Modelling the influence of pre-existing brittle fabrics on the development and architecture pull-apart basins

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Abstract

We use new analogue modeling experiments to analyze the development of pull-apart basins in an upper crust characterized by the presence of pre-existing discrete fabrics. As in previous models, lateral movement of rigid basal plates induced strike-slip deformation of a sand-pack. Local extension allowing the formation of a pull-apart basin was produced by the step-over geometry of the master faults; in this area, a basal silicone layer was introduced to distribute deformation and reproduced a weaker crust in the basin. Conditions of neutral, overlapping and underlapping interacting master faults were reproduced. The model upper crust, modelled by a sand mixture, was characterized by the presence of pre-existing structures; the orientation of these inherited heterogeneities was systematically varied in different experiments. Model results indicate that – depending on their orientation with respect to the strike-slip displacement- reactivation of the pre-existing structures can occur both within and at the margins of the pull-apart basins. Inside the basin, reactivation occurs when the pre-existing structures are orthogonal or sub-orthogonal to the strike-slip displacement; in this case, the pre-existing fabrics delay the development and linkage of cross-basin faults and increase the complexity of the deformation pattern giving rise to a new set of faults characterized by an atypical trend. Pre-existing fabrics oblique to the local extension direction may be partly reactivated in the central part of the basin as segments of cross-basin faults. At the margins of the pull-apart, reactivation occurs if the fabrics spatially coincide with the lateral boundaries of the silicone layer. In these conditions, reactivation allows a faster development of the border faults, which are less segmented than in the homogenous models; this also results in a more regular final geometry of the pull-apart

Keywords: pull-apart basins; pre-existing structures; reactivation; analogue modelling

1. Introduction

Pull-apart basins form where geometrical irregularities such as bends or step-overs in the main strike-slip fault system produce zones of local extension. They represent important features of strike-slip tectonics, and more than 160 basins around the globe have been attributed to transcurrent motion across segmented systems (Mann, 2007). Localised extensional deformation within these basins is typically accompanied by prominent subsidence and thinning of the crust and lithosphere, which may eventually lead to the break-up of the continental lithosphere (e.g., Mann et al., 1983; Umhoefer, 2011). Therefore, these basins are an important component of plate tectonics.

Analogue modelling has been proven to be a powerful technique to understand the evolution and architecture of pull-apart basins (e.g., Dooley and Schreurs, 2012). Indeed, much of the current knowledge on these basins comes from the results of analogue models (e.g., Soula, 1984; Faugère et al., 1986; Hempton and Neher, 1986; Raynaud, 1987; McClay and Dooley, 1995; Richard et al., 1995; Dooley and McClay, 1997; Rahe et al., 1998; Dooley et al., 1999; Basile and Brun, 1999; Sims et al., 1999; Atmaoui et al., 2006; Smit et al., 2008a, b; Wu et al., 2009; Mitra and Paul, 2011; Dooley and Schreurs, 2012; Corti and Dooley, 2015), which provided significant insights into the development and fault pattern of these basins in a homogeneous brittle or brittle-ductile crust, as summarized below.

1.1. General characteristics of pull-apart basins

Pull-apart basins are laterally limited by segments of transcurrent faults (standard strike-slip faults, SSFs), which constitute the principal deformation zone (PDZ; Fig. 1). The basins are bounded by fault systems with normal or oblique-slip kinematics (basin sidewall faults, BSFs) which form in the direction roughly orthogonal to the strike-slip displacement and are directly connected to the PDZs (Fig. 1). The floor of pull-apart basins is cut by a system of faults (cross-basin faults, CBFs) that link the offset PDZs, accommodate lateral displacement and commonly localise intrabasin subsidence and may separate depocenters within the basin (Fig. 1). The characteristics of the offset between the SSFs are the most important parameter controlling the architecture of pull-apart basins, which can be lozenge, lazy-Z or rhomboidal shaped depending on the offset angle (defining underlapping, neutral and overlapping interactions, see below; e.g., Dooley and Schreurs, 2012 and references therein). Other parameters (e.g., the horizontal separation between the offset SSFs, the ratio of brittle and viscous thickness, the strain rate and resulting coupling between brittle and ductile layers; e.g., Dooley and Schreurs, 2012) are important in controlling the evolution and deformation pattern of pull-apart basins.

In cross section, basin morphology displays significant along-strike variations, with transition from narrow V- and U-shaped grabens to a more symmetric, boxlike geometry passing from the basin terminations to the centre (e.g., Dooley and McClay, 1997; Dooley and Schreurs, 2012; Corti and Dooley, 2015).

