

Abstract

Fractures in rocks deformed under dominant ductile conditions typically form simultaneously with viscous flow. Material strength plays a fundamental role on fracture development in such cases, since fracture propagation can be strongly reduced by the high energy absorption of the material. Additionally, the degree and nature of anisotropy can influence the orientation and type of resulting fractures. In this study, four plasticine multilayer models have been deformed under coaxial boundary conditions to investigate the influence of strength and anisotropy on the formation of fracture networks. The experiments were made of different mixtures and presented two types of anisotropy: composite and composite-intrinsic. The transition from non-localised deformation to systems where fracture networks control deformation accommodation is determined by the ability of the material to dissipate the external work and relax the elastic strain during loading, either by viscous flow or by coeval flow and failure. Tension cracks grow in experiments with composite anisotropy, giving rise to a network of shear fractures when they collapse and coalesce with progressive deformation. The presence of an additional intrinsic anisotropy enhances the direct nucleation of shear fractures, whose propagation and final length depend on the rigidity of the medium. Material strength increases the fracture maximum displacement (d_{max}) to fracture length (L) ratio, and the resulting values are significantly higher than those from fractures in elastic-brittle rocks. This is associated with the low propagation rates of fractures in rocks undergoing ductile deformation.

1 Introduction

The deformation behaviour of Earth's crust rocks is often seen as a transition from frictional and elastic-brittle behaviour at shallow depths to ductile crystal-plastic flow at deeper levels. The change from brittle and discontinuous deformation (i.e. fracture-dominated) to ductile and continuous deformation (i.e. flow-dominated) is known as the

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brittle-to-ductile transition, and is typically characterised by systems in which displacement is accommodated by networks of shear zones where brittle and ductile deformation coexist and compete (e.g., Paterson, 1978; Passchier, 1984; Hobbs et al., 1986; Mancktelow, 2008a). It is assumed that an increase in depth progressively reduces pressure-dependent plasticity and increases viscous flow, which is mainly controlled by strain rate and temperature (e.g., Mancktelow, 2006). However, field observations and experiments suggest that coeval fracturing and rock flow are not restricted to a certain zone in the middle crust, but can affect rocks at a wide range of depths and deformation conditions from the Earth's surface to the upper mantle (e.g., Simpson, 1985; Pennacchioni and Cesare, 1997; Guermani and Pennacchioni, 1998; Mancktelow, 2009). Moreover, brittle fractures can be precursors of ductile shear zones in certain cases (e.g., Segall and Simpson, 1986; Fousseis et al., 2006; Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007). It is therefore of crucial importance to recognise the main parameters controlling systems in which brittle and ductile deformation coexist. We understand brittle behaviour here as deformation showing loss of cohesion along discrete surfaces, and we therefore assume that it results in strongly localised systems. In a different manner, we consider that ductile strain can be localised or distributed. Ductile localisation is characterised by zones of localised deformation with continuous variations of strain across their width (i.e. without discontinuity) and without loss of cohesion (e.g., Twiss and Moores, 1992). Figure 1 shows an illustrative example of the interaction of brittle and ductile deformation in a deformed quartzite (Cap de Creus, E Pyrenees, N Spain), in a greenschist environment (Gomez-Rivas et al., 2007). Layers, defined by grain-size variations and preferential orientation of phyllosilicates, can be used as markers to track the displacement field. They show that these rocks coevally fractured and flowed, as evidenced by the presence of isoclinal folds outside fracture zones and drag folds associated with small-scale faults. The resulting fractures present relatively high values of maximum displacement (d_{\max}) to length (L) ratios, with strong gradients along them. It is a common observation that d_{\max} / L ratios are significantly higher in systems dominated by ductile deformation (on the order of

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cal properties and anisotropies have been coaxially deformed at constant strain rate, to visualise the transition from non-localising systems to models where deformation is strongly localised along a few large fractures. Layers in these experiments are oriented parallel to the extension direction, and perpendicular to the maximum compression.

We aim to address cases where effective confining pressure is relatively low, like ductile rocks at shallow depths (e.g. clays, salt bodies, etc.) or middle to lower crust rocks with high fluid pressures or subjected to local tensional stress (e.g., Fagereng, 2013). We aim to: (1) analyse the influence of material strength on the transition from non-localising to strongly localised systems using the same deformation conditions and very similar analogue materials, (2) address the role of different types of transverse anisotropy (composite and composite-intrinsic) on the degree of localisation and developed structures, (3) understand how coeval ductile-brittle deformation is visualised in terms of stress-strain relations, and (4) capture the key factors controlling the style and characteristics of the resulting structures (tension and shear fractures, pinch-and-swell) and how they evolve towards well-developed fracture networks with different properties (orientations, displacement-length ratios, etc.). In order to provide proper dynamic scaling and define the mechanical reference framework, the rheology of the analogue materials was characterised prior to experiments with uniaxial compression and relaxation tests.

