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Localization and delocalization of deformation 
in a bimineralic material

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Abstract We investigate how localization and delocalization of deformation occurs in a bimineralic material composed of a strong plagioclase and a weaker quartz phase. We perform numerical, meter-scale shear experiments in which we vary the temperature and the ratio of the two mineral phases. Three micromechanical deformation fields are identified according to the mechanical behavior of the minerals at play (brittle or ductile when both phases are in the brittle or ductile regime, respectively, and semibrittle when one phase is in the brittle and the other in the ductile regime). Besides these micromechanical deformation fields, we identify three deformation types characterizing the degree of localization (type I: localized shear zone, type II: localized anastomosing shear zone, and type III: delocalized shear zone). Type I is expected in the brittle deformation field. In the semibrittle field, all deformation types can be observed depending on the amount of weak phase present. In the ductile field, deformation is dependent on the strength ratio between the two phases. For a low strength ratio, deformation of type III is always observed. For high-strength ratios, deformation of type II can be observed for a moderate amount of weak phase. A small amount of weak phase (<10%) reverses the mechanical behavior of the strong phase and leads to the formation of a narrow anastomosing shear zone (type II) where fully ductile (type III) behavior is expected. This highlights the importance of a bimineralic material for the deformation localization and overall large-scale deformation processes.

1. Introduction

In the last few decades, numerous numerical studies demonstrated that the relative strength of frictional plastic and viscous materials in the crust provides a first-order control on the deformation processes in divergent [Buck, 1991; Huismans and Beaumont, 2003, 2007, 2011; Huismans et al., 2005; Gueydan et al., 2008; Lavier and Buck, 2002; Regenauer-Lieb et al., 2006, 2008; Rosenbaum et al., 2010] and convergent [Beaumont et al., 1994; Beaumont and Quinlan, 1994; Ellis et al., 1998; Jammes and Huismans, 2012] settings. Apart from pressure, three main parameters control crustal strength: temperature [Ellis, 1988], strain rate, and composition. Most rocks are polymineratic; however, rheologies in a majority of lithospheric scale models approximate the mechanical behavior of the crust and mantle as monomineralic materials composed of wet or dry, plagioclase, quartz or olivine [Huismans and Beaumont, 2003, 2007, 2011; Huismans et al., 2005; Regenauer-Lieb et al., 2006, 2008; Rosenbaum et al., 2010]. This approach presumes that the rheology of the crust or mantle is mainly controlled by the weakest (i.e., quartz) or the most abundant (i.e., olivine) mineral phase. This is an assumption that can be debated in regards to experimental and theoretical studies of bimineralic and polymineratic rocks, which show that their bulk strength also depends on the proportion, shape, distribution, and strength ratio of the minerals [Gerbi et al., 2010; Handy, 1990, 1994; Handy et al., 1999; Hu et al., 2014; Jordan, 1988; Tullis et al., 1991]. Some lithospheric scale models use a laboratory-determined flow laws for polymineratic rock like granite, diabase, or gabbro [Lavier and Manatschal, 2006; Van Wijk and Blackman, 2005]. This approach assumes that an average flow law can approximate the mechanical behavior of polymineratic rock. As for monomineralic assemblages, this assumption implies that depending on the temperature and pressure condition, deformation mechanisms are either elastoplastic or viscoelastic. However, since the transition from the elastoplastic to the viscoelastic regime of deformation depends on the individual transition between the brittle and ductile micromechanical deformation fields of each mineral phase, it is expected that under certain conditions, one phase may deform plastically while the other exhibits viscous behavior.

Geological observations show that minerals harder than their surrounding matrix tend to remain as almost undeformed porphyroclasts or that they can undergo localized fracturing while the rest of the material
shows evidence of viscous deformation [Mitra, 1978; Wakefield, 1977; White et al., 1980], showing that a semibrittle rheology is at play. Evidence for such a behavior can be observed, for example, in quartzofeldspathic rocks at different length scales (Figure 1). At microscopic scale, the semibrittle rheology is identifiable by the presence of brittle feldspar surrounded by recrystallized lenticular quartz aggregates [Tullis et al., 2000] forming anastomosing structures (Figure 1c). At centimeter to meter scales, in deformed quartz-feldspar-rich units, this results in the coexistence of fractures and boudinage structures (Figure 1b). At a kilometer scale, the semibrittle rheology leads to large anastomosing patterns at the fossil brittle-to-viscous transition exposed for example in Cap of Creus, Spain (Figure 1a). At a lithospheric scale, undeformed continental ribbons along the conjugate Orphan-Newfoundland-Iberia margin [Peron-Pinvidic and Manatschal, 2009] also point to semibrittle behavior of the crust. Semibrittle deformation is, however, not specific to quartzofeldspathic rocks but can also be observed in olivine-rich mantle rocks in the presence of orthopyroxene or plagioclase (Figure 1d) [Kaczmarek and Müntener, 2008], in carbonate-/clay-rich rocks (Figure 1e), or for a mixture of amphibolite mafic lenses in a quartzofeldspathic gneiss [Hayman and Lavier, 2014]. All these observations suggest that a polymineralic assemblage has a strong influence on deformation processes and localization of the deformation from the microscopic to the lithospheric scale.

