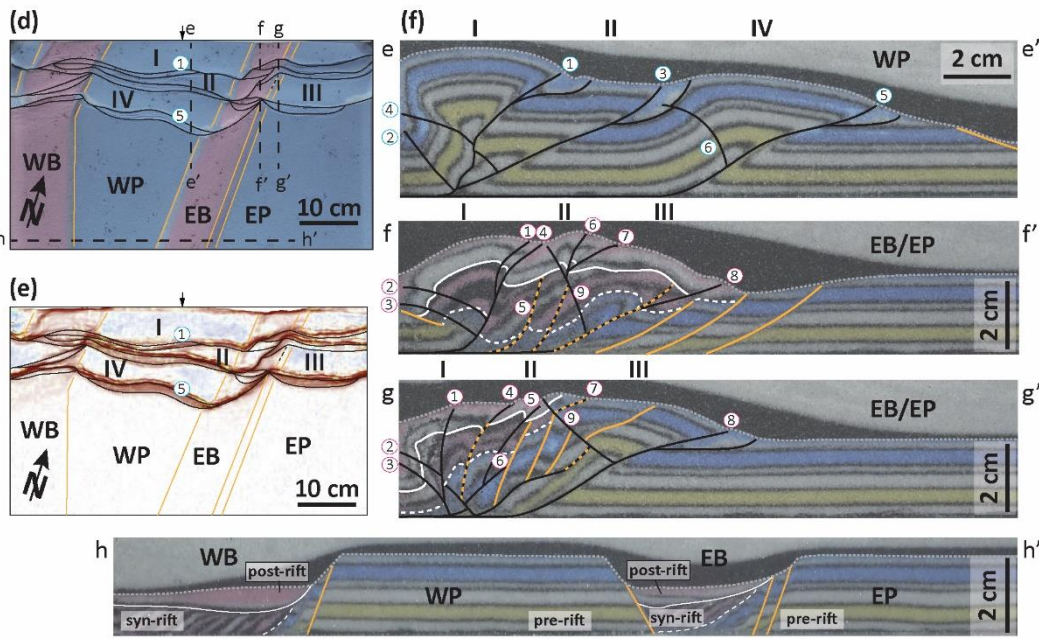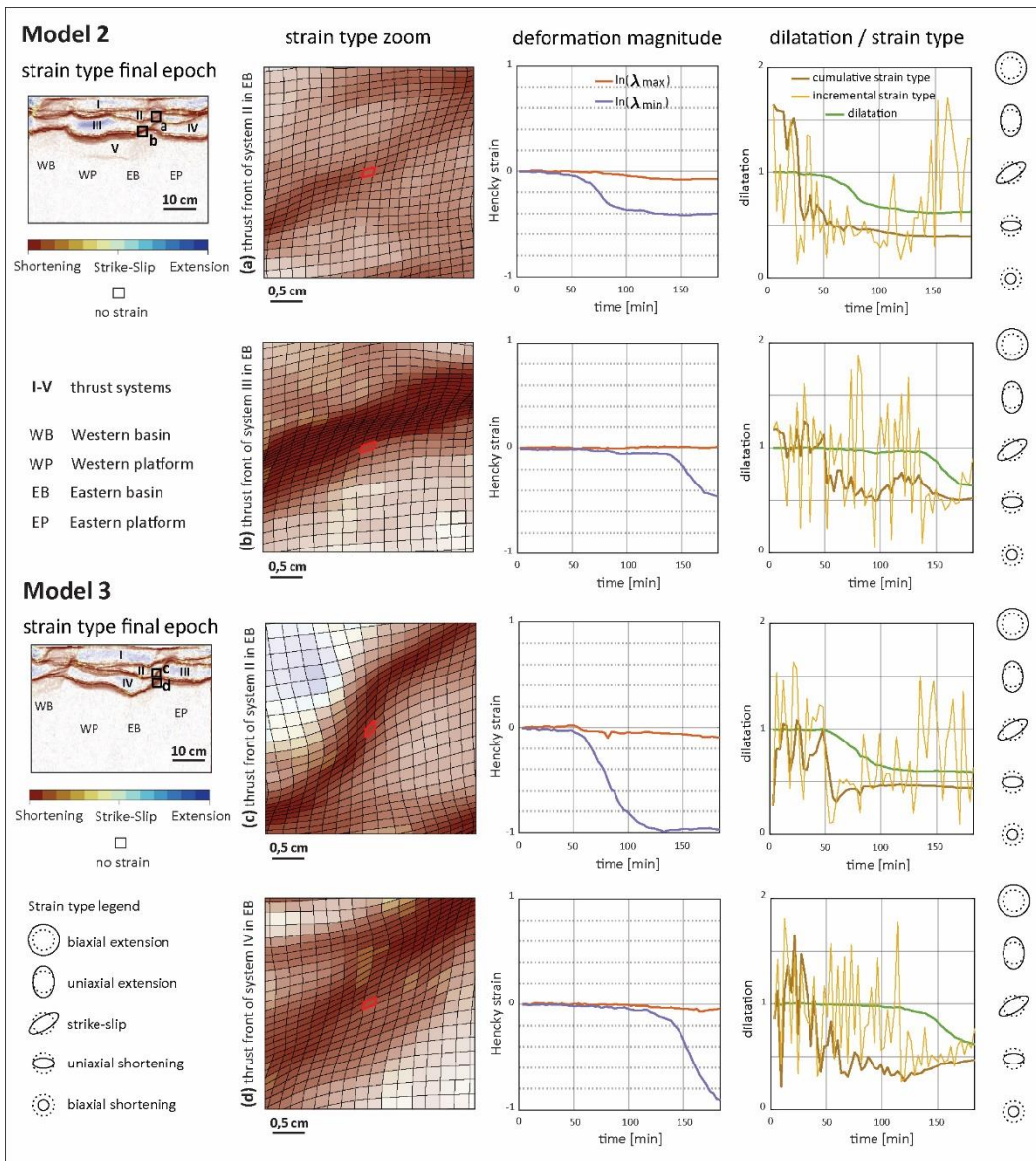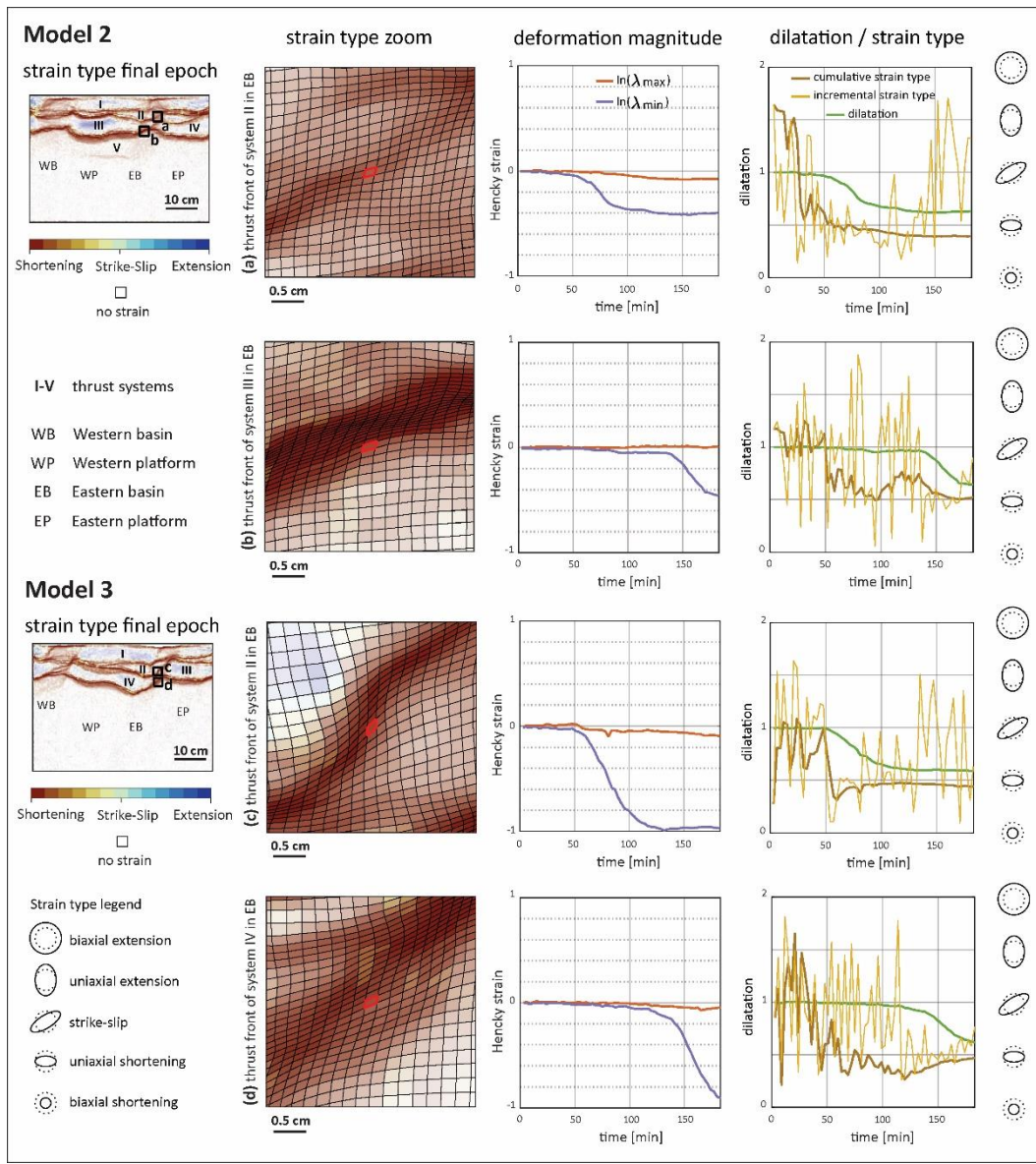
Figure 7. Temporal evolution of principal stretches and strain type during the ~~compressional~~shortening phase of model 2 (a) at the thrust front of thrust system II in the eastern basin and (b) at the thrust front of thrust system III within the eastern basin and of model 3 (c) at the thrust front of thrust system II in the eastern basin and (d) at the thrust front of thrust system IV within the eastern basin. Upper left-hand panel: strain type (final) and overview of the selected areas (a) and (b) of model 2. Middle left-hand panel: strain type (final) and overview of the selected areas (c) and (d) of model 3. Left column: zoom on the strain type including the selected grid cell (outlined in red) and neighbouring grid cells (outlined in black). Middle column: temporal evolution of the logarithm of the two principal stretches (Henky strain, blue and red line). Right column: temporal evolution of dilatation, cumulative strain type, and incremental strain type.

