Mechanics of the transition from localized to distributed fracturing in layered brittle–ductile systems

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The mechanical coupling between brittle and ductile layers in the continental lithosphere produces rheological contrasts, which are supposed to trigger localized or distributed mode of faulting. A plane-strain 2D finite-element model is used to highlight the mechanical role of the brittle–ductile coupling in defining the patterns of fracturing. The coupling is performed through the shortening of a Von Mises elasto-viscoplastic layer rimmed by two ductile layers behaving as Newtonian incompressible fluids. By varying the viscosity of the ductile layers or the amount of softening in the brittle layer, the fracturing mode evolves from localized to distributed. The mechanics of brittle–ductile coupling is explained by the limitation of the fault displacement rate imposed by both brittle and ductile rheologies. On these bases, an analytical approach is presented in order to estimate the maximum velocity along each fault permitted by both brittle and ductile media. This velocity is then compared to the velocity required by the boundary shortening rate. If the velocity in the fault is not large enough, the development of new faults is necessary. From this analysis, we define four fracturing modes in a brittle–ductile media: the localized mode with the onset of a few large faults, the distributed mode with very dense fault patterns, and finally, the ductile-control mode and the brittle-control mode, where the number of faults increases with an increase in the ductile viscosity and a decrease in the brittle softening respectively.

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1. Introduction

Deformation in nature can be either localized or distributed. At the scale of the continental lithosphere, for instance, extension can result either in narrow rifts or wide rifts (Buck, 1991). The contrasting deformation modes are supposed to result from the competition between two deformation mechanisms: brittle failure and viscous flow. These two mechanisms coexist in the continental lithosphere both at large scale between the brittle and ductile crust for example (Goetze and Evans, 1979; Brace and Kohlstedt, 1980; Carter and Tsenn, 1987; Ranalli, 1995), but also at smaller scale, where different lithologies are superposed. Analogue experiments at lithosphere scale have shown the role of viscous layers on the level of fracturing within the brittle layers in compressive settings (Davy and Cobbold, 1988, 1991; Sornette et al., 1990, 1993) or in extensional settings (Faugère and Brun, 1984; Vendeville et al., 1987; Allemand et al., 1989; Benes and Davy, 1996; Brun, 1999; Brun and Beslier, 1996; Brun et al., 1994; Corti et al., 2003; Corti, 2005). These previous studies have shown that in deformed sandwiches of sand (brittle media) overlying silicone putty (ductile media), an increase in either the applied velocity or the ductile viscosity or a decrease in the thickness of the brittle layer always implies a larger density of faults in the brittle material. Conversely a low viscous midcrust is required to obtain localized faulting in the brittle crust (Brun, 2002). A quantification of the role of brittle–ductile coupling in compression has been experimentally proposed by (Davy et al., 1995; Bonnet, 1997; Schueller and Davy, 2008). 3D experiments were designed to mimic lithosphere scale collision by uniaxial shortening of the superposition of a dry sand layer (i.e. brittle crust) and a silicone putty layer (i.e. ductile crust at a constant viscosity) floating upon honey (mantle). Two types of deformation modes can be identified for different viscosities of the ductile layer. The localized damage mode occurs for low ductile layer strength relatively to the brittle one (high brittle–ductile strength ratio) and is marked by the localization of deformation into two macroscopic plastic shear bands. In contrast, for low brittle–ductile strength ratio, the homogeneous damage mode prevails. However, although analogue experiments are versatile in modelling complex rheologies, the exact nature of the brittle–ductile coupling remains poorly constrained due to the difficulty of tracking mechanical and strain parameters, and of investigating a large range of parameters.

In this respect, numerical experiments are a better way for identifying the parameters and processes that eventually control the
level of fracturing in a brittle media, for instance the brittle strain-softening (Huismans and Beaumont, 2002; Lavier et al., 2000), the rate of brittle strain-softening (Behn et al., 2002), the thickness of the brittle layer (Lavier and Buck, 2002), the viscosity of the ductile layer (Huismans et al., 2005), the boundary velocity (Bellahsen et al., 2003), or the geometric hardening (Buck, 1993; Lavier et al., 2000). The pattern of faulting and the size of fault offsets are found to strongly depend on the amount of cohesion reduction in the fault (Poliakov and Buck, 1998), on the rate of brittle weakening as well as on the thermal structure of the lithosphere and thus on the brittle–ductile rheological layering (Lavier et al., 1999; Lavier et al., 2000; Behn et al., 2002; Lavier and Buck, 2002). A high loss of cohesion associated with faulting as well as a relative thin brittle layer will promote large offset along fault and asymmetry in rifting (Lavier et al., 2000; Huismans et al., 2005). Few numerical studies have pointed out the role of the ductile strength in defining the level of fracturing. Bellahsen et al. (2003) show that a high strength of the viscous layer result in a more distributed fault pattern. Nagel and Buck (2004) and Gueydan et al. (2008) make use of 2D thermo-mechanical models of lithosphere to emphasize that the viscosity of the deep crust strongly controls the modes of lithosphere deformation during extension: a low viscous deep crust for instance is a prerequisite of lithosphere necking (e.g. localized mode of deformation at the scale of the lithosphere). The mechanical coupling occurring at the interface of the brittle and viscous layers was not analyzed in these models. Huismans et al. (2005) and Buiter et al. (2008) have studied the coupling between brittle and ductile layers in an extending continental lithosphere by calculating the total rate of energy dissipation in both brittle and ductile layers. The principle of minimum energy rate dissipation allowed quantifying the roles of the ductile viscosity and the brittle strain softening on the transition between different deformation modes presenting either one, two or multiple shear zones. In compression, we have emphasized by 2D numerical models the limitation imposed by the viscous layer on fault displacement (Schueller et al., 2005). The viscous layer exerts a viscous friction on the fault zone, explaining the increase in the number of faults induced by an increase in the ductile viscosity. The novelty of the present paper with respect to Schueller et al. (2005) is 1) to give a full description of the parameters that control the brittle–ductile coupling and 2) to propose a simple analytical approach that fully describes the mechanics of the brittle–ductile coupling inferred from the 2D numerical results.