1.2. The role of pre-existing structures in strike-slip tectonics and pull-apart development

The above-mentioned modelling works focused on the architecture and evolution of pull-apart basins in a homogeneous crust, with no pre-existing discrete structural heterogeneities. However, natural examples and modelling studies have shown that inherited brittle fabrics such as shear zones, faults, foliated rocks, and dykes inside the upper crust exert an important control on the evolution of strike-slip systems. For instance, recent work by Rotevatn and Peacock (2018) has shown that pre-existing segmented normal faults have a large control on the characteristics of the deformation during later phase of strike-slip motion. In agreement with these findings, multiphase deformation analogue models by Richard and Krantz (1991) indicate that faults formed during a first dip-slip stage are reactivated at depth during later strike-slip deformation. Similar results were obtained by Dooley and Schreurs (2012) who showed a control exerted by extensional basins formed during a first phase of extension on the distribution of later transcurrent motion. Models by Viola et al. (2004) illustrate how the reactivation of pre-existing discrete fabrics in the upper brittle crust is able to influence the pattern and evolution of strike-slip faults, a process which has likely controlled the Late Oligocene–Neogene evolution of the Giudicarie fault system in the Italian Eastern Alps. Koyi et al. (2008) have illustrated reactivation of pre-existing discrete fabrics in centrifuge models of simple shear deformation. Besides inherited discrete fabrics, pre-existing heterogeneities of variable nature (e.g., weak bodies such as salt diapirs) have been shown to exert an important control on the pattern of deformation during strike-slip tectonics e.g., (Dooley and Schreurs, 2012).

Field examples indicate possible influence of inherited fabrics on the development and architecture of several pull-apart basins. For instance, in the Coso geothermal field, hosted in a transtensional pull-apart basin, the polyphase history of deformation may have involved fabric reactivation (e.g., Dewey et al., 2008), with pre-existing structures at the margins of the basin influencing the development of BSFs (Fig. 2a; Dooley and Schreurs, 2012). In the Cinarcik basin, Sea of Marmara, Turkey, pre-existing basement structures may have controlled the architecture of deformation, resulting in a complex structural pattern deviating from the classical pull-apart architecture (Sugan et al., 2014). Several other examples testify the influence of inherited fabrics on the development of pull-apart basins (e.g., the Erzincan and Merzifon-Suluova basins, North Anatolian Fault Zone, Turkey, Temiz, 2004; Rojay and Koçyiğit, 2012; basins on the Yunnan-Myanmar region, Indochina, Morley, 2007). Recent work by Piippo et al. (2019) and Skyttä et al. (2019) indicates that the evolution and architecture of pull-apart basins developed in the Palaeoproterozoic Perapohja Belt in northern Finland was strongly influenced by the structural anisotropy of the Archaean crust. Skyttä et al. (2019) support these observations by means of analogue modelling of a pull-apart basin developing in an upper crust characterized by the presence of inherited, discrete brittle fabrics (Fig. 2b). The results of this model indicate that pre-existing fabrics reactivate during pull-apart development influencing the fault pattern and giving rise to additional fault sets, with atypical trend, affecting the basin floor and causing a prominent segmentation of the CBFs (Fig. 2b).

1.3. Aims of this work

Skyttä et al. (2019) present a single analogue model with pre-existing structures orthogonal to the trend of the strike-slip faults; therefore, the conditions under which the pre-existing structures were reactivated and the role of parameters such as the orientation of inherited fabrics with respect to the trend of the main strike-slip faults on reactivation were not systematically analyzed.

In this work, we fill this gap and present new analogue modeling experiments aimed at systematically investigating the influence of pre-existing structures (with different orientations with respect to the trend of the main strike-slip faults) on the development and architecture of pull-apart basins of variable master fault geometries (under- and overlapping, neutral). We show that that -in specific conditions- reactivation of the pre-existing structures can occur both within and at the margins of the basins, strongly affecting the pattern and evolution of pull-aparts.

2. Model set-up and experimental series

We conducted 15 modelling experiments at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources - National Research Council of Italy and the Department of the Earth Science of the University of Florence (Table 1). The experiments were ran under normal gravity conditions (1*g*) and the set-up consisted of two crustal blocks that relatively moved past each other to simulate simple shear deformation (Fig. 3). Motion was imposed by motor-driven lateral displacement of a basal Plexiglas plate whose geometry was characterised by an offset of the main strike-slip fault system in order to produce a zone of localised extension and give rise to a pull-apart basin (Fig. 3). Since there is only one mobile plate, the experiments are asymmetric pull-apart basin models.