2 Materials and methods

2.1 Deformation apparatus

A strain rate and temperature controlled apparatus (BCN-stage; Carreras et al., 2000) was used to deform the plasticine models. The prototype is based at the Universitat Autònoma de Barcelona (Spain), and can apply deformations from pure to simple shear ($0 < Wk < 1$) at variable temperatures. This apparatus has been used for several

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analogue modelling studies (Druguet and Carreras, 2006; Bons et al., 2008; Druguet and Castaño, 2010; Gomez-Rivas, 2008; Gomez-Rivas and Griera, 2009, 2011, 2012).

2.2 Experimental setup and deformation conditions

Plasticine is an ideal analogue of rocks undergoing coeval ductile and brittle deformation, because it can flow and also fracture at the same time depending on its composition and deformation conditions (temperature, strain rate, boundary conditions). It therefore presents elastoviscoplastic behaviour. Two kinds of commercial plasticine were utilised in this study. They were sold under the trademarks OCLU-PLAST and JOVI, both manufactured in Barcelona (Spain). Using them as a base, four different mixtures were created in order to build four models: type A (white and purple OCLU-PLAST pure plasticine), type B (white and purple OCLU-PLAST plasticine mixed with 10% paper flakes), type C (white and green JOVI pure plasticine) and type D (blue and red JOVI plasticine mixed with 10% paper flakes). Please note that the type A plasticine was the same material used for the experiments of Gomez-Rivas and Griera (2011, 2012). Flakes were made of different coloured paper and had a size of ~ 2 mm and a density of 80 grm^{-2} . The models were created by stacking layers (4 to 5 mm thick) of alternating colours, oriented perpendicular to the Z direction (Fig. 2). Materials were mixed by hand at room temperature, and then flattened with an industrial rolling pin. In that way, paper flakes were preferentially oriented parallel to layers. This procedure also avoided the presence of air bubbles within the models.

Transverse anisotropy in all models was defined by the stacking of beds, which created a composite layering. Additionally, experiments containing paper flakes (B and D) also presented an intrinsic anisotropy defined by their preferred orientation. Each model had an initial size of $30 \times 15 \times 10$ cm, and was compressed in the Z direction and extended in the X direction, while the Y direction remained constant using a reinforced transparent glass. Strain rate and temperature were kept constant at $2 \times 10^{-5} \text{ s}^{-1}$ and 26°C , respectively. The samples were deformed until a bulk finite strain ratio of $RX/Z \sim 4$ (i.e. $\sim 50\%$ shortening). Stress was recorded using gauges parallel to X

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systematically from model A to model D. Deformation was mainly accommodated by homogeneous flow during the first deformation stages in all models. Such flow was associated with a stress increase. At about 10% shortening the yield stress was reached for the stiffer models (C and D), and progressively decreased in these experiments up to the end without reaching a clear steady state. The first macroscopic fractures were not visible until ~15–18% shortening. In the softer models (A and B) a sharp yield stress was not identified, and stress progressively rose with strain until a steady state was reached. This steady state behaved slightly different in each experiment, as stress kept slowly growing in model B while it slightly decreased in model A.

The type of fractures and their orientations with respect to the deformation axes are also significantly different depending on the material (Figs. 7, 8, 9). Strain localisation and material embrittlement are enhanced when stiffness (or viscosity) is increased, and therefore the density and type of developed fractures strongly depend on how stiff the analogue material is. After 50% bulk shortening, deformation in experiment A was mainly accommodated by homogeneous flattening associated with viscous flow (Figs. 5, 8a–c). The estimated strain localisation factor was $l_{loc} \sim 1.04$ and normal shortening measured using the reference layers of Fig. 5 ranged between 50 and 52%. Traction structures along layer interfaces associated with potential inter-layer slipping were not observed. Layers were thinned with increasing deformation, and only a very small number of tension cracks and shear fractures could develop in this experiment. Such structures only started to be macroscopically visible after 30% shortening. Tension cracks were formed until ~40% shortening. The collapse of voids and cracks gave rise to the formation of hybrid fractures (or mixed mode I–II fractures). They evolved to become shear fractures organised in two conjugate sets (Fig. 8a–c). With very few exceptions, shear fractures formed at angles of ~40 to ~50° with respect to Z, and tended to rotate towards X at a rate significantly slower than a passive line (Fig. 7a, Table 4). At the end of the experiment, the length of fractures within the sampling area varied between 0.33 and 1.47 cm, following an exponential distribution. The cumula-

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tive fracture slip was always less than 20 % of the fracture length. Relatively variable maximum displacement (d_{\max}) – length (L) ratios could be found in this case (Fig. 9a).