Several field-based studies on polymineralic rocks highlight the importance of precursor fractures filled with weak materials (i.e., quartz) on the localization of deformation under a wide range of pressure and temperature conditions [Fusseis et al., 2006; Hayman and Lavier, 2014; Mancktelow and Pennacchioni, 2005; Pennacchioni, 2005]. Laboratory and analogue experiments demonstrate that the coexistence of phases in the brittle and ductile regime enhances the localization of the deformation [Gumbsch et al., 2001; Higashi and Sumita, 2009; Reber et al., 2014]. In lithospheric scale modeling studies [Lavier and Manatschal, 2006], midcrustal deformation is initiated by the occurrence of phase changes at midcrustal level depending on the amount of accumulated work. In their approach, the assemblage is initially monomineralic but becomes bimineralic after initial localization of the deformation. The strength ratio between the two minerals favors the development of midcrustal shear zones strongly controlling the rifting processes. According to these previous studies and observations, it is reasonable to assume that bimineralic (and by extension polymineralic) assemblages have a strong impact on localization and deformation processes.

Here we investigate the relation between a bimineralic assemblage and delocalization of the deformation. To simplify our experiments and to reduce the number of parameters, we perform meter-scale numerical models with a quartzofeldspathic assemblage using shearing boundary conditions leading to a fracture-like localization.
within a range of temperatures. With this approach, we seek to answer the following question: how does the delocalization of deformation occur in bimineralic materials? What impact does the percentage of weak versus strong phase have? And how does the temperature, controlling the strength difference between the two minerals, affects the delocalization and deformation processes? Possible extrapolation of our results for different assemblages, polymineradic, and different scale systems will be discussed.

2. Model Description

For this study, we use an extension of the PARAVOZ software (based on the Fast Lagrangian Analysis of Continua (FLAC) algorithm) [e.g., Poliakov et al., 1993; Tan et al., 2012] for elasto-visco-plastic material, called DynEarthSol2D [Choi et al., 2013]. Improvement of the flexibility and performance of the FLAC algorithm results from the use of a finite element approximation and the replacement of the structured quadrilateral mesh by an unstructured triangular mesh. Complex problems on unstructured triangular meshes can be solved while keeping the simple explicit material update critical to the field of lithospheric deformation. The use of state-of-the-art mesh generation tools for triangulations allows for the following: (i) adaptive mesh refinement in regions of highly localized deformation when triangular element got to distorted, (ii) a high-quality mesh is maintained by adjusting nodal connectivity, (iii) easier and more faithful tracking of curvilinear boundaries, and (iv) Lagrangian markers are used to keep track of the phase boundaries in the adaptive mesh. An implementation of the methodology used in this code is released to the public with the publication of this paper and is available for download at http://bitbucket.org/an2/dynearthsol2.

With this code, we perform multiple shearing experiments of a bimineralic visco-elasto-plastic material at constant temperature conditions and in the absence of gravity. The mineral phases are randomly distributed among the Lagrangian markers, extrapolated onto the nodes, and then averaged in the triangular elements. In our experiments, the two phases used are wet quartz and plagioclase, but similar experiments could be performed for olivine-orthopyroxene or olivine-plagioclase. At low temperatures, the two minerals follow Coulomb elastic plastic rheology [Choi et al., 2013] written as following:

$$\tau = C + \tan(\phi)\sigma_n$$

where \(\tau\) is the shear stress at yield, \(C\) is the cohesion, \(\phi\) is the friction angle, and \(\sigma_n\) is the normal stress. In our case, the normal stress is imposed by the boundary conditions and is constant for all numerical experiments. At increased temperatures, minerals deform by thermally activated creep, approximated as a nonlinear Maxwell viscoelastic temperature- and strain rate-dependent flow:

$$\sigma_{\text{yield}}^\text{II} = A\cdot\sigma^n_0\cdot(\frac{\sigma_0}{K})^\frac{1}{n}$$