The models consisted of a single 4 cm-thick sand-pack simulating the brittle behaviour of the upper crust; this sand-pack was unconfined in all directions above the basal plates. For this layer, we used a mixture of Quartz and K Feldpsar sands (70% - 30% in weight, respectively), characterised by an angle of internal friction of ~39°, density of ~1400 kg m^{-3} and cohesion of ~10 Pa (Montanari et al., 2017). A basal, 1 cm-thick layer of silicone (Polydimethylsiloxane, PDMS) was placed in the offset area in order to distribute deformation in the basin (Fig. 3). This silicone layer, analogous the use of a basal rubber sheet between rigid plates (e.g., Dooley and Schreurs, 2012) or of a weak zone within the offset area between two rigid blocks (Corti and Dooley, 2015), was intended to simulate weaker crust in a pull-apart.

Top-view photos of the models were taken at regular intervals in order to monitor the evolution of surface deformation. Experiments were repeated at least twice; in all cases, the first order results were similar. At the end of each experiment, the models were soaked in water and cut in a set of cross sections to analyse their 3-D internal geometry.

2.1. Type of experiments

In the experiments, the geometry of the basal plate was varied to reproduce the three conditions of neutral (Series 1 models), overlapping (Series 2 models) and underlapping (Series 3 models) master faults (Fig. 3a), identical to those investigated by many previous experimental works (see for instance Dooley and Schreurs, 2012 and references therein). For each of these series, we made manual vertical cuts to the sand pile with a knife at regular intervals (~4 cm) to reproduce the presenceof pre-existing structures (with width of 3-4 mm) within the upper crustal layer (e.g., Viola et al., 2004; Bellahsen and Daniel, 2005); the basal polymer was not affected by these cuts. In different experiments, the orientation of these pre-existing heterogeneities was varied with respect to the trend of the main strike-slip faults (Fig. 3b; Table 1). For comparison, homogenous models (i.e., with no pre-existing cuts) were also preformed (Table 1).

2.2. Scaling

The models were built with a geometric scaling ratio of $\sim 3.3\times10^{-6}$, such that 1 cm in the experiments corresponded to ~3 km in nature. This allowed modelling ~12 km of lateral displacement of a ~12-km-thick upper crust. For a density of natural upper crustal materials of 2700-2800 Kg m^{-3} (resulting in a density model to nature ratio $\rho^*=\rho_{model}/\rho_{nature}$ of ~0.5), a gravity ratio of 1 (the gravity is the same in nature and experiments) and the above reported geometric scaling ratio ($h^* \sim 3.3\times10^{-6}$) give a model to nature ratio of stresses ($\sigma^*=\rho^* g^* h^*$) of $\sim 2\times10^{-6}$ (Hubbert, 1937; Ramberg, 1981). Since the scaling ratio of cohesion is $c^*= \sigma^*$, the cohesion of the sand mixture (10 Pa) scales down to a natural cohesion of rocks of ~5 MPa.

Since the silicone at the base of the models does not correspond to any specific layer in nature but it is an experimental expedient to distribute deformation, the scaling of velocity is not critical in these models. However, the viscosity of the PDMS at room temperature (η=2x10^4 Pa s) and the velocity of deformation applied to the models (v=5 cm/hr) can be scaled down considering the relation $\sigma^*=\eta^* v^*/h^*$ (Hubbert, 1937; Ramberg, 1981). According to this, natural viscosities between ~4,4x10^{19} and 1,5x10^{21} Pa s correspond to a natural velocity in the range ~1–35 mm yr^{-1}, well correlating with natural strike-slip systems (see Corti and Dooley, 2015 and references therein).

3. Model results

3.1. Series 1 models: Neutral master faults

The models with neutral master faults display initial development of Riedel shears and E-W strike-slip faults in the PDZs, together with NNW-SSE trending BSFs which accommodate subsidence of the pull-apart basin above the basal PDMS (Figs. 4-7; Figs. SI 1-2). Within the basin, deformation is normally accommodated by early development of CBFs, which obliquely cut across the depression and connect the offset PDZs (e.g., Fig. 4). The pull-apart basin in the homogenous model is characterised by the presence of normal faults (internal faults; IFs) that delineate minor horsts which abut against CBFs. Owing to the transcurrent component of motion, the southern and northern margins of the basin are characterised by a typical en-echelon arrangement of major faults (Figs. 4-7). The length/width ratio of the basin at the end of deformation is ~1.1.