We first describe the model set-up and the evolution of deformation in numerical models. In a second part, we analyze the role played by the different rheological and geometrical parameters. A particular emphasis is put on the viscosity of the ductile layers, on the amount of strain softening, and on the plastic viscosity in the brittle layer. Finally, a 1D analytical solution is presented to quantify the parameters that control the fault displacement rate and hence the modes of fracturing.

2. Model set-up

2.1. Geometry and boundary conditions

The model set-up consists of a brittle layer rimmed by two ductile layers (Fig. 1). The length of the structure is \( L \) and the widths of the brittle and ductile layers are \( b_0 \) and \( b_0 \), respectively. Both ductile layers have the same width. A displacement \( U \) (at constant velocity \( V \)) is imposed at the bottom of the model, while the top is pinned. The two vertical boundaries are free (neither friction, nor imposed displacement). Both brittle and ductile layers undergo the same displacement and therefore the same amount of shortening. The ductile strips on both sides of the brittle layer damp out the classical corner that develop in brittle media (or any material with a non-linear rheology) with these boundary conditions. Models with \( L \) lower than \( b_0 + b_0 \) (Fig. 1) will thus be disregarded because of large boundaries effects. The role of length and width of the studied structure will be discussed in a parametric study.

2.2. Brittle and ductile rheologies

The two ductile layers are described by an incompressible Newtonian fluid, such that the equivalent shear stress \( \tau_D \) is a function of the strain rate \( \dot{\varepsilon} \) and the viscosity \( \eta_D \):

\[
\tau_D = \eta_D \dot{\varepsilon} Y.
\]

The equivalent shear stress \( \tau_D \) and strain rate \( \dot{\varepsilon} \) are defined by

\[
\tau_D = \sqrt{\frac{1}{2} \tau_q \tau_{ij}} \quad \text{and} \quad \dot{\varepsilon} = \sqrt{2D_{ij} D_{ij}},
\]

where \( \tau_q \) and \( D_{ij} \) are the Kirchoff stress tensor and the rate of deformation tensor, respectively.

![Model setup and boundary conditions](image)

Fig. 1. Model setup and boundary conditions. The brittle rheology (Von Mises associated elasto-visco-plasticity) is presented on the right: the solid line corresponds to the plastic yield criterion and the dashed line to von Mises equivalent shear stress (\( \tau_{VM} \), Eq. (5)). See Table 1 for the meaning and values of the different parameters. The velocity is fixed to 1 in all the simulations.
The brittle layer is described by a pressure-independent Von-Mises associated elasto-visco-plastic material. Before yielding, the material is described by a classical linear elasticity law, with a Young modulus $E$, and a Poisson ratio $\nu$ (cf. Table 1). Yielding occurs when the elastic shear stress is greater than the yield stress $\sigma_0^\nu$ (Eq. 1). The equivalent Von Mises shear stress and the equivalent plastic strain are defined by:

$$\tau_{VM} = \sqrt{\frac{3}{2}} \tau_0 \nu \nu$$

and

$$\varepsilon^p = \sqrt{\frac{3}{2}} \frac{D_p_D_p}{D_p_D_p}$$

for $D_p_D_p$ stands for the plastic strain tensor. The yield stress $\sigma^\nu$ is a three-linear function of the plastic strain $\varepsilon^p$:

$$\sigma^\nu(\varepsilon^p) = \sigma^\nu_1 \varepsilon^p + \sigma^\nu_0, \text{ for } 0 < \varepsilon^p < \varepsilon^p_0,$$

$$\sigma^\nu(\varepsilon^p) = \sigma^\nu_2 \varepsilon^p + \sigma^\nu_1, \text{ for } \varepsilon^p_0 < \varepsilon^p < \varepsilon^p_2,$$

$$\sigma^\nu(\varepsilon^p) = \sigma^\nu_2, \text{ for } \varepsilon^p > \varepsilon^p_2.$$

with $\sigma^\nu_1 > \sigma^\nu_2 > \sigma^\nu_0$. The yield stress-plastic strain relationship is given in Fig. 1. Plastic strain develops when the yield stress reaches $\sigma^\nu_0$, then the yield stress-plastic strain relationship slightly increases (plastic hardening) before decreasing during a plastic softening phase. In natural deformed rocks, the hardening corresponds to the irreversible and cumulative formation and growth of cracks (Jaeger and Cook, 1979) and the subsequent softening is essential to fully develop plastic shear bands (Labuz et al., 1996; Lockner et al., 1991; Fang and Harrison, 2001). The value of $\Delta \varepsilon = \varepsilon_2^p - \varepsilon_1^p$ controls the softening rate and thus the duration of plastic strain localization. The influences of both parameters are analyzed in this study. The use of a pressure independent failure criterion (the Von Mises visco-plasticity) entails faults to form at 45° to the principal compression axis. A plastic viscosity $\eta_p$ was introduced to avoid catastrophic fault propagation. It defines a time-scale for the change of plastic deformation:

$$\tau_{VM} = \eta_p \dot{\varepsilon}^p + \sigma^\nu(\varepsilon^p)$$

where $\tau_{VM}$ is the equivalent shear stress in the plastic domain, $\sigma^\nu(\varepsilon^p)$, the plasticity criterion that depends on the plastic deformation $\varepsilon^p$, and $\dot{\varepsilon}^p$ the plastic strain rate (Eqs. (3) and (4)). The equivalent shear stress in the plastic domain is represented in Fig. 1 as dashed curve and will be called in the rest of the paper “brittle stress” for the sake of simplicity. By introducing a time-dependent change of plastic deformation (e.g. plastic viscosity), the brittle stress can be larger than the yield stress, even if strain localization occurs (Eq. (5)). This explains in what follows why fault zone is often marked by brittle stress larger than $\sigma^\nu_2$.

### 2.3 Governing equation and finite element approximation

This model is primarily designed to understand the mechanics of brittle–ductile coupling. The model setup is far from geological layering, and heat conduction and gravity are disregarded. Orientation of the model ("vertical layers"), symmetry (both lateral ductile layers), and simple rheologies (in particular the Newtonian viscosity for ductile layers) result from the willing to focus on the basic physical processes of brittle–ductile coupling. This model is thought to be generic for either outcrop-scale or large lithosphere-scale deformations. An important step forward in the future will be to account for more realistic geometries and rheologies, with in particular a temperature sensitive viscosity, in order to model the brittle–ductile coupling in the lithosphere.