Model 7

(a)

(b)

(c)

Model 8

(d)

(e)

(f)

Legend:

— thrust fault

— normal fault

– – reactivated normal fault

– · – section

boundary between syn- and post-rift sediments

boundary between pre- and syn-rift sediments

model topography

I-II thrust systems

Extension   Strike-Slip   Shortening

no strain

① thrust on platform

① thrust in basin

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

Model 5

(a) I, II, III — WB, WP, a', b', EP, EB — N — 10 cm

(c) I, II — WP — a — a' — f.d. — f.d. — f.d. — frictional décollement (f.d.) — 2 cm

(b) I, II, III — WB, WP, EB, EP — N — 10 cm — b — b' — I, II — EB — f.d. — f.d. — frictional décollement — 2 cm

c — WB — post-rift — post-rift — EB — c' — syn-rift — WP — pre-rift — syn-rift — EP — pre-rift — frictional décollement — 2 cm

Model 7

(d) I, II — WB, WP, EB, EP — relay ramps — not interpreted, only for conceptual reasons — N — 10 cm

(f) I, II — WP — d — d' — v.d. — viscous décollement (v.d.) — 2 cm

(e) I, II — WB, WP, EB, EP — not interpreted, only for conceptual reasons — N — 10 cm — e — e' — I, II — EB — v.d. — shear zone — viscous décollement — 2 cm

f — WB — post-rift — post-rift — EB — syn-rift — f' — syn-rift — WP — pre-rift — pre-rift — EP — pre-rift — pre-rift — viscous décollement — 2 cm

Legend:
— thrust fault
— normal fault
— reactivated normal fault
— section
— boundary between syn- and post-rift sediments
— boundary between pre- and syn-rift sediments
— model topography