The evolution and architecture of the model with N-S pre-existing structures (Fig. 5) display significant differences: the inherited fabrics are reactivated during the initial phases of deformation (reactivated faults, RFs); this reactivation also affects the development of the CBFs. In contrast to the homogenous model, the CBFs are unable to rapidly link to form a single throughgoing fault connecting the PDZs. Rather, CBFs in this model are initially (1cm of displacement) highly segmented and their linkage occurs for 2cm of displacement only. Once linked, the CBFs cut the RFs, which are progressively rotated clockwise to attain a final average NNE-SSW orientation (Figs. 4, 6). The final length/width ratio of the basin is ~1.1.

The model with E-W fabrics (Figs. 6, 7) has a similar evolution with respect to the homogenous model, with early development and linking of the CBFs. In this model, however, influence of the pre-existing structures is evident at the southern and northern margins of the basins where, for increasing deformation, major linear faults develop. This is in contrast to the homogenous model where, as explained above, the southern and northern margins are characterised by segmented, en-echelon major faults. The length/width ratio of the basin at the end of deformation is ~1.2.

The model with N45°W-oriented pre-existing structures (Fig. 7; Fig. SI 1) shows reactivation of an inherited fabric in the central part of the pull-apart; in this case, the reactivated fabric corresponds to segments of CBFs. The evolution and pattern of deformation is rather similar to that of the homogenous model, although the development of internal normal faults seems to be influenced by the pre-existing fabrics, as testified by the trend of some of these faults which tends to parallelize the inherited NW-SE heterogeneities. The length/width ratio of the basin at the end of deformation is ~1.0.

Similarly, to the two previous models (with N-S and N45°W-oriented fabrics) the development of CBFs in the model with N45°E-oriented pre-existing structures (Fig. 7; Fig. SI 2) seems to be slightly delayed with respect to the homogenous model. However, in this case no apparent influence of the inherited fabrics on the fault pattern within or outside the pull-apart basin is observed. The final length/width ratio of the basin is ~1.0.

3.2. Series 2 models: Overlapping master faults

The homogenous model with overlapping master faults displays early development of NNW-SSE trending normal faults bounding the subsiding pull-apart basin, and CBFs connecting the PDZs

(Figs. 8, SI 3-7). For increasing lateral displacement, a set of BSFs with NNE-SSW trend normally develops at the margins of the basal PDMS (Fig. 8). Sets of NW-SE-trending internal faults give rise minor horsts within the basin. Similar to series 1 models, the southern and northern margins of the basin are characterised by a typical en-echelon arrangement of major faults (Figs. 8, SI3). The length/width ratio of the basin at the end of deformation is ~1.0.

Fabric reactivation in the model with N-S pre-existing structures (Figs. 8, SI4) inhibits again the rapid linkage of the CBFs; in this case, these structures remain highly segmented during deformation and their linkage does not clearly occur even for 4cm of displacement. The reactivation of the inherited fabrics also inhibits the development of NE-SW faults at the margins of the PDMS; therefore, differently from the homogenous model, the BSFs are roughly N-S oriented in this model. The RFs within the basin are progressively rotated clockwise with progressive displacement (Figs. 8, SI4). The final length/width ratio of the basin is ~1.0.

As in Series 1 models, reactivation of E-W inherited fabrics (Figs. 8, SI5) is evident at the northern margin of the basins where a major linear fault develops at the beginning of deformation. This contrasts with the segmented, en-echelon major faults characterising the corresponding margin in the homogenous model. No similar linearity of faults is observed in the southern margin, likely because the pre-existing fabric did not spatially correspond to the margins of the basal PDMS. The evolution of the basin is otherwise similar to that of the homogenous one, with NNE-SSW-trending BSFs developing for displacement >2cm, systems of internal faults and CBFs giving to a complex fault pattern affecting the pull-apart depression. The length/width ratio of the basin at the end of deformation is ~1.0.

Pre-existing N45°W fabrics (Figs. 8, SI6) are partly reactivated in the central part of the pull-apart during early stages of deformation. Differently from the homogenous model, the NNE-SSW-trending BSFs are less developed and their trend is roughly N-S in this model. Notably, in this case, the CBFs display a linear geometry which contrast with the significant curvature or segmentation of the CBFs in all other overlapping models. The length/width ratio of the basin at the end of deformation is ~1.0.