where \(\sigma_{\text{yield}}^\text{II}\) is the second invariant at yield, \(A\) is the creep law preexponent, \(Q\) is the activation energy, \(\sigma_0\) is the square root of the second invariant of the strain rate, \(n\) is the creep law exponent, \(R\) is the gas constant, and \(T\) is the temperature. The mechanism of deformation which requires less energy or effective stress (second invariant of stress tensor) is favored. For a given value of strain rate, each phase has a characteristic transitional temperature where the deformation changes from elastoplastic to viscoelastic. The parameters of the constitutive equations describing the viscous flow are deduced from laboratory measurements on “wet” quartz [Brace and Kohlstedt, 1980] and plagioclase [Shelton and Tullis, 1981]. Using the parameters in Table S1 in the supporting information, the transition from elastoplastic to viscoelastic behavior occurs around the characteristic temperature value of 140°C for wet quartz, while for plagioclase, the transition occurs around 400°C. Based on these values, we can define three different micromechanical deformation fields. At a temperature lower than 140°C, the micromechanical deformation field is described as brittle since both phases are in the elastoplastic regime. Between 140 and 400°C, the micromechanical deformation field can be described as semibrittle with one phase in the elastoplastic regime (plagioclase) and the other one in the viscoelastic regime (quartz). Above 400°C, both phases are in the viscoelastic regime, and the micromechanical deformation field can be described as ductile. However, for temperatures lower than 600°C, there is a significant strength ratio (>5) between the two phases which might affect deformation processes. In the case of a monomineralic assemblage (i.e., 0% of quartz or 100% of quartz), the definition of semibrittle material is not applicable, and the material is either brittle or ductile depending on the temperature.
The model domains are 1 m in width and 2 m in length. Velocity boundary conditions are imposed only on the right and the left boundary of the model. In the upper half of right and left boundary, the normal component of the velocity is equal to $6.3 \times 10^{-15} \text{ m s}^{-1}$ or $2 \times 10^{-7} \text{ m yr}^{-1}$ and is equal to 0 in the lower half. For both halves, the vertical (shear) components are free. On the upper and lower boundaries, the horizontal (shear) components are free while the normal components are fixed to 0 in order to avoid any rotation of the model. With these velocity conditions, the top half moves relative to the bottom half forming to a velocity jump and the potential for strong localization in the middle of the model. The initial triangular mesh elements have side lengths close to 2 cm. Several sets of models with different temperatures and no pressure dependence are studied. We present the result of four of them ($T = 100^\circ\text{C}$, $T = 300^\circ\text{C}$, $T = 430^\circ\text{C}$, and $T = 600^\circ\text{C}$) in this paper. Strain softening is introduced in the models by a linear decrease of cohesion to account for the formation of faults. It occurs for $(\varepsilon)^{1/2} > 0.1$, with a loss of cohesion from $C = 4.4 \times 10^7 \text{ Pa}$ to $C = 4.4 \times 10^6 \text{ Pa}$ affecting only the elastoplastic rheology. As a consequence, no strain softening occurs at high temperature, but at low temperature, this leads to fracture-like structures propagating in a straight line across the entire model following the cohesion weakening imposed in the plastic rheology. In each set of experiments at a given temperature, we vary the proportion of quartz between 0% and 100% (with 10% increments).

Because of the nature of the finite element numerical approximation, localization in a plastic shear band is mesh dependent [Needleman, 1988]. The resulting width of a plastic shear band is set by the size of the elements and is 3 to 4 elements wide [Lavier et al., 2000]. However, since we are mainly interested in the departure of the deformation from highly localized shear in elasto-visco-plastic material, we use localization in shear zones of 3 elements wide as a reference from which other shear bands depart when delocalization occurs. Moreover, when the ductile phase is active in the model, the presence of a viscous material in the semibrittle experiments introduces a physical length scale controlled by the viscosity [Loret and Prevost, 1990].

### 3. Results

All results are presented after 20 cm of shearing in the horizontal direction. The material distribution (Lagrangian markers) for the four sets of models (100°C, 300°C, 430°C, and 600°C) with a concentration of quarts.
quartz equal to 20, 40, 60, and 80% are presented in Figure 2. Corrugations of the main shear boundary located on both extremities of the models are due to boundary effects and will not be taken into account for the analysis of the data. Figure 3 shows the distribution of the accumulated plastic strain (on the elements) for the same models as shown in Figure 2 but also including results for a quartz concentration of 0%. In general, plasticity describes the deformation of a material undergoing nonreversible changes of shape in response to applied forces regardless the deformation process. However, in this study, the plastic strain refers to

Figure 3. Distribution of the accumulated plastic strain for a concentration of quartz equal to 0, 20, 40, 60, and 80% shown after 20 cm of shearing. The inset in the right bottom corner of each model shows the distribution of the second invariant of the strain or effective strain ($\varepsilon_{II}$) with a corresponding Gaussian approximation along a cross section through the central part of the model, an estimation of the maximum value of $\varepsilon_{II}^{\max}$ and the width of the shear zone ($W$). Temperature set at (a–e) 100°C, (f–j) 300°C, (k–o) 430°C, and (p–t) 600°C.