The behaviour of model B, which was a mixture of soft plasticine and paper flakes, was significantly different. The presence of heterogeneities associated with flakes enhanced the nucleation of a large population of small-scale shear fractures (Fig. 5). Small voids and tension cracks were also recognisable within the sample (Fig. 8d–f), although flakes prevented their propagation in a way that large cracks could not form. In this case, a large number of millimetre-scale voids formed at the interfaces between layers or between flakes and plasticine. Pinch-and-swell and boudinage structures also started to develop in the first deformation stages. Two symmetrical sets of conjugate shear fractures formed in three different ways with increasing strain: (1) they directly nucleated (i.e. without precursors) enhanced by the heterogeneity of the two-phase (plasticine-paper flakes) system, (2) by progressive necking of pinch-and-swell and boudinage structures and (3) by coalescence and collapse of voids and tension cracks (Fig. 8d–f). Shear fractures formed at an angle higher than 45° with regard to the Z axis (Fig. 7b). The percentage of fractures oriented at more than 45° with Z ranged between 88 at 20 % shortening to more than 94% for 30–50 % shortening, thus indicating that fractures slightly rotated towards X . Average orientations increased between ~ 49 and $\sim 56^\circ$ at 20 and 50 % shortening, respectively (Table 4). At the end of the experiment, shear fracture lengths ranged between 0.5 and 1.9 cm. and the cumulative fracture slip was approximately 25 % of the total length. The ratio between maximum displacement (d_{\max}) and length (L) was considerable higher than that of model A (Fig. 9), even though fracture propagation was not very high in model B since new fractures nucleated all the time until the end of the experiment (see n values in Table 4). At the model scale deformation was approximately homogeneously distributed, as evidenced by a strain localisation factor of $I_{\text{loc}} \sim 1.16$ and shortening normal to the reference layers ranged between 47 and 54 %.

The evolution of model C resembles that of model A, but with a considerably higher amount of fractures. In this case, strain localisation was related to the nucleation and

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growth of a very large population of relatively long tension cracks, which evolved to form two conjugate sets of shear fractures with increasing strain (Fig. 7c, Table 4). Tension cracks formed during the first experiment stages and up to $\sim 30\%$ shortening. When deformation increased, their nucleation and propagation was aborted and they started to quickly collapse and rotate towards the extension direction, thus enhancing the formation of two conjugate sets of shear fractures. This process took place by void and crack collapse and coalescence and by fracture segment linkage (Fig. 8g, i). Such mechanisms enhanced fracture connectivity, thus amplifying the direct nucleation of secondary shear fractures. Fracture statistics illustrate the clear transition from a tension- to a shear fracture-dominated system with progressive deformation. Almost no shear fractures were observed at 20% shortening, while many tension cracks developed. At 30% shortening there were still more tension than shear fractures, which were oriented at an average of $\sim 35^\circ$ with respect to Z (with a standard deviation of $\sim 7^\circ$; Table 4). A marked change in the properties of the fracture network took place between 30 and 40% shortening. At 40% shortening only a few tension cracks remained active, while a dense network of shear fractures was observed. Such fractures had at this stage widely variable orientations with respect to Z (from ~ 25 to $\sim 55^\circ$), being 43% of them oriented at angles higher than 45° . These variable orientations remained at 50% shortening, when all tension cracks have disappeared. At this stage 67% of shear fractures were oriented at more than 45° with Z . Despite the differences in material behaviour and type of fractures, the ratio between fracture length and accumulated displacement was similar to the one observed for the type B model (Fig. 9). At the model scale, strain localisation by the fracture network was resolved at a length scale smaller than the sample length. The calculated normal shortening ranged between 45 and 55% , and the strain localisation factor was therefore relatively low ($I_{loc} \sim 1.2$).

Finally, the stiffer model (type D) experienced a very different deformation history than the previous three experiments. Despite this, it presents some similarities with model B, mainly associated with the presence of a second phase (i.e. paper flakes). Large tension cracks were not observed in model D (Fig. 5). Instead, a small number of

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very large shear fractures developed, with lengths ranging between 2.5 and 9 cm. It is important to notice that these measurements refer to individual fracture segments, but fracture zones composed of several segments were of course significantly longer than that. Some of them propagated up to the limits of the model and were able to accommodate considerably larger displacements than the ones registered in the other three experiments (Fig. 9). This observation is clearly supported by the fact that the maximum fracture displacement was approximately 40 % of the total fracture length. Another special feature of this model is that the two conjugate shear fracture sets were not symmetric, since the sinistral set nucleated earlier than the dextral one, which subsequently cross-cut and displaced the early sinistral fractures (Fig. 8j–l). Shear fractures in this model were, on average, oriented at 43 to 50° with Z . However, these angles were very variable and some large fractures formed a lower angle with the maximum compression axis. Fractures in this model tended to accommodate deformation by slip, instead of rotating towards X (Fig. 7d, Table 4), in a contrary way to the other three experiments where the two sets were always symmetrical with respect to the X and Z axes. At the model scale, deformation was heterogeneously distributed and strong necking was observable at the central part of the experiment, where relative large shear fault zones crosscut. A strong strain partitioning was detected between high and low strain domains, where layer-normal shortening was about 63 and 30–36 %, respectively. The strain localisation factor (I_{loc}) was higher than 2.0.