The model with N45°E-oriented pre-existing structures display an early development of NE-SW-trending BSFs, which correspond to the reactivation of inherited fabrics parallel to the margins of the PDMS (Figs. 8, SI7). These structures progressively accumulate deformation for increasing lateral displacement. This model results in more distributed extensional deformation and higher number of internal faults. The final length/width ratio of the basin is ~0.9.

3.3. Series 3 models: Underlapping master faults

Similarly, to the previous corresponding experiments, the homogenous model with underlapping master faults displays initial development of NW-SE trending normal faults (BSFs) delimiting the subsiding pull-apart basin and systems of CBFs connecting the offset PDZs (Figs. 9, SI 8-12). Internal faults are longer, more linear and fewer than in the corresponding neutral and overlapping models (Figs. 9, SI8). Curved, en-echelon normal faults again characterise the southern and northern margins of the basin (e.g., Figs. 9, SI8). The length/width ratio of the lozenge-shaped basin at the end of deformation is ~1.2.

Reactivation of N-S pre-existing structures during early stages of deformation is similar to what observed in previous models, causing again initial segmentation of the CBFs (Figs. 9, SI9). The RFs within the basin are progressively rotated clockwise with increasing deformation (Figs. 9, SI9). The final length/width ratio of the basin is ~1.1. For this model, we also present transversal cross-sections (Fig. 10), which document significant along-strike variations in basin morphology. At the basin terminations, deformation is characterised by narrow V-shaped grabens and negative flower structures; the basin centre displays instead a trapezoidal shape with high angle normal faults (dip >70°) delimiting the depression and inner minor horsts and grabens. Fault reactivation is visible within the pull-apart (see sections D-D', E-E', G-G'), whereas fabrics are not reactivated outside the basin.

As in previous Series 1 and 2 models, pre-existing E-W fabrics are reactivated at both northern and southern margins of the basin where major linear faults develop (Figs. 9, SI10). Due to the interaction between linear E-W faults and the NW-SE-trending BSFs, the basin is characterised by a very regular shape, with a final length/width ratio of ~1.4.

No pre-existing structures in the models with N45°W-oriented (Figs. 9, SI11) and N45°E-trending (Figs. 9, SI12) fabrics are reactivated within or at the boundaries of the pull-apart basin. The only differences with respect to the homogenous model are a slightly more complex fault pattern (mostly in terms of higher number of more segmented internal normal faults) in the model with N45°W-oriented fabrics (Figs. 9, SI11) and a single CBF and less segments BSFs in the model with and N45°E-trending fabrics (Figs. 9, SI12). The length/width ratio of the basin at the end of deformation is ~1.3 for both models.

4. Discussion

The current experiments document a strong control exerted by pre-existing discrete brittle fabrics on the evolution and internal architecture of pull-apart basins. Whereas the standard homogenous models (i.e., with no pre-existing structures) reproduced the typical deformation pattern of pull-aparts characterized by major normal/oblique slip faults at the margins of the subsiding basin and by transcurrent faults obliquely cutting the basin floor and connecting the main strike-slip fault segments (see section 1.1; Figs. 6-8; e.g., Dooley and Schreurs, 2012 and references therein), models with inherited fabrics documented the development of additional fault sets and atypical evolution of structures. ~~The influence or~~ Reactivation of pre-existing structures may occur within or at the margins of the pull-apart basins, depending on the orientation of the inherited fabrics with respect to the strike-slip displacement, as explained below.

4.1. Pre-existing fabrics orthogonal to the strike-slip displacement

Pre-existing fabrics orthogonal to the strike-slip displacement (N-S-trending fabrics) are always reactivated within the basin floor (Fig. 11), giving rise to fault segments characterised by a dominant left-lateral displacement (Fig. 12). This kinematics and the trend of these structures (at a high angle to the strike-slip faults) suggest that these faults can be compared to antithetic Riedel (R') shears. Therefore, displacement on these fabrics occurs because they are in a favourable orientation to be reactivated as antithetic Riedel shears, in agreement with previous analysis (e.g., Ranalli and Yin, 1990) showing that reactivation occurs when the pre-existing structures are favourably oriented with respect to the local tress field. Similar structures, although with slightly different orientation, have been observed in pull-apart experiments (e.g. Basile and Brun, 1999) or in distributed strike-slip brittle-ductile experiments (e.g., Dooley and Schreurs, 2012).