I-III thrust systems
① thrust on platform
① thrust in basin

Extension — Strike-Slip — Shortening — no strain

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

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Figure 8. Model 7̶5 and model 8̶7 – oblique (20°) basin inversion; variation in material for basal décollement (glass beads and silicon putty, respectively). (a) Interpreted top-view picture of model 7̶5 after 9,̶0 cm of shortening (10_% of bulk shortening). (b) Map of cumulative strain type of model 7̶5 after 9,̶0 cm of shortening (10_% of bulk shortening). (c) Cross-sections of model 7̶5 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line mark the post-kinematic sand cover. Cross-section locations are shown in Fig. 8a. Note that the cross-sections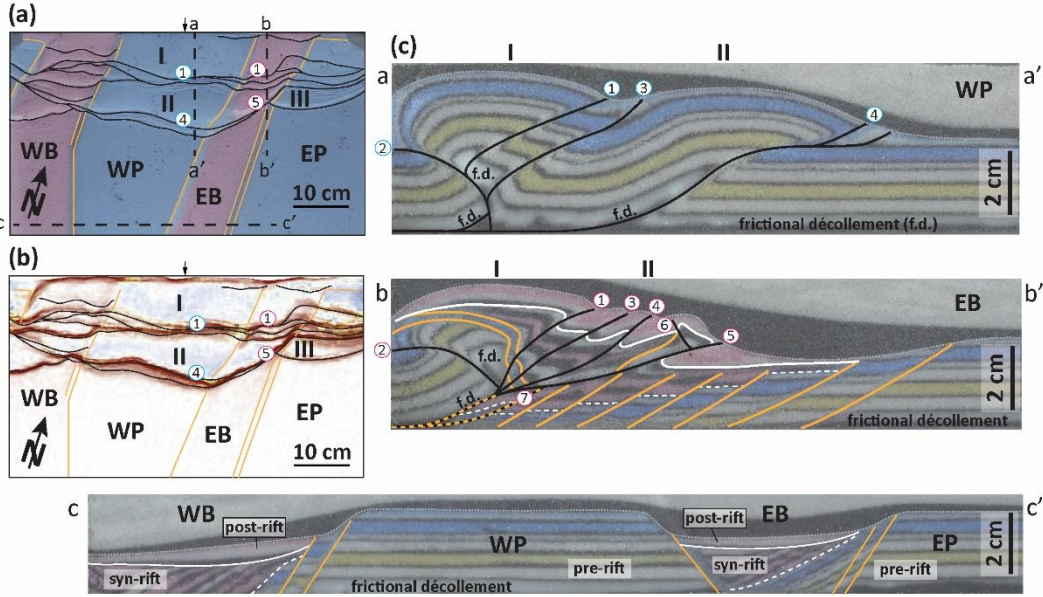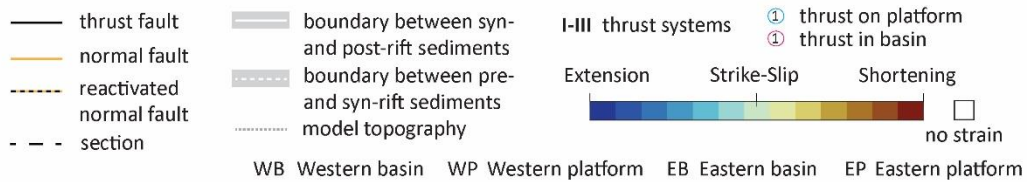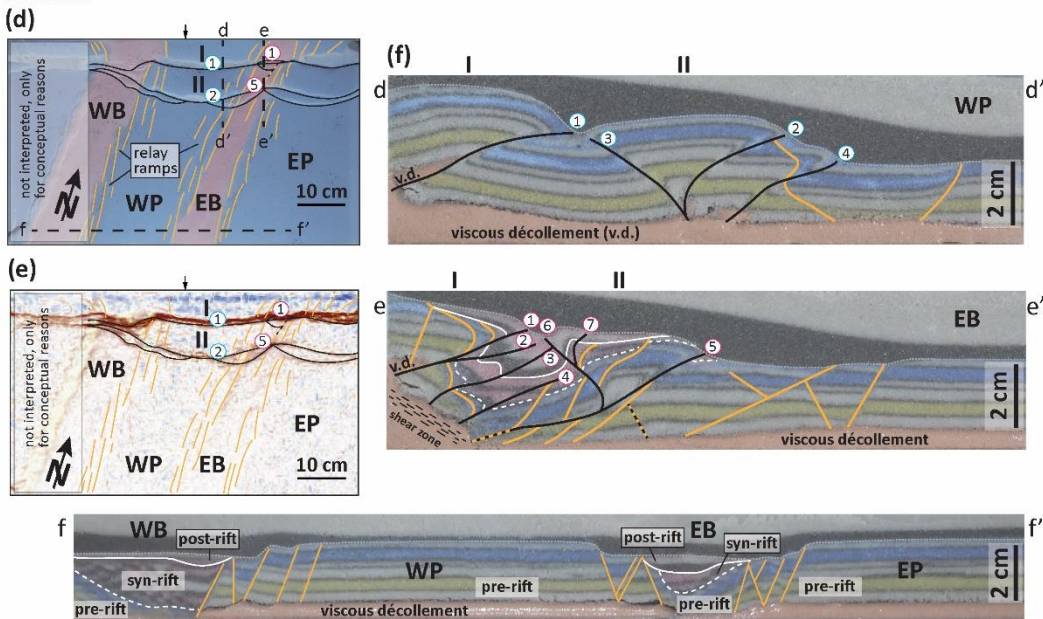 a-a' and b-b' are oriented oblique (20°) to the main shortening structures. (d) Interpreted top-view picture of model 8̶7 after 9,̶0 cm of shortening (10_% of bulk shortening). (e) Map of cumulative strain type of model 8̶7 after 9,̶0 cm of shortening (10_% of bulk shortening). Visually interpreted structures of Fig. 8a, d overlay strain type plots in Fig. 8b, e. Strain colour legend corresponds to Fig. 8b, e. The transparency of areas with a strain magnitude below the 90 percentile is increased for supressing areas without significant deformation. (f) Cross-sections of model 8̶7 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line mark the post-kinematic sand cover. Cross-section locations are shown in Fig. 8d. Note that the cross-sections d-d' and e-e' are oriented oblique (20°) to the main shortening structures.