4 Discussion

The experimental results obtained in this study indicate that the mechanical properties of an elastoviscoplastic material have a strong influence on the degree of brittle deformation and how deformation is accommodated by a fracture network (Figs. 5, 8). The style of developed structures and their properties strongly depend on the material mechanical behaviour (Figs. 7, 9, Table 4). A marked transition from distributed to strongly localised systems can be observed when variants of the same materials are deformed

under the same conditions. Our experiments are made on two commercial types of plasticine (OCLU-PLAST and JOVI), which have a similar stress exponent when they are not mixed with other components (Table 1). The effective viscosity of pure JOVI plasticine is about 3 times higher than that of pure OCLU-PLAST, while elastic shear modulus (G) values of mixtures made of JOVI plasticine are between 2 and 6 times higher than those made of OCLU-PLAST (Table 2). These variations are already high enough to result in two very different deformation systems, since model A (made of pure OCLU-PLAST plasticine) mostly accommodated deformation by homogeneous flattening associated with viscous flow while a dense network of tension and shear fractures coeval with ductile flow developed in model C (made of pure JOVI plasticine). The stronger elastoviscous behaviour of type C plasticine does not allow an efficient stress relaxation by viscous flow, even for high deformation values ($> 25\%$ shortening), thus enhancing fracture formation. The addition of paper flakes as a second phase, statistically oriented parallel to layering, produced again a remarkably different mechanical behaviour. A dense network of small shear fractures formed in model B (made of OCLU-PLAST plasticine and flakes), while a few large fractures controlling the system developed in the most rigid experiment (model D, made of JOVI plasticine and paper flakes).

As explained in Sect. 2.3, no shear bands or fractures formed in the uniaxial compression tests. This is evidenced by the lack of material discontinuities and the absence of pronounced and sharp yield points in the stress-strain curves (Fig. 3). This does not only apply to tests made of pure plasticine, but also to tests composed of mixtures B and D, which include paper flakes randomly oriented. These observations suggest that the presence of heterogeneities within the material is required to produce fracture onset. In our experiments, heterogeneities are associated with two types of transverse anisotropy: (1) composite anisotropy (Treagus, 1997) defined by stacking of layers with slight contrasting properties and (2) intrinsic anisotropy produced by the preferred orientation of elements of a second phase (i.e. paper flakes) statistically oriented parallel to layering. All experiments are composites, but models B and D include an additional

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intrinsic anisotropy. The type and degree of anisotropy (composite vs. intrinsic) can play a fundamental role on the resulting structures and the bulk material behaviour (Griera et al., 2011, 2013). Apart from the presence of heterogeneities, another reason why brittle structures nucleate could be tectonic underpressure produced by weak interfaces or contrasting rheologies between adjacent layers (e.g. Mancktelow, 2008b). However, all structures in our models (voids and tension cracks, shear fractures, pinch-and-swell, necking and boudinage) affect both all layers of different colours in the same way. This indicates that tectonic underpressure is not the reason why brittle behaviour becomes active in these experiments, since the competence contrast between alternating layers is very low and layers are well bonded thus defining strong interfaces.

The transition from ductile to coeval ductile-brittle behaviour is determined by the ability of the material to dissipate the imposed external work and relax the elastic strain energy stored as a consequence of loading (e.g. Anderson, 2005). This relaxation can take place either by viscous or coeval viscous-brittle deformation. New fractures can only grow when the strain energy released during fracture growth exceeds the sum of the surface energy of the new crack segment and the plastic deformation energy at the crack tip (e.g. Perez, 2004). These processes strongly depend on the material strength. Stress-strain curves are used to establish a qualitative relationship between the strain localisation pattern and the work necessary to deform the sample. Such curves reveal a higher degree of localisation in the harder model (type D), which registered a marked strain softening behaviour following the stress peak (~ 12% shortening) (Fig. 6). The localisation of fracture networks is related to a reduction of the active volume that is being deformed and an increase on the efficiency of the accommodation of the imposed shortening by fracture slip. The growth of a network of few large fractures in the most viscous model (type D), or the development of a well arranged but segmented fracture network in experiment C, results in strain softening after yielding (Figs. 5, 6). Fracture networks in these two models were able to accommodate the displacement imposed by the boundary conditions, although experiment C also deformed coevally by dominant viscous flow. Model A basically deformed by viscous flow, and the resulting stress-strain

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curve displays first a slight increase, and then a steady-state flow with gentle strain softening after $\sim 25\%$ shortening. On the contrary, model B evolved by coeval small-scale fracturing and viscous flow. Deformation was distributed in a large population of small shear fractures with low propagation rates. Viscous relaxation was able to soften the increase of stress and inhibit the propagation of large faults in this case, and the stress-strain curve thus registered a very slight hardening associated with steady-state flow.