Reactivation occurs during the early stages of strike-slip motion and leads to the development of N-S fault segments, which are not observed in any homogenous model. Deformation along the N-S striking structures delays the development of CBFs, which cannot rapidly link to form a continuous system obliquely cutting the basin floor as observed in the homogeneous models (Fig. 11). This testifies that the inherited fabrics, once reactivated, may inhibit the propagation of newly formed faults, as evidenced in previous works (e.g., Teufel and Clark, 1984). In all models, the reactivated N-S faults accumulated only limited amount of deformation: their activity decreased rapidly during progressive strike-slip motion until they were deactivated, cut by CBFs and progressively rotated clockwise. Their final orientation (variable from roughly NNE-SSW to NE-SW) gives rise to a fault system which is atypical with respect to those observed in classical homogenous models. As a result, the complexity of deformation patterns increased as normally observed in cases of fault reactivation (e.g., Morley, 1999; Peacock and Sheperd, 1997; Rotevatn and Peacock, 2018).

4.2. Pre-existing fabrics oblique to the strike-slip displacement

Reactivation of NW-SE- and NE-SW-trending fabrics is strongly dependent on their position and orientation with respect to the margins of the basal silicone layer (which in turn controls the distribution of deformation in the upper crust). Reactivation is favoured when the inherited structures are spatially coincident with the margin of the PDMS layer (i.e., the margins of a weaker crust in the basin): in this case, the strain localisation effect generated by the pre-existing weak fabric adds to the strength contrast between the PDMS and the surrounding sand. A favoured reactivation in case of spatial coincidence between inherited structures and location of development of newly formed faults have been already observed in previous experimental works (e.g., Viola et al., 2004). If this condition is satisfied, reactivation occurs if the trend of pre-existing fabrics is similar to the angle of offset between the two PDZs (i.e., the inherited fabrics are parallel to the long side of the basal PDMS layer), as exemplified in Figs. 13, 14. Reactivation at the basin margins strongly affects the development of BSFs by accelerating their development, decreasing their segmentation and therefore promoting a more linear geometry (Figs. 13, 14), but does not influence significantly the architecture of deformation within the basin floor. However, partial reactivation of NW-SE-trending fabrics is observed in the central part of the pull-apart basin in models with neutral and overlapping master faults (Figs. 7, 8; Figs. SI 1, SI 6); in this case, reactivation occurs because the pre-existing structures are favorably oriented to directly link the offset master faults and are reactivated as segments of CBFs.

4.3. Pre-existing fabrics parallel to the strike-slip displacement

Pre-existing fabrics parallel to the strike-slip displacement (E-W-trending fabrics) are typically reactivated at the northern and southern margins of the basin, when there is a spatial coincidence between inherited structures and the short side of the basal PDMS layer (Figs. 13, 14). In this case, major linear faults develop, contrasting with the more segmented, en-echelon nature of the BBFs in corresponding margins of the homogenous model. This also results in a more regular shape of the basin, as exemplified by model with underlapping master faults (see Figs. 9, Si10).

4.4. Summary of model results

The current models document an important control exerted by pre-existing fabrics on the evolution and the structural pattern of pull-apart basins, with reactivation of pre-existing occurring both within and at the margins of the basins. Inside the basin, reactivation occurs when the pre-existing structures are orthogonal to the local strike-slip displacement, i.e., favorably oriented to be reactivated as antithetic Riedel shears (N-S-trending fabrics); in this case, the pre-existing fabrics delay the development and linking of cross-basin faults and increase the complexity of the deformation pattern. Indeed, reactivation gives rise to a new set of faults characterized by an atypical trend, absent in homogenous models. Partial reactivation may also occur when the pre-existing structures are favorably oriented to directly link the master faults (NW-SE-trending fabrics); in these conditions, the inherited heterogeneities are reactivated as segments of cross-basin faults in the central portion of the pull-apart basin. At the margins of the pull-apart, reactivation occurs if the fabrics spatially coincides with the boundaries of a basal silicone layer introduced to distribute deformation. In these conditions, reactivation allows a faster development of the border faults, which are less segmented than in the homogenous models; this also results in a more regular final geometry of the pull-apart. Overall, in line with previous analysis of fault reactivation (e.g., Ranalli and Yin, 1990), these modelling results support that reactivation occurs for favourably oriented pre-existing fabrics and is favoured by a significant strength contrast (in this occurring at the margins of the pull-apart basin).