Mechanical equilibrium with no gravity and no heat flow is solved by the 2D finite element code SARPP (Gueydan et al., 2003, 2004), which is designed for large finite strain. The brittle layer has been divided into $30 \times 60$ 9-nodes Lagrangian elements, yielding a mesh size of 0.033 for $L_0 = 1$ and $L = 2$ (Fig. 1). Mechanical equilibrium yields a condition of constant pressure, which is arbitrarily set to zero. Since ductile behaviour and Von Mises plasticity are pressure independent, the value of the pressure has no influence on the results presented hereafter. The displacement $U$ is the only unknown nodal parameter. Note that all the values are dimensionless (stress, viscosity, velocity, ...).

A reference model is first presented in terms of ductile viscosity and brittle rheology. The role of rheological and geometrical parameters will then be discussed through a parametric study.

### 3. Results of the reference model

The rheological and geometrical parameters of the reference model are given in Table 1.

#### 3.1 Strain distribution through time

Fig. 2 presents the evolution of the total strain and plastic strain in the brittle layer of the reference model and the equivalent stress in the brittle ($\tau_{VM}$, Eq. (5)) and ductile ($\tau_p$, Eq. (11)) layers. The evolution of the total strain $\varepsilon^{tot}$ is first characterized by a concentration of strain and stress in the middle of the brittle media with a more or less homogeneous distribution for displacement lower than 0.05 corresponding to a shortening of 2.5%. The nearly undeformed triangular zone along the top and bottom boundaries is due to the fixed condition that avoids displacements parallel to the boundaries. In the ductile layers, the stress is also more or less homogeneously distributed apart from stress concentrations in the corners of the models due to boundary condition effects. Then for a displacement above 0.05, strain and stress progressively localize in the model according to a pattern that will prefigure the fault pattern. The first faults appear after a boundary displacement of 0.065. The faults are identified as regions where the plastic strain is greater than 0.12 (Eq. (4), Fig. 1). For displacements larger than 0.1 (i.e. 5% of shortening), strain is ultimately localized in a growing fault pattern. The fault pattern structure is reached for a displacement of 0.2 (Fig. 2) and concentrates the plastic deformation.

The fault zones are marked by low values of stress (around 70–80 in colour scale, Fig. 2) because of the brittle softening occurring within the fault zone (Eq. (4), Fig. 1). Note however that for increasing value

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**Table 1**

Description of the simulation parameters in the reference model and for the parametric study: $E$: Young modulus; $\nu$: Poisson ratio; critical values of the Von Mises associated visco-plasticity (see Fig. 1); $\sigma_0^\nu$, $\sigma_0^p$, $\sigma_0^\nu$ yield stresses; $\bar{\varepsilon}_p$, $\dot{\varepsilon}_p$, plastic strains; $\eta_p$, plastic viscosity; $\eta_0$, viscosity of the ductile layers; $L$, length; $l_B$, brittle layer width; $l_p$, width of each ductile strip.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Reference model</th>
<th>Range of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>$5.5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>$\sigma_0^\nu$</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>$\sigma_0^p$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$\sigma_0^\nu$</td>
<td>60</td>
<td>20–120</td>
</tr>
<tr>
<td>$\bar{\varepsilon}_p$</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$\dot{\varepsilon}_p$</td>
<td>0.12</td>
<td>0.07–0.28</td>
</tr>
<tr>
<td>$\eta_p$</td>
<td>1</td>
<td>0.5–10</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>50</td>
<td>1–10,000</td>
</tr>
<tr>
<td>$L$</td>
<td>2</td>
<td>1–4</td>
</tr>
<tr>
<td>$l_B$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$l_p$</td>
<td>0.1667</td>
<td>0.066–1</td>
</tr>
</tbody>
</table>
of displacement, the brittle stress $\tau_{VM}$ within the fault zone increases and exceed the yield stress $\sigma_y$. This feature reflects the time-dependent brittle rheology (e.g. plastic viscosity) as discussed in previous section (Fig. 1, Eq. (5)). Brittle material adjacent to the fault zone is characterized by value of brittle stress of 100, typical of the maximum yielding stress ($\sigma_y$, Table 1) with no weakening. The fault edges are characterized by large stress values, which is typical of crack-tip stress concentration. In the ductile layers, the shear stress distribution is directly related to the vicinity of fault tips close to the brittle–ductile interface.

Observation of the evolution of deformation allows us to define 3 successive stages: 1) the pre-localization stage for displacements between 0.025 and 0.05, which is marked by a more or less homogeneous distribution of the total strain in the brittle media; 2) the localization stage that corresponds to the lost of homogeneity in the strain field and to the onset of fault growth; and 3) the post-localization stage, during which the fault pattern develops and strain accumulates within faults.

### 3.2. Active plastic domain and active fault domain

In order to quantify the time evolution of the strain field and the fault pattern, we introduce two specific spatial measures: the Active Plastic Domain (APD) and the Active Fault Domain (AFD). The APD is a sub-domain of the brittle layer, where the plastic strain and plastic strain-rate are non zero ($\varepsilon_p \neq 0, \dot{\varepsilon}_p \neq 0$). It thus corresponds to regions that always accumulate plastic strain through time. The AFD is a sub-region of the APD, where the plastic strain is larger than $\varepsilon_p^2$ (end of microscopic softening, 0.12 in the reference model; Eq. (4), Fig. 1). The AFD thus defines the faults or localized plastic shear zone within the APD.

The history of the APD and AFD in the reference model is presented in Fig. 3. For a small amount of displacement ($<0.025$), the APD slightly increases up to 0.85. These initial high values (0.75–0.9) indicate that nearly all the brittle media is deforming plasticly. For a larger amount of displacement (0.025–0.07), the APD decreases with increasing displacement towards an asymptotic value that corresponds to 50% of the total area. The localization of brittle deformation is characterized by a sharp

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**Fig. 2.** Evolution of the deformation pattern in the reference model as a function of time or displacement. The total displacement at the end of the simulation is 0.2 corresponding to a shortening of 10% of the model. Note that the scale of total strain is changing between the pre-localization stage and the post-localization one. The distributions of total and plastic strains are only presented in the brittle media. The equivalent stress is represented in both brittle and ductile layers. The limit between the brittle and the ductile layer is emphasized by a red thin line. The localization stage lasts from $t = 0.05$ to $t = 0.075$ and corresponds to the onset of fault growth in the brittle media.