When loading started, ductile deformation was dominant in all models and macroscopic fractures only began to nucleate after 15–20% shortening. The type of early structures strongly depends on whether the anisotropy is only composite (models A and C) or composite plus intrinsic (models B and D). In composite anisotropic experiments, the first developed fractures were relatively large tension cracks that evolved to mixed-mode and shear fractures when fault planes rotated towards the extensional direction or when cracks collapsed and coalesced (Figs. 7, 8a–c). Shear fractures in these cases are oriented at $\sim 45^\circ$ with regard to the maximum compression axis Z . On the contrary, the presence of hard flakes prevented the propagation of large tensional cracks in composite-intrinsic experiments, but enhanced the nucleation of numerous small voids. Their fast collapse favours the formation of a conjugate shear fracture network oriented at relative high angles from the maximum compressive stress. Very small cracks and voids were visible in model B but they were not the only precursors of shear fractures, since the latter could also nucleate directly from heterogeneities associated with the presence of flakes. Not many tension cracks were observed in model D, suggesting that this material accumulated stresses until brittle yielding was reached and then relatively large shear fractures directly nucleated. Tension cracks are related to low effective confining pressure and low differential stress conditions, which enhance the presence of tensional stresses. Such cracks stop nucleating when viscous flow and/or slip along the shear fracture network are more efficient in dissipating the applied stress. Gomez-Rivas and Griera (2011) presented experiments with the model A configuration, but performed at different strain rates, and found that tension cracks

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A, B and C does not allow enough energy accumulation at crack tips for propagation. On the contrary, such energy is high enough in model D, where fractures could grow.

The results of the experiments presented in this study contribute to the understanding of the main controls on fracture localisation in ductile materials as well as the accommodation of deformation by different fracture networks depending on the rock mechanical properties. These models illustrate how strain localisation processes operate in a dominant ductile regime and allow visualising the transition from brittle to ductile behaviour using materials with a similar rheology. The progress onset, interaction and evolution of different types of structures (tension cracks, voids, pinch-and-swell, hybrid fractures, shear fractures) define a progressive change in the behaviour of the system. The presence of composite or combined composite-intrinsic transverse anisotropy plays a fundamental role, since it enhances brittle behaviour, promoting fracture formation and helping to dissipate the applied stress.

5 Conclusions

This contribution presents an experimental study on the influence of material strength on the formation of fracture networks in materials that are deformed by dominant viscous flow. Four plasticine multilayers, made of different mixtures, were deformed under coaxial boundary conditions at a constant strain rate and temperature. The following main conclusions arise from these experiments:

1. The increase of material strength causes a progressive transition from a non-localising end member, where deformation is mostly accommodated by homogeneous flattening, to a strongly localised system where a few fractures accommodate displacement. This ductile-to-brittle transition is controlled by the ability of the material to dissipate the external work and relax the elastic strain during loading, either by viscous flow or coeval flow and failure. Shear fractures, which are oriented at $\sim 45^\circ$ from σ_1 in most experiments, form by the collapse and coalescence

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of tension cracks and voids, from the evolution of pinch-and-swell structures or by direct nucleation associated with heterogeneities.

2. Stress-strain curves record the progressive transition from ductile-dominated to fracture-dominated systems. Models deformed by dominant viscous flow are characterised by the absence of yield points and a slight stress increase followed by steady state behaviour. On the contrary, localising systems record higher stress magnitudes and clear yield points followed by subsequent strain softening associated with deformation accommodated by fractures.
3. Additional intrinsic anisotropy, resulting from the presence paper flakes statistically oriented parallel to layers, produces a change in the deformation behaviour inhibiting the nucleation of tension cracks and voids. Enhanced transverse anisotropy in the soft model reduces fracture propagation and favours the formation a dense network of small-scale shear fractures oriented at high angles ($> 45^\circ$) with σ_1 . On the contrary, flakes significantly increase the rigidity of the material when added to the harder plasticine, and promote the formation of an asymmetric arrangement of a reduced number of large fractures controlling the system.
4. Material strength increases the fracture maximum displacement (d_{\max}) to length (L) ratios. Such values are relatively high compared to those resulting from fractures formed in elastic-brittle media. This is associated with the low propagation rates of fractures in rocks undergoing ductile deformation, and also with the presence of anisotropy.

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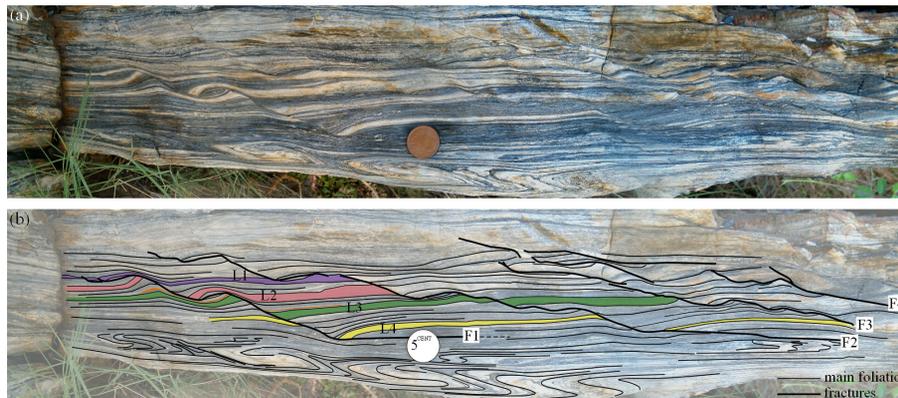