Figure 4. Representation of the second invariant of the strain superimposed on the material distribution for a concentration of quartz equal to 0, 20, 40, 60, and 80%. All figures show the models after 20 cm of shearing. Temperature set at (a–e) 100°C, (f–j) 300°C, (k–o) 430°C, and (p–t) 600°C.
deformation accommodated by brittle process, only, as opposed to crystal plastic behavior, usually a consequence of dislocations. As a consequence, the representation of the accumulated plastic strain indicates when and where the elastoplastic flow occurs; it is therefore indicating the development of fracture-like or brittle structures in the material. The inset in the right bottom corner of each model shows the distribution of the square root of the second invariant of the strain or effective strain ($\varepsilon_{II}$) with a corresponding Gaussian approximation along a cross section through the central part of the model. The Gaussian approximation is used to estimate the maximum value of $\varepsilon_{II}$ and the width of the shear zone. To reduce the effect of noise, the width of the shear zone is measured where the Gaussian curve intersects a line corresponding to 5% of the maximum value of $\varepsilon_{II}$. In Figure 4, the value of the second invariant of strain $\varepsilon_{II}$ for a total displacement of 20 cm is superimposed on the material distribution. We chose a consistent color scale between all the models where for $\varepsilon_{II}$, only values between 0.05 and 1 are depicted. The large-scale “augen” pattern is due to boundary effects and is disregarded in the following description and discussion. The distribution of the second invariant of the strain indicates where most of the deformation is accommodated. Elements with high strain and no plastic deformation are deforming viscously. Comparison of Figures 3 and 4 allows us to identify the domains in which elastoplastic and viscoelastic flow occurs. Enlargements of the key model observations can be found in Figure 5.

We identify three different types of deformation in the numerical experiments. They are characterized by differences in the distribution of plastic strain and second invariant of the strain and are related to the amount of deformation delocalization in the models. We then connect the deformation types to the three different micromechanical deformation fields identified above (brittle, semibrittle, and ductile).

3.1. Deformation Types

In type I “localized shear zone” (i.e., Figures 2a–2f, 3a–3f, and 4a–4f), the deformation is localized in a thin, straight shear zone. Inside the shear zone, the marker distribution (Figure 2) shows a clear foliation with S fabrics, and both quartz and plagioclase phases appear to be stretched and broken apart; (2) model (h) with 40% of quartz and $T = 300^\circ$C, note the example of S fabric affecting the quartz and the augen-shaped lenses delimited by fracture-like structures that follow the distribution of quartz; and (3) model (o) with 80% of quartz and $T = 430^\circ$C, note that the minerals are neither stretched nor broken.

Figure 5. Enlargements of the key model observations from top to bottom row: material distribution, distribution of the accumulated plastic strain, and representation of the second invariant of the strain superimposed on the material distribution. Enlargement of models: (1) model (c) with 40% of quartz and $T = 100^\circ$C, both quartz and plagioclase phases appear to be stretched and broken apart; (2) model (h) with 40% of quartz and $T = 300^\circ$C, note the example of S fabric affecting the quartz and the augen-shaped lenses delimited by fracture-like structures that follow the distribution of quartz; and (3) model (o) with 80% of quartz and $T = 430^\circ$C, note that the minerals are neither stretched nor broken.
3g–3i and 3l–3n, and 4g–4i and 4l–4n. The distribution of markers in Figures 2g–2i and 2l–2n shows that the shear zone is not a straight, thin line but rather a zone of more distributed deformation. Prominent S fabrics are visible and affect both the quartz and the plagioclase, which are deformed and stretched but neither phase is broken apart (Figure 5). The scattered distribution of plastic strain (Figure 3) shows that only plagioclase is affected by plastic deformation, while the distribution of the second invariant of the strain (Figure 4) suggests that quartz accumulates viscoelastic deformation (the zones of high strain II overlap with the quartz minerals in the area of active deformation). In Figures 4g–4i and 4l–4n, the second invariant of the strain shows an anastomosing geometry with multiple augen-shaped lenses delimited by fracture-like structures that follow the distribution of quartz (Figure 5). Moreover, in Figures 3g–3i and 3l–3n, a wider Gaussian distribution of $\varepsilon_{II}$ is visible. The shape of the Gaussian curve correspondingly flattens and widens depending on the amount of quartz. The shear zone width varies between 180 and 920 mm, and the maximum value of the second invariant of the strain ($\varepsilon_{II}$) ranges between 0.28 and 1.16.