**Fig. 3.** Evolution with time of the Active Plastic Domain (APD) and the Active Fault Domain (AFD) in the reference model. The square boxes correspond to the strain pattern presented in Fig. 2.
decrease of the APD from 90% to around 50% of the brittle media. Then the APD is about constant during the post-localization stage (displacement greater than 0.075, Fig. 3). The AFD has an evolution opposite but correlated to the APD. It is nil during the pre-localization stage (e.g. no fault in the system) and is starting to increase during the localization stage (displacement between 0.05 and 0.075, Fig. 3). During the post-localization stage however, the AFD continues to increase while the APD is about constant. This feature is classical of strain localization process: deformation tends to concentrate in narrow zones that eventually form shear bands. These different stages can be related to the microscopic yielding history in the brittle media (Fig. 1). The maximum APD is reached for a displacement of around 0.025. This value is very close to $\varepsilon^* = 0.02$ that marks the end of the hardening (Eq. (4), Fig. 1). The decrease of the APD is related to the softening, which causes the development of fault zone in the brittle media and thus the increase in the AFD. The AFD domain increases then by accumulation of strain on the fault pattern developed at the end the macroscopic strain and accumulates strain.

4. Role of the geometrical parameters

In this section, the role of the length $L$, of the width of the brittle and ductile layers, $l_B$ and $l_D$, respectively are tested. Except for $L$, $l_B$ and $l_D$, the other simulation parameters correspond to the ones of the reference model presented in Table 1. We will only discuss here the final patterns of faults within the brittle media that has developed after the localization stage. The AFD parameter will be used to compare the experiments.

4.1. The length $L$

Fig. 4A presents the influence of the model length $L$ on the value of AFD taken at a shortening of 5%. We have taken that value of shortening because the common value of 7.5% that will be always used in what follows, implies too large displacement to obtain a numerical solution for large values of $L$. The pattern of plastic strain is indicated for each experiment. Note that increasing $L$ result in decreasing the average strain-rate applied at the system boundaries: $\dot{\varepsilon} = \varepsilon/L$. Experiments with $L$ varying from 2 to 4 exhibit fault patterns that have more or less similar densities with nearly same values of AFD. For $L = 4$, the faults observed for $L = 2$ are repeated twice, which leads to a similar fault density. For $L = 1$, the AFD value is slightly higher. This is likely due to the boundary conditions and strong border effects, as discussed earlier. Indeed a model that is wider than larger ($L<1$) imposes two important constraints on the fault development: 1) in order to accommodate the applied deformation, faults must reach the free lateral boundaries and thus propagate at an angle to the compression axis less than the 45° required by the Von Mises rheology; and 2) both boundary walls with no-slip conditions prevent the creation of new faults, so the fault zones have to widen in order to accommodate the applied shortening.

We conclude from this part that the length of the model has little impact on the fault density, and thus on the fracturing mode, although it changes the locations of faults in the model. A length of 2 was chosen thereafter.

4.2. The brittle- and ductile-layer widths: $l_B$ and $l_D$

Fig. 4B illustrates the role of the ratio of the ductile width over the brittle width on the fracturing mode. Numerical experiments were performed with $l_B$ and $L$ kept to their reference values (Table 1), and $l_D$ varying from 0.066 to 1. The results are presented as a function of the ratio $l_D/l_B$. The AFD is almost constant for $l_D/l_B$ larger than 0.3. Below this value, the AFD is an increasing function of $l_D/l_B$. The rationale of this trend can be found in analyzing the dampening function of ductile layers with respect to faults. As for elastic problems, the indentation of a Newtonian fluid by a crack leads to an ellipse-shaped stress concentration zone, which characterizes the resistance of ductile layer to fault motion (shear stress patterns in brittle and ductile layers shown in Fig. 4B). For an infinitely wide ductile layer, this extra-stress is proportional to the fault slip rate (this is the main difference with elastic dislocation, where the deformation factor is the fault offset), and is likely decreasing as the square root of the distance to fault tip. The key geometrical parameter is the characteristic length of the extra-stress. The maximum efficiency of the ductile resistance is obtained when the width of the ductile layer is larger than this characteristic length. If not, the resistance is less, faults can propagate at higher rate, brittle localization is likely more efficient and the AFD is smaller. Numerical simulations presented in Fig. 4B shows that, for this configuration, a loss of resistance occurs at $l_D/l_B=0.3$ and at lower ratios. Note however that the ratio $l_D/l_B$ has a little impact on faulting pattern, compared to the role of ductile and brittle rheologies, as it will be discussed in what follows.

5. Role of the ductile viscosity

The ductile viscosity $\eta_B$ strongly controls the level of fracturing in the brittle layer (Schueller et al., 2005). In the following section, the ductile viscosity $\eta_D$ is varied between 1 and 1000 in order to constrain...
the role of the ductile layers on the brittle fracturing. The other parameters are those of the reference model (Table 1).

5.1. Strain and shear stress patterns as a function of the ductile viscosity

Fig. 5 presents the plastic strain in the brittle layer as well as the equivalent shear stress in both brittle ($\tau_{\text{VM}}$, Eq. (5)) and ductile ($\tau_{\text{D}}$, Eq. (1)) layers for viscosities ranging from 1 to 500. The fault zones are identified by regions where the plastic strain is greater than 0.12 (end of the softening, Fig. (5)). All strain patterns have been recorded after strain localization for a shortening of 7.5% (time = displacement = 0.15). The larger the viscosity is, the denser the fault pattern. Since the total boundary displacement is distributed over the fault network, the average fault displacement (or similarly the accumulated plastic strain) is inversely proportional to the fault density. For high-viscosity experiments, the fault density is particularly high in both the central and extruded parts of the model.