Figure 1. Examples of brittle deformation localisation in a ductile dominant system. **(a)** Presents small-scale shear fractures (F1 to F4) with flat/ramp segments and roll-over geometries in deformed banded quartzites of the Rabassers outcrop, at Cap de Creus (E Pyrenees, Spain) (Gomez-Rivas et al., 2007), and **(b)** the interpreted structures. Fracture planes are smooth. Antithetic, synthetic and double-sense drag folds can be observed. Note that same layers at both sides of fractures do not present the same drag fold pattern. Displacements along fault surfaces are not constant and do not show an elliptical distribution, as expected for an isolated fracture. Maximum displacement – length relationships (d_{\max}/L) range between 0.10 and 0.15. These fractures are interpreted as formed by segment linkage and growth during co-taneous brittle and ductile deformation. Fracture offsets of reference layers are: 0 (L1), 3.5–3.8 (L2), 2.5–3.0 (L3) and 3.3–3.7 cm (L4). This view is perpendicular to the foliation and fracture planes. Anisotropy of this rock is a consequence of grain size differences between dark and white layers and preferred orientation of phyllosilicates. The diameter of the EUR 5-cent coin is 21 mm.

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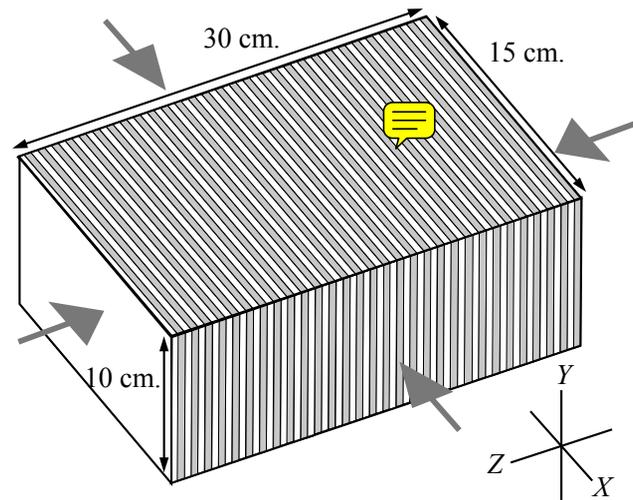


Figure 2. Sketch of a multilayer experiment. The arrows indicate the direction of the principal stresses applied by the deformation apparatus. The initial layer thickness was $\sim 4\text{--}5$ mm. After Gomez-Rivas and Griera (2011).

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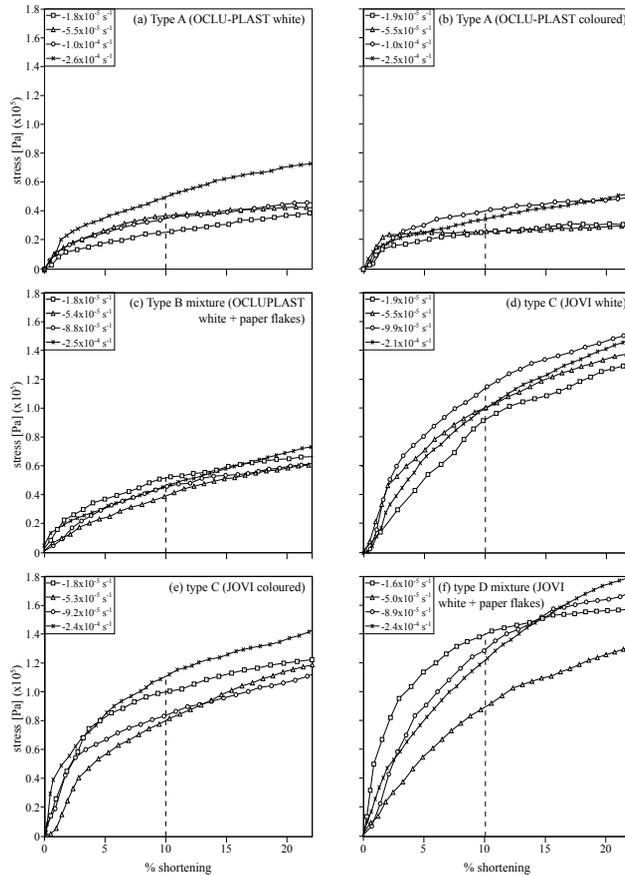


Figure 3. Stress vs. axial strain (expressed in % shortening) curves for the materials used in this study at different strain rates. Dashed lines indicate the strain reference value used for comparison of material properties (10 % shortening).