Finally, type III "delocalized shear zone" can be observed in Figures 2j, 2k, and 2o–2t. No evidence for mineral stretching or breaking can be observed (Figures 2 and 5). The plastic strain is completely scattered, and its magnitude is very low (Figure 3). The Gaussian distribution of $\varepsilon_{II}$ is very flat and wide (the maximum value does not exceed 0.2), suggesting that the shear zone affects the entire model. The strain affects a wider part of the model, and the geometry of the second invariant of the strain does not show clear anastomosing features (Figure 4).

In order to find a more quantitative way to distinguish between the different types of deformation, a systematic estimate of the shear zone width (in meters) and of the maximum value of the second invariant of the strain $\varepsilon_{II}$ is presented in Figure 6. Values are estimated for the four sets of models (see color code) and plotted against quartz concentration. The graph shows that type I deformation is characterized by a shear zone width of $\sim 130 \pm 5$ mm and a maximum value of $\varepsilon_{II}$ of $\sim 1.2 \pm 0.1$. These values are relatively constant and independent of the amount of quartz (dark gray domain). The lower value of $\varepsilon_{II}$ obtained for the model at 100°C and 80% of quartz is due to local lateral variations. In contrast, in type II
deformation, the width of the shear zone increases whereas the maximum of $\varepsilon^{II}$ decreases with an increase in quartz concentration (medium gray domain). The correlation between localization of the deformation and concentration of the weak phase is characteristic of type II deformation, where both phases are mechanically active and control the overall bulk rheology of the material. Finally, type III deformation is characterized by a constant shear zone width (~1 m) and a constant maximum value of $\varepsilon^{II}$ (0.2) for all quartz concentrations (light gray domain).

In the following paragraph, we combine the model results (Figures 2–4) and the parameters plotted on Figure 6 to identify the different types of deformation at play in the three different micromechanical deformation fields (brittle, semibrittle, and ductile) as a function of quartz concentration.

3.2. Monomineralic Material

Monomineralic materials take a special place in the field of deformation phases as they are restricted to either elastoplastic or viscoelastic behavior depending of the temperature. For a feldspathic composition, the transition between elastoplastic to viscoelastic behavior occurs at 400°C, while it occurs at 140°C for a quartztic composition. In both cases, we observe that at temperatures lower than the transitional temperature, the models show type I deformation. Above this transitional range of temperature, the accumulated plastic strain is very low, and the shear zone affects the entire model (Figures 3j, 3k, 3o, 3p, and 3t and 4j, 4k, 4o, 4p, and 4t), showing that in these cases, monomineralic materials follow type III.

3.3. Brittle Domain

For temperatures below 140°C, both feldspar and quartz deform elastoplastically. In this temperature range, all models show a deformation behavior of type I. The width of the shear zone and the maximum value of $\varepsilon^{II}$ are constant irrespective of the amount of quartz (~130 ± 5 mm and ~1.2 ± 0.1, respectively). In all brittle models, both mineral phases are stretched and broken apart; however, due to visualization limitations, broken minerals are easier to observe when the mineral concentration is lower than 50% (i.e., see Figures 2b and 2c for broken quartz and Figures 2d and 2e for broken plagioclase).

3.4. Semibrittle Domain

For bimineralic materials (0% < Qtz% < 100%), the possible temperature range for the semibrittle domain is between 140°C and 400°C. Above 140°C, the quartz starts to behave viscoelastically, and its strength decreases with temperature while plagioclase remains brittle until 400°C. The deformation type in this domain is strongly dependent on the concentration of quartz. At 300°C, for a quartz percentage lower than 20%, the deformation style is of type I, and the width of the shear zone as well as the maximum value of $\varepsilon^{II}$ remain constant (~1.2 ± 0.1 and ~180 ± 5 mm, respectively). Parameter $\varepsilon^{II}$ shows a tight Gaussian distribution with a maximum value of 1.27 (±0.05). For a percentage of quartz between 20% and 70%, deformation is following type II (Figures 2g–2i, 3g–3i, and 4g–4i). The width of the shear zone increases from 160 to 690 mm while the percentage of quartz augments, whereas the maximum of $\varepsilon^{II}$ decreases from 1.16 to 0.32 (Figures 3g–3i). The localization of strain and the deformation pattern are strongly controlled by the distribution of the quartz grains. The width of the shear zone is consequently larger than in type I and increases with the percentage of quartz. Above 70% of quartz, the plagioclase does not seem to be affected by the deformation (Figure 3j). No evidence of stretching or breaking can be observed (Figure 2j), the shear zone affects the entire model, and the maximum value of $\varepsilon^{II}$ remains constant and equal to 0.16 ± 0.02 (Figure 6). These observations and values are characteristic of type III deformation.