The shear stress pattern in the brittle layer $\tau_{\text{VM}}$ is dictated by the presence of localized plastic shear zone (e.g., fault zones). Outside the fault zone, the brittle stress is equal to $\sigma^p$, (100, Table 1) reflecting the plastic behaviour of the material without weakening (Fig. 1). In the fault zone, weakening occurs and should have lead to stress decrease (Fig. 1). The brittle shear stress is however larger in fault zone than in the undeformed adjacent brittle material, because of the existence of a plastic viscosity and hence a plastic strain rate that leads to increase the brittle shear stress within the fault zone.

For ductile viscosities ranging from 10 to 70, the AFD and the number of faults increase with the viscosity. This defines the distributed fracturing mode. For ductile viscosities ranging from 10 to 70, the AFD and the number of faults increase with the viscosity. This defines the ductile-control fracturing mode.

6. Role of the brittle rheology

The ductile viscosity is kept here constant at 50 and we vary both independent parameters that characterize the Von Mises brittle rheology:

Fig. 6. Evolution of the Active Fault Domain (AFD) as a function of the ductile viscosity $\eta_D$, for a shortening of 7.5% ($t = 0.15$). The represented plastic strain patterns for viscosities of 1, 50 and 500, respectively from left to right, are from Fig. 5.
1) the amount of brittle softening \( \Delta \sigma \), and 2) the plastic viscosity \( \eta_p \) (Eq. (4)). The significance of these two parameters has been discussed in previous sections. The rate of the brittle softening \( \Delta \sigma \) is not discussed here because it does not affect the fault pattern but only the timing of its development.

### 6.1. The amount of brittle softening \( \Delta \sigma \)

**Fig. 7A** illustrates the evolution of AFD and of the plastic strain pattern with a varying amount of brittle softening. The amount of softening \( \Delta \sigma \) corresponds to the difference \( \sigma^1 - \sigma^2 \) (Eq. (4)), and here, only the value of \( \sigma^2 \) is changed to vary the value of \( \Delta \sigma \). A value of \( \Delta \sigma \) of 20 thus corresponds to 20% of softening. When the brittle rheology is strain-hardening \( (\Delta \sigma < 0) \) or at least not strain-softening \( (\Delta \sigma = 0) \), no fault pattern develops. The whole brittle layer deforms plastically with a roughly homogeneous strain pattern. This would represent the theoretical end-member case with an infinite number of faults distributed throughout the media, thus characterized by a high value of AFD. However, defining AFD in this case is not relevant since no real fault develops. When strain-softening occurs \( (\Delta \sigma > 0) \), the larger \( \Delta \sigma \) is, the smaller the AFD is. Keeping all other parameters constant, an increase in \( \Delta \sigma \) tends to localize brittle deformation, and the brittle deformation regime switches from the distributed to the localized fracturing mode. The distributed-to-localized transition occurs for a softening of the order of 60% (Fig. 7A). Similarly to the role of ductile viscosity, three modes of brittle fracturing can be defined: 1) a distributed mode for a brittle rheology characterized by strain hardening or no softening, 2) a localized mode for values of brittle softening larger than 60%, for which deformation concentrates into two pairs of faults, and 3) a brittle–control mode of fracturing for intermediate values of softening, where the amount of faults increases with decreasing values of brittle softening.

### 6.2. The plastic viscosity \( \eta_p \)

In an elasto-visco-plastic media, the plastic viscosity \( \eta_p \) could be induced by clay minerals such as montmorillonite, vermiculite and talc that are likely to stabilize fault sliding (Logan and Rauenzahn, 1987; Moore and Rymer, 2007). This viscosity inhibits a catastrophic propagation of faults, and also stabilizes the numerical calculations. **Fig. 7B** illustrates the role of \( \eta_p \) on the AFD and on the plastic strain pattern. An increase in \( \eta_p \) induces an increase in AFD and thus modifies the fault pattern from localized at low \( \eta_p \) to distributed at large \( \eta_p \). For \( \eta_p \) larger than 4, the high viscosity in the brittle media inhibits the strain localization process and thus the nucleation of faults. A saturation of plastic strain is reached in the entire brittle media, with no proper fault pattern development, similar to the one develop when the brittle media presents either no softening or even a hardening (Fig. 7A). A value of one for the plastic viscosity was found sufficient to stabilize the numerical development of faults and has thus been selected in the computations.

The plastic viscosity plays thus also a key role on the fracturing mode: for \( \eta_p < 4 \), the decrease of \( \eta_p \) leads to a decrease of the amount of fault in the brittle media, defining a brittle–control mode of fracturing. More generally, we observe the brittle–control mode of fracturing for softening values between 10 and 60% and for plastic viscosity between 0.5 and 4.

### 7. Discussion: limitation of fault velocity in brittle–ductile media

Observations of the models provide some hints of the mechanisms responsible for the brittle–ductile coupling that takes place at the brittle–ductile interface. The ductile viscosity and the brittle rheology (both softening and plastic viscosity) have been shown to control the fracturing mode. In a previous paper, the controlling role of ductile viscosity on brittle fracturing has been explained by a concept of viscous friction (Schueller et al., 2005). The analytical solution presented below will generalize this concept of viscous friction in order to explain the controlling role of both ductile and brittle rheologies on fault pattern in term of limitation of the fault velocity.

#### 7.1. Maximum fault velocity imposed by ductile and brittle rheologies

We expect the stress regime in the ductile layer to result both from faults penetrating into the ductile layer and from the applied shear rate due to the boundary conditions. The pattern of the former is likely similar to the elastic stress concentration at the tip of an isolated crack. This is not actually surprising since both elastic and viscous equations are about similar when replacing strain by strain rate and Young modulus by
viscosity. The fault tip at the brittle–ductile interface can be characterized by a thickness $\xi$ (Fig. 8A). This region is typical of the stress concentration region ahead a propagation crack. The only difference of our work with respect to classical crack propagation analysis is that the crack tip is here in a ductile material and not in a purely elastic medium. This difference allows defining the strain rate and thus the fault velocity in both the brittle media and the ductile media (Fig. 8A). Our aim is to compare the boundary shortening rate (and the velocity it implies on each fault depending on the number of faults) with the fault velocity allowed in both brittle and ductile layer. In the brittle layer, the visco-elastic-plastic rheology (Eq. (5)) permits to define the plastic strain rate and thus the “brittle” fault velocity as a function of the yield stress, the brittle stress and the plastic viscosity as follows, if elasticity is neglected:

$$\varepsilon = \frac{V_{FB}}{\xi} = \frac{\alpha_B - \sigma^y}{\eta_p} \text{ so that } V_{FB} = \frac{\xi \alpha_B - \sigma^y}{\eta_p}$$

with $V_{FB}$ the fault velocity allowed in the brittle layer, $\alpha_B$ the stress in the fault zone close to the brittle–ductile interface, $\sigma^y$ the yield stress criterion that is a function of the plastic strain $\varepsilon_p$, and $\eta_p$ the plastic viscosity (Fig. 8A). The first term of Eq. (6) is simply the plastic strain rate (Eq. 5), $\xi$ is the thickness of the fault tip in the ductile layers. In the ductile layer, the strain-rate is simply the ratio of the ductile shear stress over the viscosity (Fig. 8A) and thus the “ductile” fault velocity is directly related to the viscosity and the ductile stress as follows:

$$\varepsilon = \frac{V_{FD}}{\xi} = \frac{\alpha_D - \sigma^D}{\eta_D} \text{ so that } V_{FD} = \frac{\xi \alpha_D - \sigma^D}{\eta_D}$$

where $V_{FD}$ is the fault velocity allowed in the ductile media, $\alpha_D$, the ductile stress in the fault-tip zone, $\xi$ is the thickness of the fault tip in the ductile layers.

The analytical solution presented here aims to quantify the maximum fault velocity allowed in both brittle and ductile layers, respectively $V_{FB}$ and $V_{FD}$, and to compare it to the boundary shortening velocity $V$. Values of both brittle and ductile stresses have thus been set to their maximum values as follows. The maximum shear stress supported by the brittle media is by definition the maximum yielding stress $\sigma^y$ (Fig. 1), implying that the brittle stress will never exceed this value: $\sigma_B \leq \sigma^y$. In contrast, the yielding stress in the Eq. (6) was set to $\sigma^D$, a value typical for the stress along active fault zone after the strain localization process (Fig. 1). At the brittle–ductile interface, the ductile shear stress has also to be less than $\sigma^D$, to prevent yielding and plasticity in the entire brittle layer: $\sigma \leq \sigma^D$. The values of the shear stress in both brittle and ductile material have thus been set to their maximum value that is the maximum yielding stress: $\sigma_B = \alpha_B = \sigma^y$. Note that this assumption is only valid for ductile viscosities lower than 100–150. As discussed earlier, the homogeneous shear stress $\eta_p V / L$ due to homogenous deformation of the ductile layers dominates for larger viscosities and leads to shear stresses values larger than $\sigma^D$ (e.g. discussion of Fig. 4). The present analysis is thus relevant to capture the transition from localized fracturing mode to ductile-control or brittle-control modes of fracturing. The onset of distributed mode of fracturing is not captured in our analysis and is simply related to very large ductile viscosities (>100) and hence large ductile stresses that induce yielding and plasticity in the entire brittle layer.

These assumptions for the maximum values of brittle and ductile stress, gathered with the definitions of the brittle and ductile fault velocities (Eq. (6) and (7)) imply that the maximum fault velocities allowed in both brittle and ductile material are

$$V_{FB} \leq \frac{\xi \alpha_B - \sigma^y}{\eta_p} = \frac{\Delta \sigma}{\eta_p}$$

$$V_{FD} \leq \frac{\xi \alpha_D - \sigma^D}{\eta_D}$$

The brittle fault velocity is directly related to the amount of brittle softening and to the plastic viscosity. The role of the brittle rheology is thus simply accounted by the ratio between the brittle softening and the plastic viscosity, $\Delta \sigma / \eta_p$. The solid line in Fig. 8B represents the fault velocity in the brittle media $V_{FB}$ as a function of this ratio. Fig. 8C presents the fault velocity in the ductile media $V_{FD}$ as a function of the
ductile viscosity. Eq. (9) implies that \( V_F \) is decreasing with increasing ductile viscosity.

The values of the fault velocity in both brittle and ductile layers are dependent upon the length of the ductile stress concentration region ahead the fault, denoted \( \xi \). In the numerical simulations, the thickness as well as the length of the faults depends on the mesh size and the boundary conditions respectively. For the calculations, \( \xi \) is assumed to be equal to the size of one mesh (\( \xi = 0.033 \)). In nature, the width of the fault zone as well as the process zone of a fracture is supposed to be dependent on the length of the fracture. From experiments and thin sections observations, relationships like \( \xi = A * l_f \) have been obtained, where \( l_f \) is the length of the fracture and \( A \) a constant ranging from 0.016 to 0.048–0.1 (Vermilye and Scholz, 1998; Zang et al., 2000). In our case, the fracture length is \( l_f \sim l_B / \sqrt{2} \), \( l_B \) being the width of the brittle layer (see Fig. 2 for example). The factor \( 1/\sqrt{2} \) is due the Von Mises rheology forcing the faults to be at 45° to the shortening direction. Taking \( \xi = 0.033 \) implies a value of the parameter \( A \) equal to 0.047, which is in the range of the accepted values defined above.

7.2 Limiting role of brittle and ductile rheologies on fault velocity

The comparison of the fault velocities imposed by both brittle and ductile rheologies with the boundary shortening rate allows us to discuss the mechanics of brittle–ductile coupling. The fault velocity \( V_F \), necessary to accommodate the boundary shortening rate, can be defined as a function of the number of fault pairs existing in the system denoted \( n_F \):

\[ V_F = \frac{V}{n_F \sqrt{2}}. \tag{10} \]