Model 7

strain type final epoch

strain type zoom

deformation magnitude

dilatation / strain type

Shortening Strike-Slip Extension

□ no strain

I-II thrust systems

WB Western basin

WP Western platform

EB Eastern basin

EP Eastern platform

Model 8

strain type final epoch

Shortening Strike-Slip Extension

□ no strain

Strain type legend

biaxial extension

uniaxial extension

strike-slip

uniaxial shortening

biaxial shortening

61

Figure 9. Temporal evolution of principal stretches and strain type during the compressional phase of model ~~7~~5 (a) at the thrust front of thrust system II on the western platform and (b) at the thrust front of thrust system II within the eastern basin and of model ~~8~~7 (c) at the thrust front of thrust system II on the western platform and (d) at the thrust front of thrust system II within the eastern basin. Upper left-hand panel: strain type (final) and overview of the selected areas (a) and (b) of model ~~7~~5. Middle left-hand panel: strain type (final) and overview of the selected areas (c) and (d) of model ~~8~~7. Left column: zoom on the strain type including the selected grid cell (outlined in red) and neighbouring grid cells (outlined in black). Middle column: temporal evolution of the logarithm of the two principal stretches (Henky strain, blue and red line). Right column: temporal evolution of dilatation, cumulative strain type, and incremental strain type.
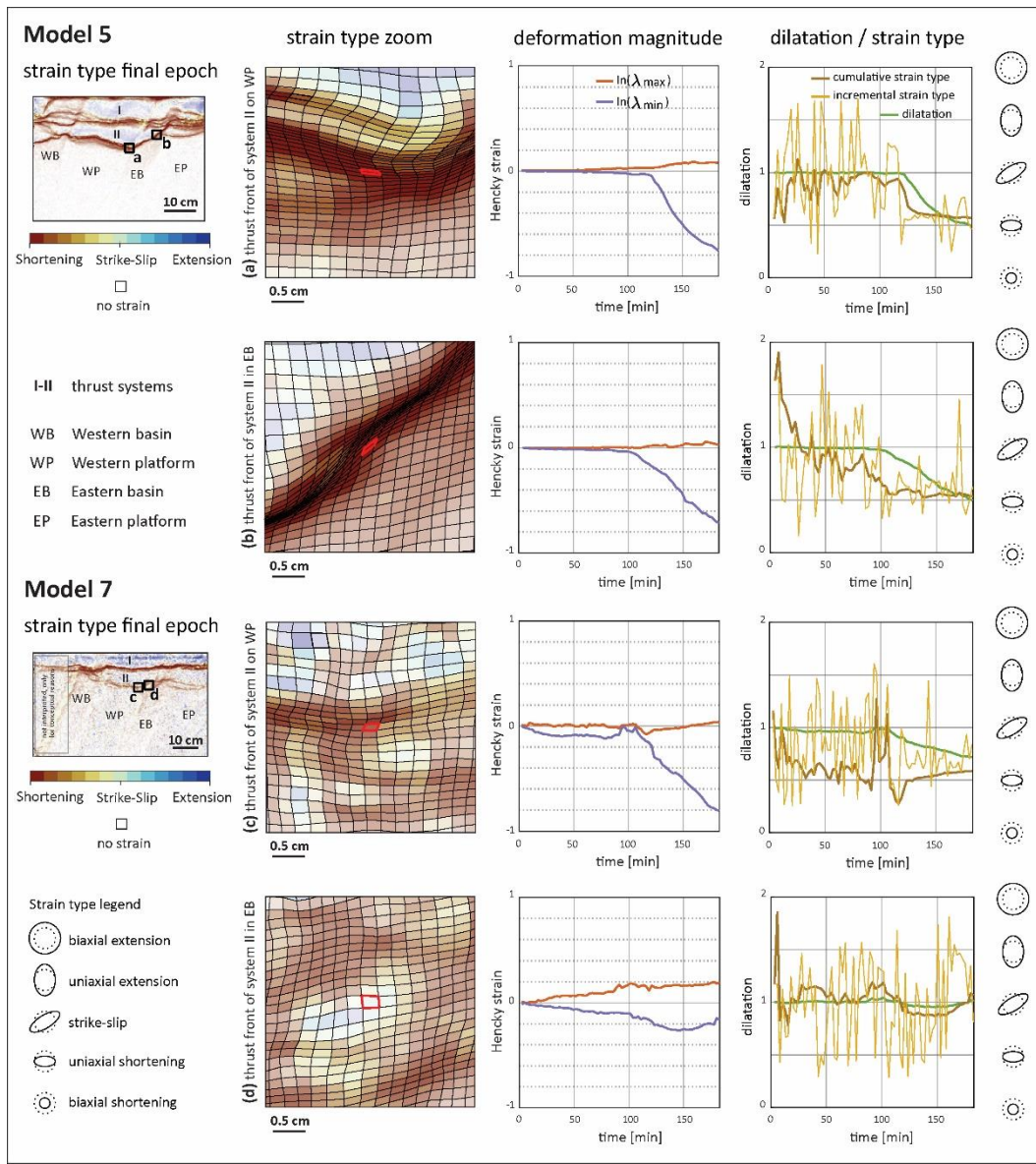
Model 4