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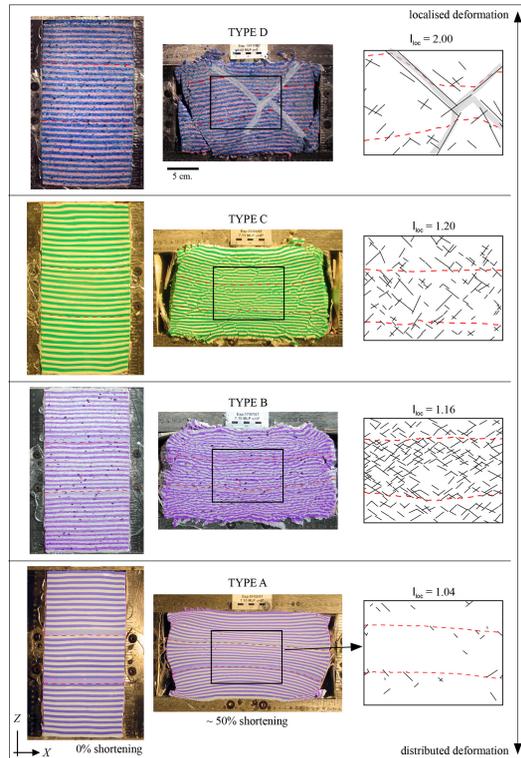


Figure 5. Photographs of the initial (0% shortening) and final (~50% shortening) stages of the four multilayer models. Maps of analysed fracture networks are displayed on the right side. Red dashed lines indicate reference layers. Grey shadowed areas in type D model show the location of large fault zones. Only structures located in the central area of each model, indicated with a rectangle, are systematically studied. I_{loc} is the localisation factor (see Sect. 2.2). The degree of localisation progressively increases from model A to model D, and depends on the strength, effective viscosity and degree of anisotropy of the models. Marked differences between the resulting fracture networks can be clearly identified.

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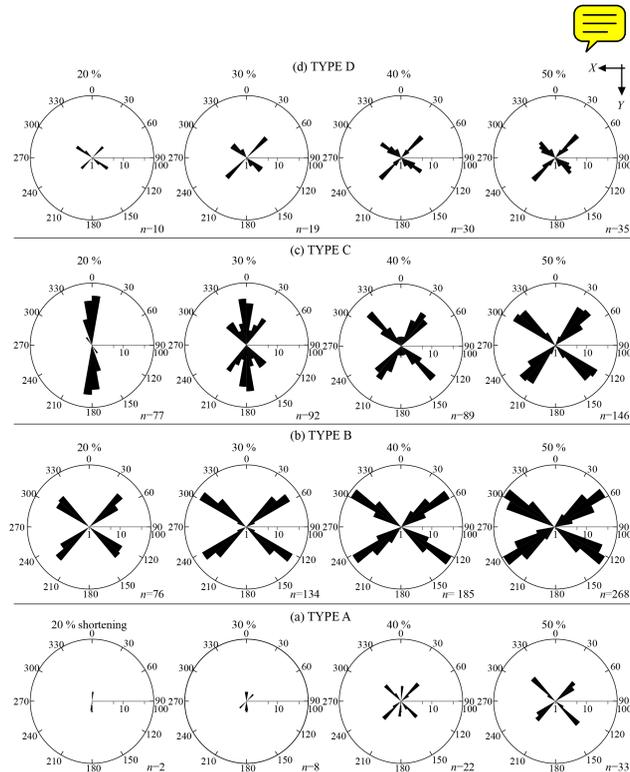
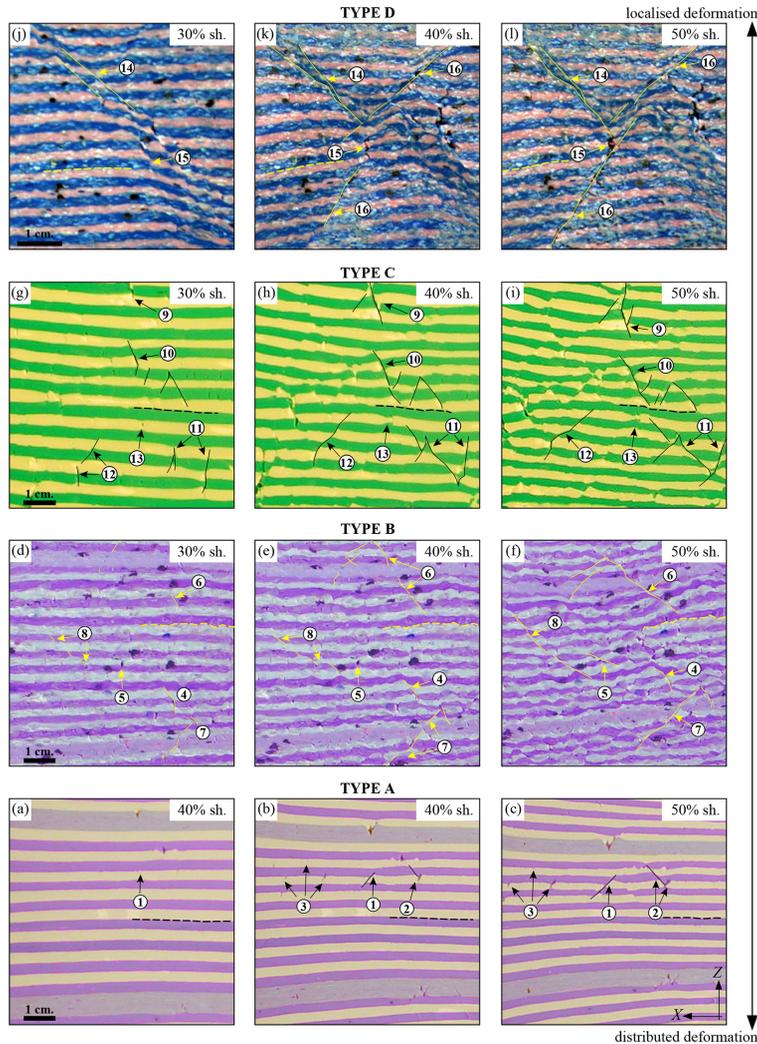