4.5. Implications for natural pull-apart basins

These results have important implications for the evolution ~~and architecture~~ of natural pull-apart basins with respect to e.g. the basin architecture, infill stratigraphy, development of pathways for fluid and magma migration and hydrocarbon traps. As explained in section 1.2, many field examples indicate multiphase deformation and possible influence of inherited brittle fabrics (such as shear zones, faults, foliated rocks, and dykes inside the upper crust) on the development of these basins (e.g., the Erzincan and Merzifon-Suluova basins, North Anatolian Fault Zone, Turkey, Temiz, 2004; Rojay and Koçyiğit, 2012; Cinarcik basin, Sea of Marmara, Turkey; Okay et al., 2000; Sugan et al., 2014; basins on the Yunnan-Myanmar region, Indochina; Morley, 2007). Pre-existing structures in these natural cases may have contributed to give rise a complex structural pattern deviating from the classical pull-apart architecture and resulting in fault sets with atypical trend, as observed in the current models. One important outcome of our experimental results is that the inherited fabrics within the basin are reactivated during early stages of deformation, and the activity of these faults decrease for increasing lateral displacement and these structures are later deactivated and cut by other fault sets. Processes such as ~~syn-deformation~~ ~~addition of sediments~~ syn-tectonic sedimentation may mask the surface appearance of these structures during progressive deformation, which however may be present at depth. This in turn may influence features such as the potential for these basin to host traps for hydrocarbons or the migration of fluids within the pull-apart, with important economic implications. As an example, in the Coso geothermal field, hosted in a transtensional pull-apart basin, the polyphase history of deformation may have involved fabric reactivation (e.g., Dewey et al., 2008; Dooley and Schreurs, 2012), which may have had an influence on the pattern of geothermal fluid transfer. In this natural example, fabric reactivation may have also influenced the development of BSFs (Fig. 2a; Dooley and Schreurs, 2012), as observed in our models.

~~In general, these experiments support that reactivation of pre-existing structures in pull-apart basins may be of significant importance, and may influence several aspects of these basins (evolution, architecture, physiography, etc.) and related processes (e.g., potential for hydrocarbons traps, fluid migration, volcanism).~~

Conclusions

New analogue models of development of pull-apart basins in an upper crust characterized by the presence of pre-existing discrete fabrics indicate that –depending on their orientation with respect to the strike-slip displacement- these latter may be reactivated both within and at the margins of the basins. Specifically:

-pre-existing fabrics orthogonal to the strike-slip displacement are always reactivated within the basin floor giving rise to a new set of faults orthogonal or sub-orthogonal to the strike-slip displacement. In this case, the pre-existing fabrics delay the development and linking of cross-basin faults and increase the complexity of the deformation pattern;

-pre-existing fabrics oblique to the strike-slip displacement are reactivated at the margins of the pull-apart if the fabrics spatially coincides with the boundaries of a basal silicone layer introduced to distribute deformation and corresponding to a weaker crust in the basin. In these conditions, reactivation allows a faster development of the border faults, which are less segmented than in the homogenous models; this also results in a more regular final geometry of the pull-apart;

-pre-existing fabrics oblique to the strike-slip displacement are partly reactivated within the basin when they are favorably oriented to directly link the offset master faults; in this case, the inherited heterogeneities are reactivated as segments of cross-basin faults in the central portion of the pull-apart basin;

-pre-existing fabrics parallel to the strike-slip displacement are reactivated at the northern and southern margins of the basin, when there is a spatial coincidence between inherited structures and the short side of the basal silicone layer. In this case, the inherited fabrics control the development major linear faults, which also results more regular final geometry of the pull-apart.

Overall, these results are in line with previous analysis of fault reactivation. They support indeed that reactivation occurs for favourably oriented pre-existing fabrics and is favoured by a significant strength contrast at the margins of the pull-apart, and result in the development of atypical fault sets characterising the deformation pattern.

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Figure captions

Figure 1. Typical fault pattern of a pull-apart basin (from Corti and Dooley, 2015). BSFs: basin sidewall faults; CBFs: cross-basin faults; SSFs: standard strike-slip faults.

Figure 2. Fabric reactivation in natural and experimental pull-apart basins. a) Summary map of the Coso pull-apart system (modified from Dooley and Schreurs, 2012), showing reactivation of pre-existing N-S fabrics at the margins of the basin. b) Evolution of an analogue model of pull-apart development with pre-existing brittle discrete fabrics (modified from Skyttä et al., 2019).

Figure 3. Set-up of the experimental series. a) Geometry of the basal plate and angle of offset between the master fault segments, giving rise to conditions of neutral (Series 1 models; offset angle A=90°), overlapping (Series 2 models; offset angle A=135°) and underlapping (Series 3 models; offset angle A=45°) master faults. The layer of Polydimethylsiloxane (PDMS) at the base of the model is indicated with the greenish colour. b) Orientation of the pre-existing cuts (red lines) in the different models (taking the experimental series with neutral master faults as exemplificative). Note that this orientation is referred to cardinal points, where the North-South direction is perpendicular to the strike-slip displacement.