\( V \) is the velocity applied at the boundaries of the model, equal to 1 in all the simulations; \( n_F \) is the number of fault pairs. The factor \( 1/\sqrt{2} \) is due the Von Mises rheology forcing the faults to be at 45° to the shortening direction. The horizontal dashed line on Fig. 8B and C corresponds to the theoretical fault velocity \( V_F \) for only 2 fault pairs (\( n_F = 2 \) in Eq. (10)). In the numerical models, two fault pairs seem to be indeed required to accommodate the boundary shortening rate, even at very low viscosity. If the maximum fault velocity allowed by the ductile layers \( V_D \) is larger than \( V_F \) for 2 fault pairs (Fig. 8C), then 2 pairs of fault are sufficient to accommodate the boundary shortening rate. On the contrary, if \( V_D < V_F \) (\( n_F = 2 \)), the velocity \( V_D \) on the two existing fault pairs will not be sufficient to accommodate the shortening rate and thus the nucleation of new faults is necessary. This limitation of the fault velocity with increasing ductile viscosity corresponds to viscous friction induced by the ductile layers (Schueller et al., 2005). A critical value of ductile viscosity \( \eta_{DC} \) can thus be defined, and for higher values of ductile viscosity, the nucleation of new faults becomes necessary (Fig. 8C). This critical ductile viscosity is the viscosity at which \( V_D = V_F \) is equal to \( V_F \) for 2 pairs of faults: \( V_D = V_F(n_F = 2) \). Combining Eqs. (9) and (10) yields:

\[ \eta_{DC} = \frac{2 \Delta \sigma \sqrt{2}}{V}. \tag{11} \]

This critical ductile viscosity \( \eta_{DC} \) is thus a function of the stress concentration region thickness \( \xi \), the ductile stress within the fault tip zone (that is set here to the maximum yield stress) and the imposed velocity. The value of that critical ductile viscosity is here 9.3. If \( \eta_D > \eta_{DC} \), the ductile viscosity becomes the controlling factor of the number of fault pairs and defines the ductile-control mode of fracturing. If \( \eta_D < \eta_{DC} \), the number of fault pairs is at its minimum (here 2) and independent on the ductile viscosity. These predictions are close to the numerical results (Fig. 6) where the ductile-control mode of fracturing occurs for \( \eta_D > 9 \rightarrow 10 \).

The same reasoning is used to quantify the limiting role of brittle rheology. Fig. 8B presents the evolution of the fault velocity induced by the brittle media (\( V_B \), Eq. (8)) as a function of the ratio \( \Delta \sigma / \eta_B \). A critical ratio of the softening over the plastic viscosity, above which fracturing is independent on the brittle rheology, can be defined as follows:

\[ \left( \frac{\Delta \sigma}{\eta_B} \right)_c = \frac{V}{2 \xi \sqrt{2}}. \tag{12} \]

This critical ratio is simply a function of the thickness of the stress concentration zone ahead the fault and of the imposed velocity. In our simulations, the value of this critical ratio is 10.7. Setting the plastic viscosity to 1 (reference value, Table 1), it implies a critical value of brittle softening of 10.7. For softening lower than 10%, nucleation of new faults is made necessary to accommodate the boundary shortening rate (Fig. 8B). These results of the analytical analysis are close to the numerical results (Fig. 7), where the distributed mode of deformation occurs for softening lower than 10%.

7.3 Prediction of ductile- and brittle-control mode of fracturing

Combining both maximum brittle and ductile fault velocities conduces to define the maximum fault velocity in a brittle–ductile media. The maximum fault velocity is imposed by the lowest velocity in both layers and corresponds either to \( V_B \) or \( V_D \), depending on which one is the limiting velocity for the fault. Calculating the number of fault pairs necessary to accommodate the boundary shortening rate comes down to calculate \( n_F \) when the maximum fault velocity is equal to \( V_F \).

Fig. 9A presents the maximum fault velocity (light grey line) in case the brittle media does not control the number of faults (e.g. efficient brittle-softening: \( \Delta \sigma / \eta_B > \Delta \sigma / \eta_{DC} \), Eq. (12)). This assumption implies that the brittle fault velocity \( V_B \) (Eq. (8)) is greater than the fault velocity imposed by the boundary condition \( V_F \) for 2 pairs of faults (Eq. (10)). This case is very similar to the numerical simulations presented in Figs. 5 and 6, where \( \Delta \sigma = 60 \) and \( n_F = 1 \), so that \( \Delta \sigma / \eta_B = 60 \). This value \( \Delta \sigma / \eta_B \) is much larger than the critical value of the ratio (10.7). In that case, the ductile media controls the maximum fault velocity, and \( \eta_{DC} \) is the transition between the localized mode (2 fault pairs) and the ductile-control mode, where the number of faults increases with \( n_F \) (Fig. 9B). Since the fault velocity \( V_F \) is decreasing with increasing \( \eta_B \), the number of faults tends to be infinite, which is possible neither in nature nor in numerical simulations. Note that as discussed earlier, our simple analysis is only relevant to capture the transition from localized fracturing mode to ductile-control or brittle-control modes of fracturing (Eqs. (11) and (12)). The onset of distributed mode of fracturing is thus not captured in our analysis and simply occurs for very large ductile viscosities (>100) and hence for large ductile stresses that induce yielding and plasticity in the entire brittle layers. On this basis, we assume in this analytical approach that the onset of distributed mode of fracturing occurs when fault saturation is reached in the brittle layer. Assuming that faults need to be separated at least by the distance of one fault thickness, \( \eta_{max} \) is around 15. Another transition in ductile viscosity can thus be defined, corresponding to \( \eta_B = 15 \) (Eq. (10)): \( \eta_{DC} \sim 70 \) (Fig. 9B), above which, fault saturation is reached, leading to the distributed mode of fracturing. The transitions obtained from this analytical approach are consistent with the different transitions obtained from the experiments defined in Fig. 6. Fig. 9B underlines also the sharp transition between the localized and distributed mode which covers less than one order of magnitude in ductile viscosity.

Fig. 9C illustrates the different fracturing modes when the brittle rheology partly controls the number of faults (e.g. low softening to hardening: \( \Delta \sigma / \eta_B < (\Delta \sigma / \eta_{DC})_c \), Eq. (12)). Fig. 9C corresponds to the case where \( \Delta \sigma / \eta_B = 4 \). This implies that the brittle fault velocity \( V_B \) (Eq. (6)) is lower than the fault velocity imposed by the boundary conditions \( V_F \) for two pairs of faults (Eq. (8)). Despite low ductile viscosities, the system is forced to generate 6 pairs of faults in order to...
accommodate the boundary shortening rate (Fig. 9D). The localized mode hence does not exist and is replaced by a mode independent on the ductile viscosity and only controlled by the critical ratio between the softening rate and the plastic viscosity. In some cases (very low $\Delta \sigma/\eta_P$), the brittle rheology solely controls the pattern of fault and results are in agreement with those obtained by models taking only the influence of the brittle layer into account (Lavier et al., 2000; Lavier and Buck, 2002). When $V_{FP}$ becomes the controlling velocity ($V_{FP}<V_{FB}$) for $\eta_D>25$ (Fig. 9C), the viscosity of the ductile layers controls the number of fault pairs and a narrow transition toward the distributed mode is observed (Fig. 9D).