Model 11

Model 12

thrust fault
normal fault
reactivated normal fault
section

boundary between syn- and post-rift sediments
boundary between pre- and syn-rift sediments
model topography

I-IV thrust systems

① thrust on platform
① thrust in basin

Extension   Strike-Slip   Shortening

no strain

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

63

Model 8

Model 9

Model 10

thrust fault
normal fault
reactivated normal fault
section
boundary between syn- and post-rift sediments
boundary between pre- and syn-rift sediments
model topography
I-IV thrust systems
thrust on platform
thrust in basin

Extension   Strike-Slip   Shortening

no strain

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

Figure 10. Model ~~4~~8, model ~~11~~9 and model ~~12~~10 – oblique (20°) basin inversion; variation in material ~~representing~~of the ~~basins~~basin fill (quartz sand, ~~glass beads, and~~ feldspar sand, and glass beads, respectively). (a) Interpreted top-view picture of model ~~4~~8 after 9~~,~~0 cm of shortening (20 % of bulk shortening). (b) Map of cumulative strain type of model ~~4~~8 after 9~~,~~0 cm of shortening (20 % of bulk shortening). (c) Cross-sections of model ~~4~~8 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line mark the post-kinematic sand cover. Cross-section locations are shown in Fig. 10a. Note that the cross-sections a-a', b-b', and c-c' are oriented oblique (20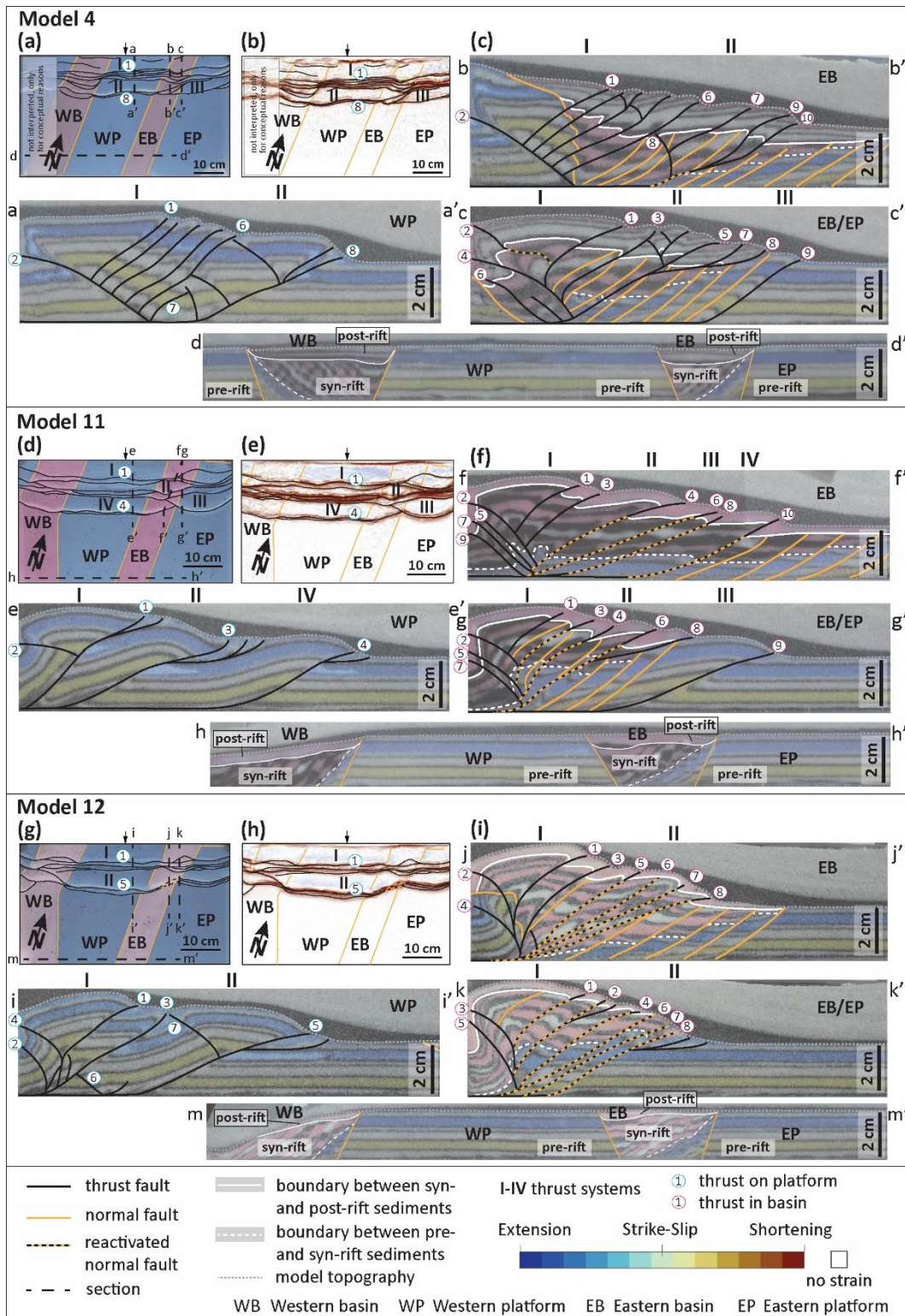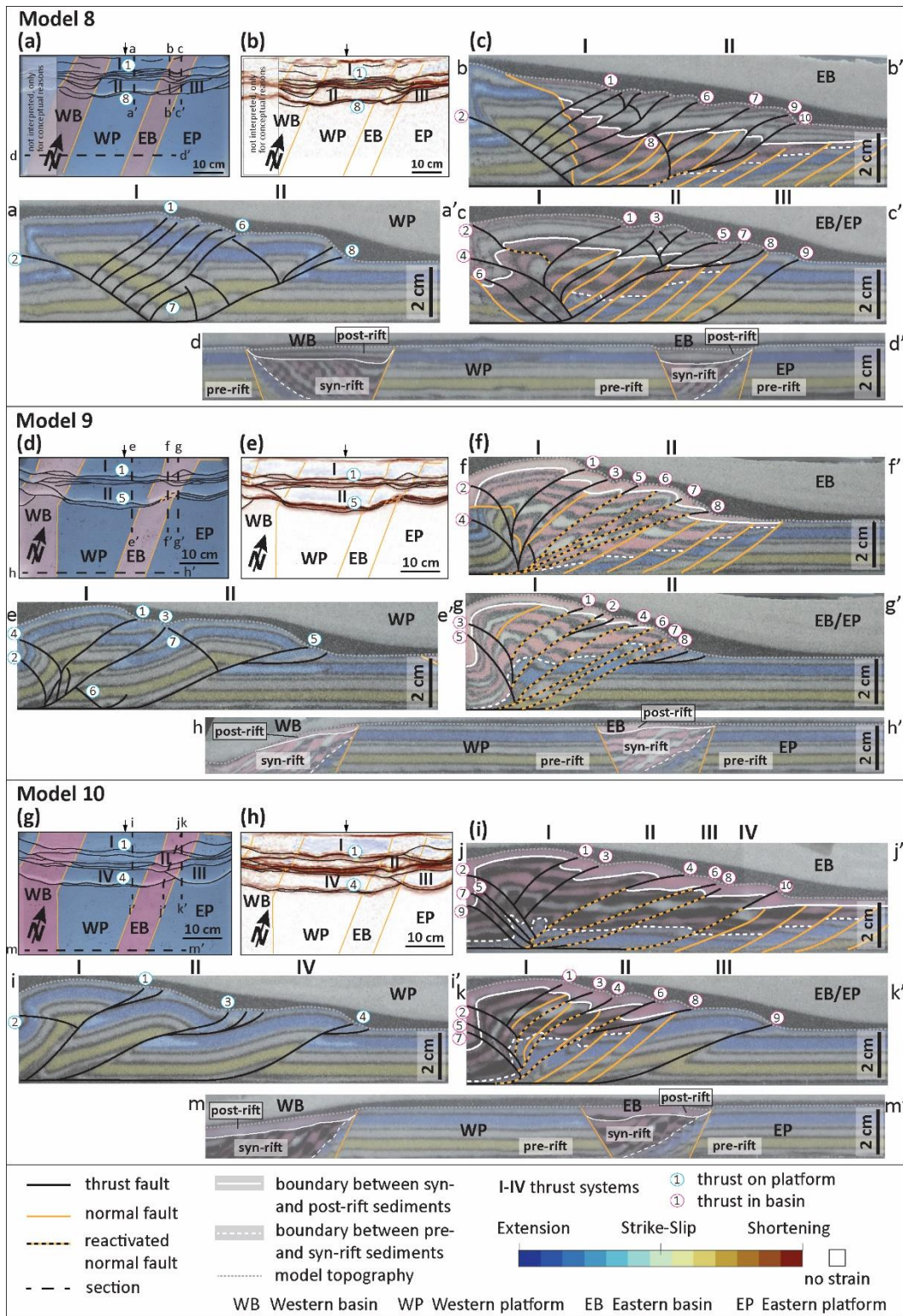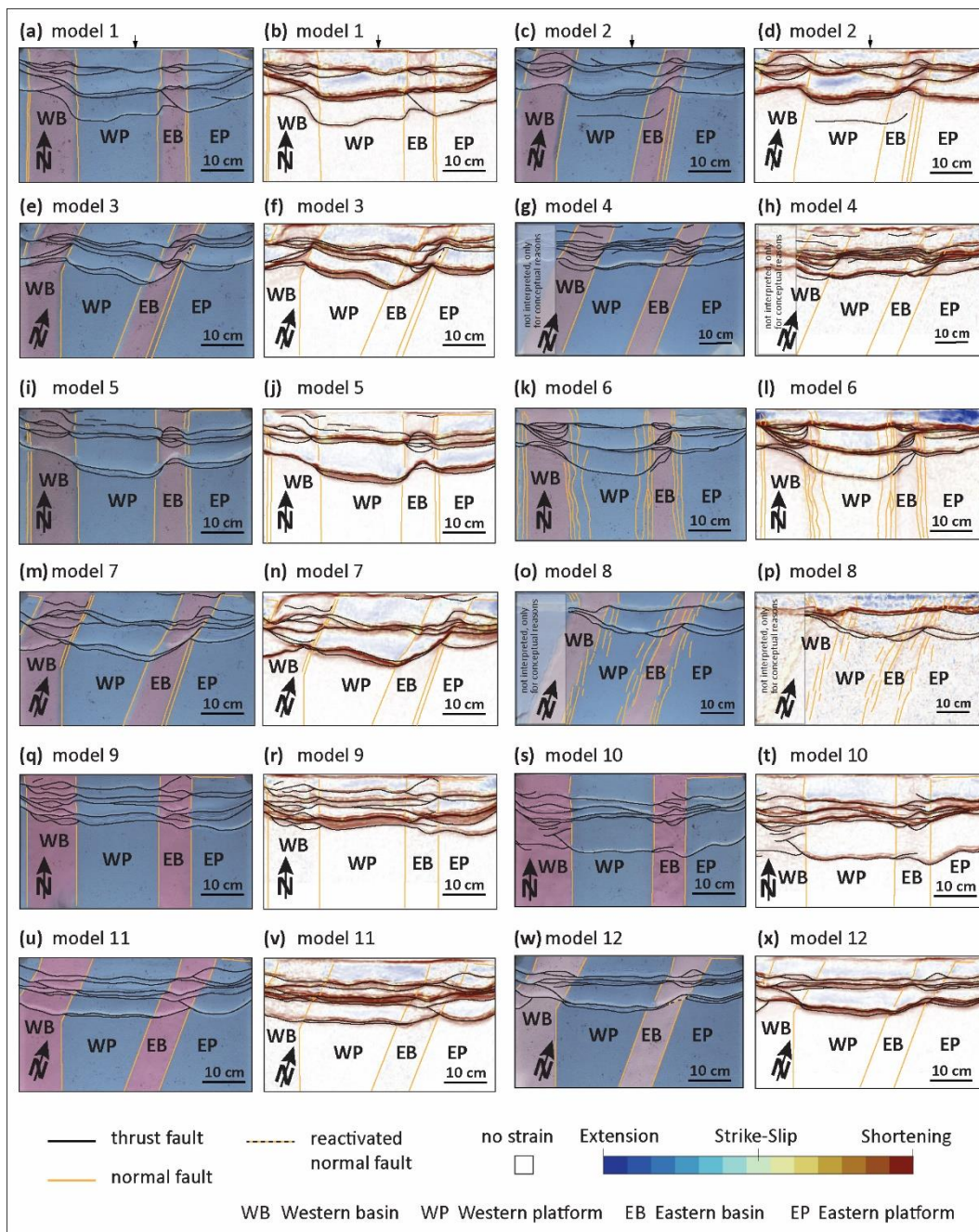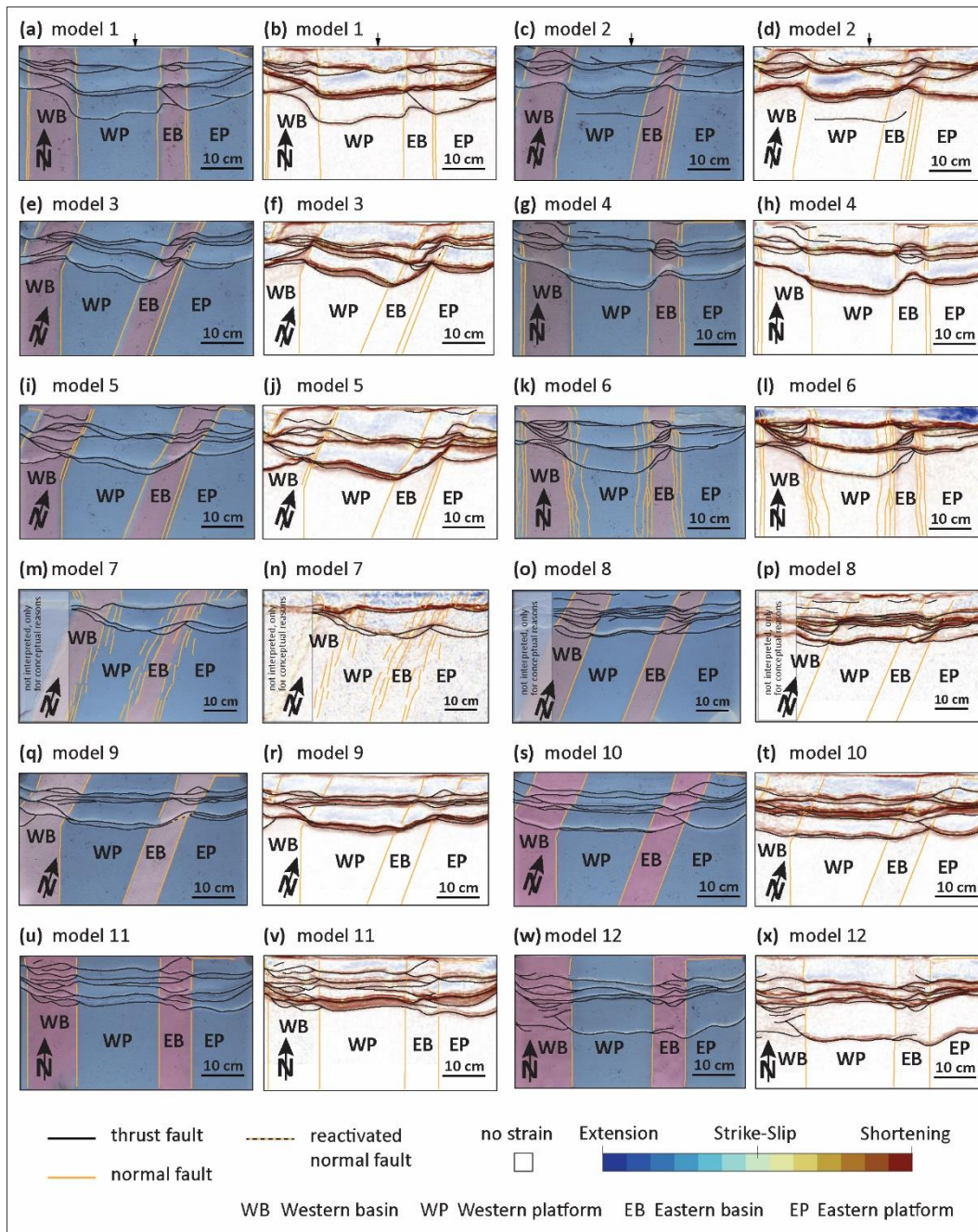°) to