3.5. Ductile Domain

Above 400°C, both mineral phases are expected to deform viscoelastically. However, if a significant strength difference between the mineral phases remains for temperatures between 400 and 600°C, the deformation type is still temperature dependent and forces a subdivision of the ductile domain into a “semiductile” and a “fully ductile” domain.

3.5.1. Semiductile Domain (High-Strength Ratio Between the Two Phases)

To investigate the semiductile domain, we run models at 430°C. Similar to the models at 300°C, the models depend strongly on the concentration of quartz. At 430°C, for a percentage of quartz between 10% and 70%, the models have the characteristics of type II deformation (Figures 2l–2n, 3l–3n, and 4l–4n). The plagioclase still exhibits elastoplastic behavior while the quartz accommodates viscoelastic deformation, generating an
anastomosing pattern in the distribution of the second invariant of the strain. The width of the shear zone and the maximum value of $\varepsilon^I$ are dependent on the amount of quartz. The transition from type II to type III occurs for a proportion of quartz larger than 70% (Figures 2o, 3o, and 4o). The plastic strain accommodated is very low, and the shear zone affects the entire model for all quartz concentrations above 70%. Comparison with a monomineralic feldspar experiment demonstrates that when the quartz ratio is higher or equal to 10%, the behavior reverts from fully ductile (type III) to a localized shear zone with type II features (difference between Figures 3k and 3l).

3.5.2. Fully Ductile Domain (Low-Strength Ratio Between the Two Phases)

At a temperature of 600°C, the strength difference between the two mineral phases becomes low enough so that it does not affect the deformation processes. In that case, the entire model deforms viscoelastically (Figures 2q–2t, 3p–3t, and 4p–4t). Independent of the amount of quartz, all models show that type III deformation and a wide shear zone (affecting the entire width of the model) as well as the maximum value of $\varepsilon^I$ remain constant (~1 m and 0.2, respectively).

3.6. Effect of Boundary Conditions

We believe that the boundary conditions have an effect on the anastomosing patterns observed in the distribution of the second invariant of the strain. Also, to confirm the validity of our experiments and determine the exact effect of the boundary conditions, we conducted a test in a type II model with simple shear boundary conditions (see Figure S1 in the supporting information). We observe a different strain distribution close to the boundaries of the model. The central part of the model, however, remains similar to the one described in the result section (S fabrics affecting both the quartz and plagioclase, scattered distribution of the plastic strain, and anastomosing structures controlled by the distribution of the quartz minerals). Aware of these limitations, our results can then be discussed independently of the boundary conditions, and implication for large-scale tectonic processes can be addressed.

4. Discussion and Conclusions

We investigate the process controlling the delocalization of deformation departing from a single narrow shear band in a two-phase material. We show that delocalization of deformation is dependent on the relative percentage of the two phases and the strength ratio between them, which is in turn linked to temperature and strain rate.

4.1. Deformation Field as a Function of Composition and Strength Ratio

Similar to our experiments, in an experimental and theoretical study on microstructures of natural quartzofeldspathic tectonites, Handy [1990] identified three end-member types of mechanical behaviors depending on the proportion of weak phase and the strength ratio of the two mineral phases. Both studies show that type I deformation is controlled by the strong phase. At low temperatures, both phases are equally strong, but in the presence of a weak phase, the strong phase forms an interconnected load-bearing framework surrounded by the weak phase, and deformation is accommodated along a straight and thin shear zone. Type II is characterized by the formation of anastomosing structures controlled by the distribution of the weak phase while the strong phase forms elongated augen; the significant strain in both phases indicates that they are both mechanically active. In type III, the stronger phase forms relatively undeformed clasts in a weak matrix and is consequently inferred to be mechanically passive.

While the three deformation types presented in this paper show a similar overall behavior to the deformation types defined by Handy [1990], their distribution in a quartz fraction-strength ratio space is different. Our modeling study explores a wider range of strength ratios and micromechanical deformation fields. While Handy [1990] focused mainly on the semibrittle domain with a strength ratio between 1 and 100, we explore deformation processes in the brittle, semibrittle, and ductile micromechanical deformation fields. Accordingly, only part of our results can be directly compared to the study by Handy [1990].