7.4. Possible impact at lithosphere scale

The viscosity of the ductile layers and the amount of brittle softening appear to play the most important roles in brittle–ductile coupling and thus in the mode of fracturing, confirming results from other models (Lavier et al., 2000; Lavier and Buck, 2002; Huismans et al., 2005; Buitier et al., 2008). A step forward in this study is to quantify in the same framework the effects of both brittle and ductile rheologies, as it is summarised on Fig. 10.

The localized fracturing mode requires efficient brittle softening/low plastic viscosity (e.g. $\Delta \sigma/\eta_P > (\Delta \sigma/\eta_P)_c$) and low ductile viscosity ($\eta_D < (\eta_D)_c$).

The distributed mode, corresponding to a saturation of the system with faults, requires no softening: $\Delta \sigma < 0$, or high ductile viscosities $\eta_D > 10(\eta_D)_c$.

In between, two additional modes are defined depending on the controlling rheology:

- the brittle-control mode, which requires $0 < \Delta \sigma/\eta_P < (\Delta \sigma/\eta_P)_c$ and $\eta_D < 10(\eta_D)_c$,
- the ductile-control mode, which requires $(\eta_D)_c < \eta_D < 10(\eta_D)_c$ and $\Delta \sigma/\eta_P > 0$.

At the scale of lithosphere, different factors could induce transitions in the different observed fracturing modes. Variations in the brittle rheology can be related to variations in fault zone weakening. The amount of fault weakening can change during fault displacement due to fluid flow, fluid over-pressure and/or mineral transformation (Zoback et al., 1987; Holdsworth, 2004; Gratier and Gueydan, 2007; Moore and Rymer, 2007). Likewise, metamorphic reactions, fluid–rock interaction, local heating or phyllosilicate interconnection can trigger a ductile viscosity decrease (Montési

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**Fig. 9.** Influence of both brittle and ductile media on the fault velocity. The grey thick line corresponds to the maximum fault velocity taking into account both brittle and ductile media. A) Evolution of the maximum fault velocity compared to the fault velocity required if there are only 2 pairs of faults, according the ductile viscosity $\eta_D$, in case the brittle layer is not controlling the number of faults (efficient brittle softening). B) Evolution of the number of fault pairs for case A. C) Evolution of the maximum fault velocity compared to the fault velocity required if there are only 2 pairs of faults, as a function of the ductile viscosity $\eta_D$, in case the brittle layer is partly controlling the number of faults (low brittle softening to brittle hardening). D) Evolution of the number of fault pairs for case C.
and Zuber, 2002; Gueydan et al., 2003, 2004; Cowie et al., 2005; Montési, 2007). For example, the development of a thermal perturbation in deeper lithosphere leading to a regional temperature gradient may cause the transition from widely distributed faulting and crustal thinning to constricted faulting directed toward a well defined rift centre (Behn et al., 2002; Nagel and Buck, 2004; Gueydan et al., 2008). Large deformation in lithosphere mantle is also responsible for a large decrease of the ductile mantle strength due to dynamic grain size reduction (Précigout et al., 2007; Précigout and Gueydan, 2009) and could lead to a change from distributed lithosphere deformation at high mantle strength to localized lithosphere deformation at low mantle strength.

More generally, the thermal and rheological layerings of the lithosphere evolve during deformation, and the brittle–ductile coupling at brittle–ductile interfaces thus changes with time, inducing possible variations in fracturing mode. Our simple 2D models show that slight variations in ductile viscosity or in brittle softening are sufficient to trigger transitions between different fracturing modes. As a consequence, such transitions in the fracturing pattern are likely to occur at the lithosphere scale because of variations in ductile or brittle rheologies during deformation. The present study is thus a first step in understanding the brittle–ductile coupling at lithosphere-scale, since it has permitted to constrain the limiting role of ductile viscosity and brittle softening in the fault displacement rate. A next step will be to accurately model brittle–ductile coupling with temperature-dependant ductile rheology and pressure-sensitive brittle rheology.

8. Conclusion

The role of the brittle–ductile coupling in defining the pattern of fracturing has been studied using a plane strain 2D finite element model. The transition from a localized to a distributed fault pattern is explained by the combined effect of the strength of the viscous layers and the rheology of the brittle layers. By comparing the fault velocity imposed by both brittle and ductile rheologies with the boundary shortening velocity, the mechanics of brittle–ductile coupling is described, and the following conclusions are reached (Fig. 10):

1) The viscosity of the ductile layers induces a “viscous friction” along the faults in the brittle layer. Increasing the ductile viscosity leads to decrease the velocity of the faults and hence favour the creation of more faults.

2) The brittle media controls the fault velocity through the amount of softening $\Delta\sigma$ and the plastic viscosity $\eta_P$. Decreasing the ratio $\Delta\sigma/\eta_P$ leads to decrease the fault velocity allowed by the brittle media and hence favour the creation of new faults.

3) The fault velocity imposed by both brittle and ductile rheologies controls the fracturing mode. If the fault velocity imposed by the brittle–ductile media is large (higher than the fault velocity required to accommodate the boundary shortening velocity), a few faults are sufficient to accommodate the boundary deformation; defining the localized mode of fracturing. On the contrary, if the fault velocity is very low, a dense fault pattern is required to accommodate the boundary deformation; defining the distributed mode of fracturing. In between, the fault density depends on the fault velocity imposed either by the brittle media or by the ductile media, defining the brittle- or ductile-control fracturing mode, respectively.

4) The simulations show that a slight modification of one parameter (viscosity or softening) can result in a change of fracturing mode.

5) In geological systems at the scale of lithosphere, the localized mode and the distributed one constitute two end-members (maybe even not reached). However rapid changes between the brittle-control mode and the ductile-control mode are likely to occur, meaning that evolving geological systems (undergoing changes in the temperature field or modifications of the mechanical property of rocks) could experience different fracturing modes in time.

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