the main shortening structures. (d) Interpreted top-view picture of model ~~11 after~~ 9~~,~~0 after 9 cm of shortening (20 % of bulk shortening). (e) Map of cumulative strain type of model ~~11~~9 after 9~~,~~0 cm of shortening (20 % of bulk shortening). (f) Cross-sections of model ~~11~~9 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line mark the post-kinematic sand cover. Cross-section locations are shown in Fig. 10d. Note that the cross-sections e-e', f-f', and g-g' are oriented oblique (20°) to the main shortening structures. (g) Interpreted top-view picture of model ~~12~~10 after 9~~,~~0 cm of shortening (20 % of bulk shortening). (h) Map of cumulative strain type of model ~~12~~10 after 9~~,~~0 cm of shortening (20 % of bulk shortening). Visually interpreted structures of Fig. 10a, d, g overlay strain type plots in Fig. 10b, e, h. Strain colour legend corresponds to Fig. 10b, e, h. The transparency of areas with a strain magnitude below the 90 percentile is increased for supressing areas without significant deformation. (i) Cross-sections of model ~~12~~10 at the end of the experiment. Grey dashed line marks the model topography at the end of the experiment. Black and grey layers above the topography line mark the post-kinematic sand cover. Cross-section locations are shown in Fig. 10g. Note that the cross-sections i-i'~~, j-j'~~ and k-k' are oriented oblique (20°) to the main shortening structures.