We summarize our results in Figure 7, where we correlate the calculated temperature-dependent strength profile of wet quartz and plagioclase (Figure 7a) to a phase diagram showing the different deformation types observed in the numerical experiments depending on the quartz concentration (Figure 7b). Our temperature-dependent strength profile is the equivalent of a regular depth-dependent strength profile.
We calculated it by extracting the maximum value of the first invariant of the stress (pressure) and the mean value of the second invariant of the stress (effective stress for viscoelastic behavior) after 20 cm of shearing from models with 0% and 100% of quartz at a range of different temperatures. Since in our experiment the normal stress is constant, the value of the first invariant of the stress is representative of the shear stress at yield for the elastoplastic mechanical behavior at different temperatures. The values of the second invariant of the stress give the stress postyield for the viscoelastic mechanical behavior at different temperatures. The intersection of these two curves creates an approximate temperature-dependent strength profile for quartz and plagioclase, where the constant yield stress for low temperature corresponds to the confinement pressure imposed by the boundary conditions. Similar temperature-dependent strength profiles are also available for models with 20%, 40%, 60%, and 100% of quartz and are used to identify the boundaries between the different deformation types (thin black lines in Figure 7b). The clear transition between elastoplastic and viscoelastic mechanisms helps determine the limit between type I and type II deformations.

The transition from type II to type III is less pronounced but is associated with a very low value of the second invariant of the stress (<3 MPa). A clearer transition between type II and type III can be determined by looking at the deformation patterns (Figure 3). We ran additional experiments (160°C, 180°C, 200°C, 400°C, 460°C, and 500°C; the gray symbols in Figure 7b show temperature and composition of all conducted experiments). We used both model observations and characteristic values (width of the shear zone and the maximum value of the second invariant of strain (i.e., Figure 6) to determine a deformation field (Figure 7).

In the brittle domain, the cohesion of both minerals are equal, as a result the strength ratio is equal to 1. Contrarily to Handy’s [1990] theoretical model, polymineralic rocks behave in a brittle manner and deform according to type I deformation independent of the quartz concentration. In the semibrittle domain, Handy [1990] predicts that a direct transition from type I to type III is expected for high-strength ratios and increasing amounts of the weak phase. Our simulations, however, demonstrate that in the semibrittle domain, the direct transition from type I to type III does not occur and that type II deformation always takes place for an intermediate concentration of weak phase (Figure 7b).

In the semibrittle and semiductile domains, the transition between type I and type II and between type II and type III occurs along an S-shaped curve. The slope of the transitional curves shows that with increasing temperature, a smaller ratio of weak phase is required for the deformation type to change. Also, as temperature increases, the strength ratio first increases as quartz softens and then decreases when plagioclase also starts to soften. These changes in strength ratio determine the inflection point in the S-shaped curve. In

Figure 7. (a) Temperature-dependent strength profile of wet quartz and plagioclase (equivalent of the regular depth-dependent strength profile (or Christmas tree) without the effect of lithostatic pressure). (b) Phase diagram showing the different types of deformation observed in the numerical experiments depending on the quartz concentration, the temperature, and corresponding strength ratio between the two phases. The thin black lines represent the temperature-dependent strength profiles for the models with 20%, 40%, 60%, and 100% of quartz. The small gray symbols mark the conditions for all calculated models: star-type I, cross-type II, and ellipse-type III.
the semibrittle domain, the slope of the curves between 140°C and 400°C gives an indication of the impact of the strength ratio on the deformation type. When the strength ratio is lower than 10, the slopes are relatively shallow and the transition between the deformation type is dependent on the composition. On the contrary, for strength ratios between 10 and 80, the slope is steep and the transition between the deformation types is independent of the composition. As the temperature increases above 400°C, plagioclase starts to deform viscously but can still accommodate brittle deformation since it is not yet fully viscous. Type I deformation is not possible anymore and disappears in favor of type II or type III. Below 500°C, type II is possible only for a percentage of quartz larger than 10% and lower than 70%. For temperatures higher than 500°C, the strength ratio decreases again to values lower than 10, and the transition between type II and type III deformation becomes dependent on the composition as was observed for low-strength ratios between 140°C and 200°C. In the fully ductile field of the ductile domain (above 600°C), the strength ratio between the two phases is low enough that any dependence on the relative proportion of the phases vanishes and all deformation takes place as type III.

Using the deformation field in Figure 7b, we show that all types of deformation (I, II, and III) can coexist at the same temperature for different ratios of brittle and ductile phases. For low-strength ratios, the coexistence of brittle and ductile behaviors in type II is strongly dependent on the composition. Finally, since the transition between the different types of deformation occurs at higher and lower temperatures for higher and lower strain rates, respectively (i.e., velocity), the transitions between the deformation types will be coherently shifted downward or upward according to the strain rate.