Figure 7. Rose diagrams showing the orientation and number of fractures (at orientation intervals of 10 degree) of experiments: **(a)** type A, **(b)** type B, **(c)** type C and **(d)** type D. n is the number of data measurements in each diagram. Only fractures measured within the sampling area are included. Note that horizontal scales are logarithmic.



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Figure 8. Detailed photographs showing the evolution of structures in the four different experiments. **(a–c)** Type A experiment: (1) a shear fracture forms by collapse of a tension crack; (2) coeval development of a tension crack and a shear fracture; (3) tension cracks keep forming until $\sim 40\%$ shortening. **(d–f)** Type B experiment: (4) mixed-mode fracture with associated drag folds. The propagation rate was very low due to plastic deformation at fracture tips; (5) tension crack/void that collapsed and gave rise to a shear fracture; (6) in-plane shear fracture with enhanced propagation at one of the tips; (7, 8) linkage of fracture segments produced larger fractures with heterogeneous displacements. **(g–i)** Type C experiment: (9) nucleation and propagation of a tension crack that evolved to a mixed-shear mode fracture; (10) progressive enlargement of individual fractures as a result of progressive tip-line propagation and linkage with the nearest fracture segments; (11) nucleation of conjugate shear fractures from tension cracks, resulting in sharp fracture segments; (12) relatively long shear fracture that formed by linkage of a tension crack and a shear fracture; (13) small tension crack that evolved to form heterogeneous asymmetric boudinage. **(j–l)** Type D experiment: (14) formation of two parallel dextral fractures that propagate, join and their lower tip ends at a larger conjugate fracture; (15) development of a void from a tension crack at the intersection between large shear fractures; (16) a very large sinistral fracture with zig-zag geometry forms by segment linkage from side to side of the model. Solid lines represent fractures, while dashed lines indicate layering.

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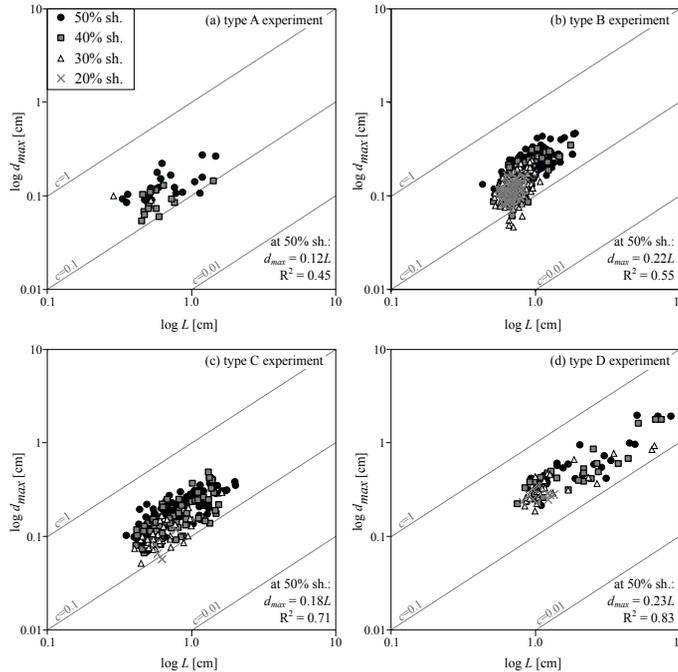


Figure 9. Log maximum fracture length (d_{max}) vs. log maximum fracture displacement (L) graphs for models (a) type A, (b) type B, (c) type C and (d) type D. Data correspond to shear fractures measured at 20%, 30%, 40 and 50 % of shortening within the sampling area. Grey lines indicate linear relationships in the log-log graph for different c values in Eq. (1).

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