(a) model 1   (b) model 1   (c) model 2   (d) model 2
(e) model 3   (f) model 3   (g) model 4   (h) model 4
(i) model 5   (j) model 5   (k) model 6   (l) model 6
(m) model 7   (n) model 7   (o) model 8   (p) model 8
(q) model 9   (r) model 9   (s) model 10   (t) model 10
(u) model 11   (v) model 11   (w) model 12   (x) model 12

thrust fault   reactivated normal fault   no strain   Extension   Strike-Slip   Shortening
normal fault

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

Figure 11. Interpreted top-view pictures and cumulative strain type maps of the final stages of all 12 experiments after 9,0 cm of shortening (20 % of bulk shortening). Visually interpreted structures of Fig. 12a11a, c, e, g, I, k, m, o, q, s, u, w overlay strain type plots in Fig. 12b11b, d, f, h, j, l, n, p, r, t, v, x. Strain colour legend corresponds to Fig. 12b11b, d, f, h, j, l, n, p, r, t, v, x. The transparency of areas with a strain magnitude below the 90 percentile is increased for supressing areas without significant deformation. The black arrow in the uppermost row of panels indicates the direction of the shortening direction (i.e., moving wall) for all 12 experiments.

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(a)

(b)

Western basin Eastern basin

(a)

(b)

Western basin Eastern basin
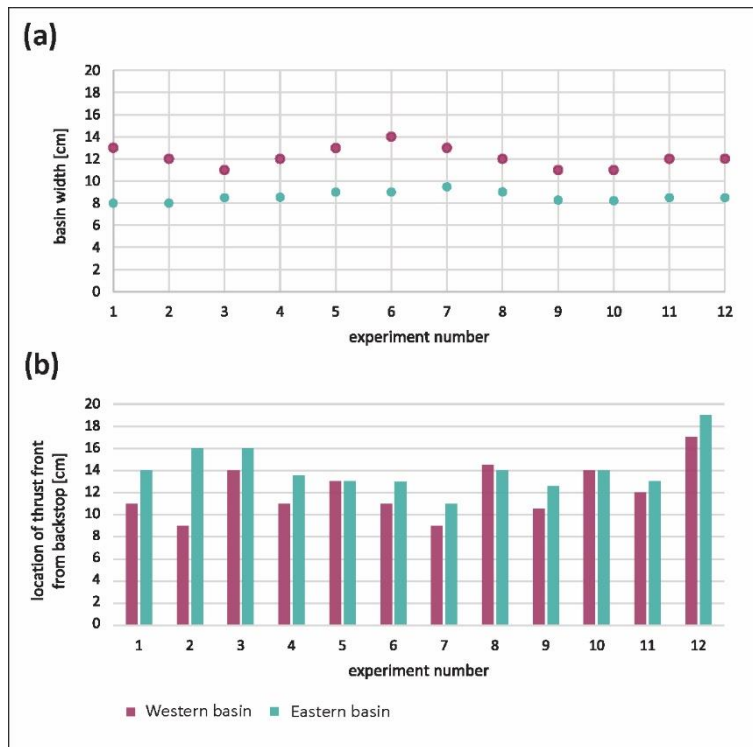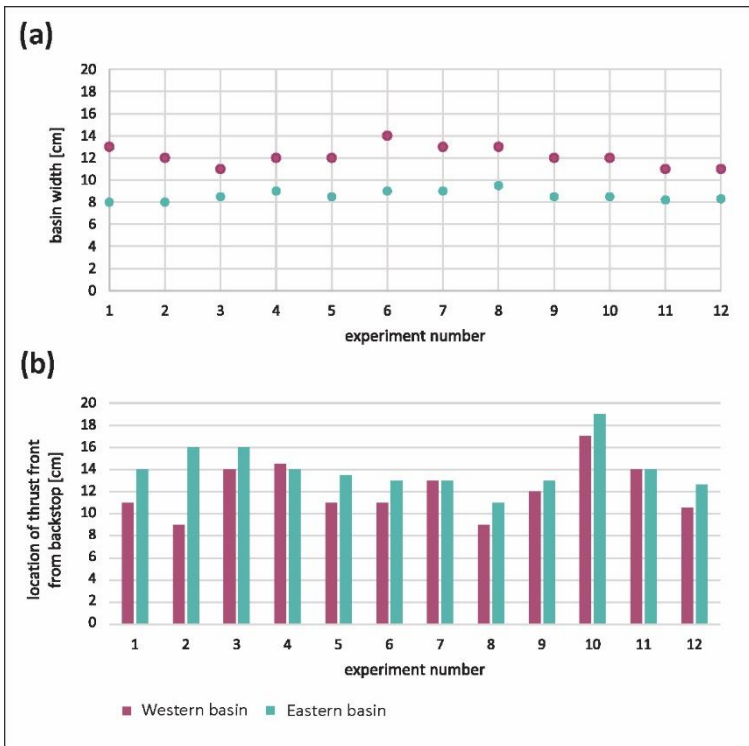
Figure 12. (a) Chart of basin widths of the western and eastern basins of each experiment, measured at the final stage (20 % of bulk shortening) of the experiment in W-E direction, perpendicular to platform boundaries. (b) Histogram showing the distance of the thrust fronts in basinal areas from the backstop, measured at the final stage (20 % of bulk shortening) of the experiment on top-view photographs.

1560
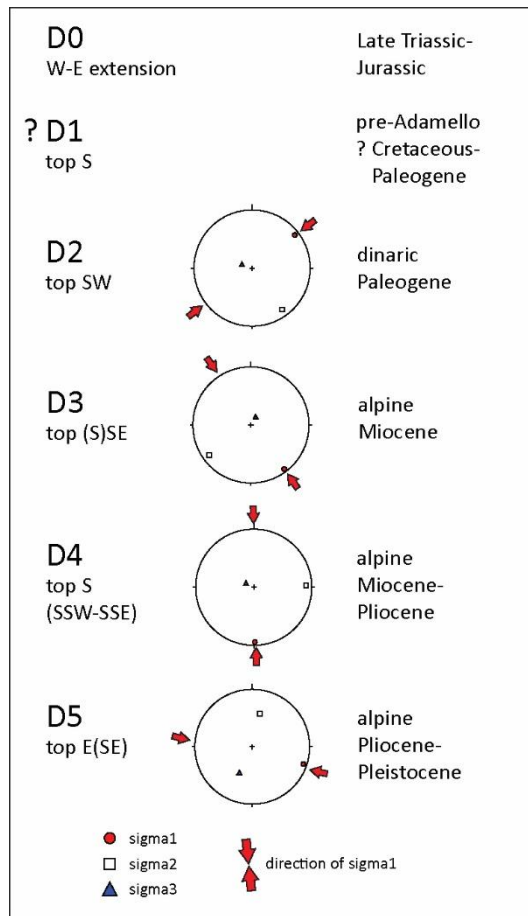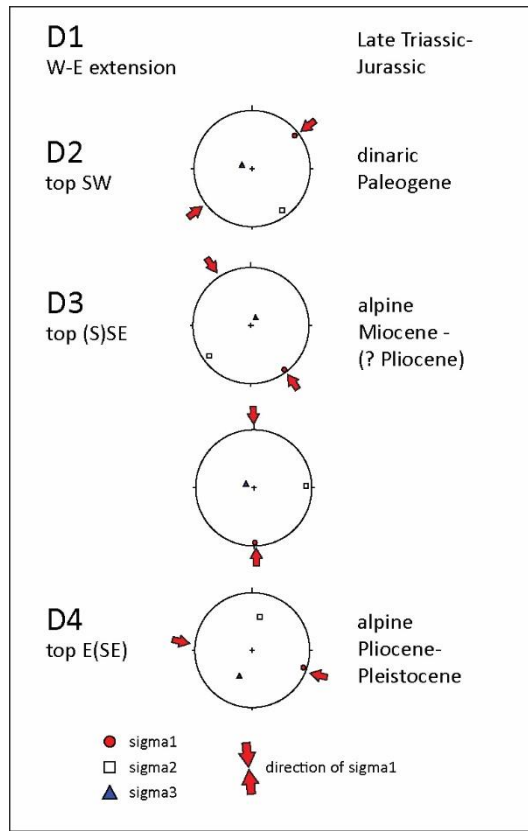
Figure 13. Schematic overview of the main deformational phases ~~D0~~D1 to ~~D5~~D4 of the eastern Southern Alps (compiled from Caputo (1996); Castellarin and Cantelli (2000); ~~Nussbaum (2000~~Caputo et al. (2010)) and this study).