Figure 4. Evolution of the homogenous model with neutral master faults illustrated as top-view photos (top) and schematic fault pattern (bottom). IFs: internal faults; other abbreviations as in Fig. 1.

Figure 5. Evolution of model with neutral master faults and N-S pre-existing fabrics illustrated as Fig. 4. RFs: reactivated faults; other abbreviations as in Figs. 1 and 4.

Figure 6. Evolution of model with neutral master faults and E-W pre-existing fabrics illustrated as in Fig. 4.

Figure 7. Summary of experimental results of Series 1 models (neutral master faults)

Figure 8. Summary of experimental results of Series 2 models (overlapping master faults)

Figure 9. Summary of experimental results of Series 3 models (underlapping master faults)

Figure 10. Transversal cross-sections for model with underlapping master faults and N-S pre-existing heterogeneities.

Figure 11. Comparison between homogeneous models (left column) and models with N-S pre-existing fabrics (right column) with neutral, overlapping and underlapping master faults (top, middle and bottom panels, respectively) for 1cm of horizontal displacement. Colour coding as in previous figures.

Figure 12. Kinematics of faults in the models, exemplified by experiment with underlapping master faults and N-S-trending pre-existing fabrics. Top panel: slip vectors along single faults calculated by

using Particle Image Velocimetry (see Philippon et al., 2015 for details of calculations); bottom panel: interpretation of fault kinematics.

Figure 13. Comparison among homogeneous models (left column) and models with pre-existing fabrics (right panels) in model with overlapping (top panels) and underlapping (bottom panels) master faults for 1cm of horizontal displacement. Pre-existing fabrics are oriented NE-SW and E-W in case of overlapping and underlapping master faults, respectively. Colour coding as in previous figures.

Figure 14. Summary of the influence of pre-existing fabrics on the architecture of pull-apart basins, as exemplified by models with neutral master faults. Note the atypical fault pattern with NNE-SSW to N-S trend in the model with N-S fabrics (central panel), not present in the homogenous model (upper panel); also note the linear faults bordering the northern and southern margins of the basin in the model with E-W pre-existing fabrics (bottom panel), which contrast with the segmented, en-echelon major faults characterising the same margins in the homogenous model.

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Experimental series	Model	Type of master fault interaction	Orientation of pre-existing fabrics	Displacement (cm)
1	1	*Neutral*	-	4.1
1	2	*Neutral*	N-S	4.0
1	3	*Neutral*	N45°W	4.0
1	4	*Neutral*	N45°E	4.2
1	5	*Neutral*	E-W	4.0
2	6	*Overlapping*	-	4.0
2	7	*Overlapping*	N-S	4.1
2	8	*Overlapping*	N45°W	4.0
2	9	*Overlapping*	N45°E	4.1
2	10	*Overlapping*	E-W	4.0
3	11	*Underlapping*	-	4.1
3	12	*Underlapping*	N-S	4.1
3	13	*Underlapping*	N45°W	4.1
3	14	*Underlapping*	N45°E	4.0
3	15	*Underlapping*	E-W	4.2

Table 1. Characteristics of the different experiments

Supplementary Figure captions

Figure SI1. Evolution of model with neutral master faults and NW-SE pre-existing fabrics.

Figure SI2. Evolution of model with neutral master faults and NE-SW pre-existing fabrics.

Figure SI3. Evolution of the homogenous model with overlapping master faults.

Figure SI4. Evolution of model with overlapping master faults and N-S pre-existing fabrics.

Figure SI5. Evolution of model with overlapping master faults and E-W pre-existing fabrics.

Figure SI6. Evolution of model with overlapping master faults and NW-SE pre-existing fabrics.

Figure SI7. Evolution of model with overlapping master faults and NE-SW pre-existing fabrics.

Figure SI8. Evolution of the homogenous model with underlapping master faults.

Figure SI9. Evolution of model with underlapping master faults and N-S pre-existing fabrics.

Figure SI10. Evolution of model with underlapping master faults and E-W pre-existing fabrics.

Figure SI11. Evolution of model with underlapping master faults and NW-SE pre-existing fabrics.

Figure SI12. Evolution of model with underlapping master faults and NE-SW pre-existing fabrics.