(a)

❶ top SSW   ❷ top S   ❸ top SSE

direction of sigma1

fault slip data

4 data   27 data   4 data

fold axes

37 data   26 data   25 data   28 data

● P axes   ● mean fold axis
□ B axes   ● parasitic fold axis
▲ T axes   ○ pole to bedding

(b)

Periadriatic fault system
Fault
Blind fault
Country borders
Cities
Basin
Platform
Athesian Volcanic Complex (AVC)

(c) model 1 (18% BS)   (d) model 7 (12 % BS)

WB   WP   EB   EP   10 cm   WB   WP   EB   EP   10 cm

WB Western basin   WP Western platform   EB Eastern basin   EP Eastern platform

(a)

I top SSW **II** top S | direction of sigma1 | contour plot of fault slip lineations | **III** top SSE

fault slip data

4 data | 27 data | 27 data | 4 data

fold axes

37 data | 26 data | 25 data | 28 data

● P axes ● mean fold axis
□ B axes ● parasitic fold axis
▲ T axes ○ pole to bedding

(b)

Periadriatic fault system
—— Fault
- - - Blind fault
—— Country borders
○ Cities
Basin
Platform
Athesian Volcanic Complex (AVC)

(c) model 1 (18 % BS) (d) model 5 (12 % BS)

WB Western basin WP Western platform EB Eastern basin EP Eastern platform

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Figure 14. (a) Fault slip data with local stress directions and fold axes with indicated shortening directions of the Belluno thrust (Valsugana fault system). Locations I to III are indicated in Fig. 12b. (b) Late Triassic/Jurassic platform-basin configuration (modified from Winterer and Bosellini, 1981; Busetti et al., 2010; Masetti et al., 2012; Martinelli et al., 2017; Picotti and Cobianchi, 2017; Picotti et al., 2022) projected over the present day geography and overlain by the tectonic map of the Dolomites Indenter (modified from Schönborn, 1999; Castellarin and Cantelli, 2000; Schmid et al., 2004; Ponton, 2010; Viscolani et al., 2020). Note the change in shortening directions along strike of the Belluno thrust. Locations I to III represent segments of different strike of the Belluno thrust. Coordinates are in WGS 84/UTM zones 32T and 33T. Abbreviation red: VF – Villnöss/Funes fault, WF – Würzjoch/Passo delle Erbe fault, TTF – Tremosine-Tignale fault, VB – Val Bordaglia fault, CF – Calisio fault, VdS – Val di Sella back-thrust, CL – Caneva line. Abbreviation black: CadR – Cadore region, CarR – Carnia region, FriR – Friuli region, VB – Val Badia/Gadertal, Ap – Asiago pop-up structure, Sg – Seren graben. (c) PIV analysed top-view picture of parallel basin inversion of model 1 at 18 % of bulk shortening (BS). Black arrows indicate vectors of particle flow direction. (d) PIV analysed top-view picture of oblique (20°) basin inversion of model 5 at 12 % of bulk shortening (BS). Black arrows indicate vectors of particle flow direction.

Table 1. Geometrical model parameters used in this study. ~~Model type: B – brittle, BD – brittle-ductile.~~ Rheology of basal décollement: B – brittle, D –ductile. Material of basal décollement: qs – quartz sand, gb – glass beads, sp – silicon putty. Material of basin fill: qs – quartz sand, fs – feldspar sand, gb – glass beads.

Model number	Model type	Thickness brittle layer platform [cm]	Thickness brittle layer basin [cm]	Thickness ductile layer [cm]	Velocity engine pull extension [cm/h]	Velocity engine push compression [cm/h]	Total shortening [cm]	Angle of obliquity for inversion [°]	Scaled thickness platform [km]	Scaled thickness basin [km]
1	B	2,0	1,4	-	5,0	3,0	9,0	0	16,0	11,2
2	B	2,0	1,4	-	5,0	3,0	9,0	10	16,0	11,2
3	B	2,0	1,4	-	5,0	3,0	9,0	20	16,0	11,2
4	B	2,0	2,0	-	5,0	3,0	9,0	20	16,0	16,0
5	B	2,6	2,0	-	5,0	3,0	9,0	0	20,8	16,0
6	BD	2,0	1,4	0,6	2,5	2,5	9,0	0	20,8	16,0
7	B	2,6	2,0	-	5,0	3,0	9,0	20	20,8	16,0
8	BD	2,0	1,4	0,6	2,5	2,5	9,0	20	20,8	16,0
9	B	2,0	2,0	-	5,0	3,0	9,0	0	16,0	16,0
10	B	2,6	2,6	-	5,0	3,0	9,0	0	20,8	20,8
11	B	2,0	2,0	-	5,0	3,0	9,0	20	16,0	16,0
12	B	2,0	2,0	-	5,0	3,0	9,0	20	16,0	16,0

Model number	Angle of obliquity for inversion [°]	Rheology/Material of basal décollement	Material of basin fill	Thickness brittle layer platform [cm]	Thickness brittle layer basin [cm]	Thickness ductile layer [cm]	Engine velocity extension [cm/h]	Engine velocity compression [cm/h]	Total shortening [cm]
Set 1 - Obliquity of inversion									
1	0	B/qs	qs	2.0	1.4	-	5.0	3.0	9.0
2	10	B/qs	qs	2.0	1.4	-	5.0	3.0	9.0
3	20	B/qs	qs	2.0	1.4	-	5.0	3.0	9.0
Set 2 - Rheology of décollement									
4	0	B/gb	qs	2.6	2.0	-	5.0	3.0	9.0
5	20	B/gb	qs	2.6	2.0	-	5.0	3.0	9.0
6	0	D/sp	qs	2.0	1.4	0.6	2.5	2.5	9.0
7	20	D/sp	qs	2.0	1.4	0.6	2.5	2.5	9.0
Set 3 - Rheology of basin fill									
8	20	B/qs	qs	2.0	2.0	-	5.0	3.0	9.0
9	20	B/qs	fs	2.0	2.0	-	5.0	3.0	9.0
10	20	B/qs	gb	2.0	2.0	-	5.0	3.0	9.0
11	0	B/qs	gb	2.0	2.0	-	5.0	3.0	9.0
12	0	B/gb	gb	2.6	2.6	-	5.0	3.0	9.0

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Table 2. Properties for brittle and ductile material used in this study.

Brittle material	Grain size [μm]	Density [kg/m³]	Cohesion [Pa]	Coefficient of peak friction	Coefficient of dynamic friction	Coefficient of reactivation friction
Quartz sand	100-300	1500	10-40	0,63	0,48	0,52
Feldspar sand	100-250	1300	15-35	0,68	0,55	0,61
Glass beads	100-200	1530	25	0,48	0,40	0,44

Material	Grain size [μm]	Density ρ [kg/m³]	Cohesion C [Pa]	Coefficient of peak friction μ_p	Coefficient of dynamic friction μ_d	Coefficient of reactivation friction μ_r	Viscosity η [Pas]	Stress component n
Brittle								
Quartz sand	100-300	1500	10-40	0.63	0.48	0.52	-	-
Feldspar sand	100-250	1300	15-35	0.68	0.55	0.61	-	-
Glass beads	100-200	1530	25	0.48	0.40	0.44	-	-
Ductile								
PDMS + Rhodorsil gomme mixture	-	1500	-	-	-	-	3.8×10^4	1.15