### 4.2. Effect of Bimineralic Rheology in the Semibrittle and Semiductile Mechanical Domains

Another remarkable result is the difference of behavior between the monomineralic and the bimineralic materials in the semibrittle and semiductile parts of the ductile domain. Without quartz (0%), deformation is accommodated by a thin, straight shear zone in the semibrittle domain (140–400°C) and follows type I. On the other hand, for temperatures higher than 400°C, the model is deforming according to type III, showing that the strength of the plagioclase is low enough to allow for ductile deformation. However, the addition of a small amount of quartz (<10%) leads to type II localized deformation in the semiductile domain, whereas we observe a widening of the shear zone leading to a transition from type I to type II in the semibrittle domain. In the semibrittle domain, the widening of the shear zone with the increase of the amount of quartz can be explained by the delocalizing effect of the weak viscous quartz that allows for the accommodation of a fraction of the deformation in a ductile manner. The viscous quartz forms a viscous buffer between grains of strong brittle plagioclase. These buffers impede the propagation of plastic deformation between grains of plagioclase across the shear zone and generate a wider zone of strain accumulation. The width of the shear zone is therefore proportional to the amount of weak phase. A small amount of weak phase generates small buffers and narrower shear zones, while a large amount of quartz creates large buffers and wider shear zones (Figures 3g–3i and 4g–4i). In the semiductile part of the ductile, domain deformation in monomineralic rocks is strongly delocalized, whereas in bimineralic rocks, with the addition of a small amount of weak phase, the deformation localizes (Figures 3k–3o and 4k–4o). In this temperature range, both plagioclase and quartz should deform in a ductile manner (Figures 3k and 4k). However, when some fraction of weak phase is added to the strong phase (Figures 3k–3o and 4k–4o), the strength ratio causes the weak phase (quartz) to nucleate high deformation rates in a small area. In response to localized high strain rates, plagioclase can behave in an elastoplastic manner and localize deformation. This process leads to the formation of type II shear zones (Figures 3l–3n and 4l–4n). Therefore, the addition of a minor fraction of weak phase to a monomineralic ductile medium leads to localization of the deformation while it delocalizes deformation in the monomineralic brittle field. It is a remarkable and maybe a counterintuitive result showing that the initial role of the weak phase is dependent on the strength ratio between the weak and the strong phase (Figure 7).

### 4.3. Application to Lithospheric Scale Model

Our models show that the localization in a two-phase material is significantly different from a single-phase material. Depending on the strength ratio, the temperature, and the strain rate, deformation can be accommodated in types I, II, or III resulting in various degrees of localization in shear zones. Our study focuses on quartzofeldspathic rocks, but similar results are expected for any mineral phase combination with a sufficiently large strength contrast (olivine/orthopyroxene, olivine/plagioclase, or...
To date, most of the crustal/lithospheric scale models approximate the rheology by the mechanical behavior of mono-mineralic material such as wet or dry plagioclase or quartz (Buck, 1991; Gueydan et al., 2008; Huismans and Beaumont, 2003, 2007, 2011; Huismans et al., 2005; Lavier and Buck, 2002; Regenauer-Lieb et al., 2006, 2008; Rosenbaum et al., 2010), even though 95 vol % of all rocks on Earth is polymineralic. To address this problem, several studies have attempted to determine a bulk strength envelope for polymineralic rocks according to the different proportions of the different phases (Gerbi et al., 2010; Handy, 1994; Handy et al., 1999; Huet et al., 2014; Tullis et al., 1991). These studies, however, do not take into consideration the local interaction between the different phases. As an example, a bulk strength envelope determined for a granitic rock defines two micromechanical deformation fields (brittle and ductile), and only two types of deformations are expected (type I or type III) depending of the temperature conditions. The behaviors described in the semibrittle and semiductile parts of the ductile micromechanical deformation fields are neglected, and the deformation of type II leading to anastomosing shear zones cannot be captured.

Based on our results, using a bimineralic assemblage seems to be a necessary first step for a better approximation of the rheological complexity of the crust. However, due to the absence of depth dependence, the upscaling of our results is not straightforward. We expect that the integration of lithostatic pressure will not significantly change the results but lead to an increased strength contrast and reinforce the described behavior. Our study demonstrates the importance of the strength contrast between the two phases on shear localization. Such a strength difference can not only be found between different mineral phases but also in the strongly heterogeneous crust, where individual blocks have different strength ratios. Localization of the deformation in the crust will then strongly depend on the depth, geotherm, and local anisotropy. Figure 7b illustrates this idea. Considering a Moho at about 500°C, deformation in pure plagioclase crust will be extremely localized (deformation of type I) in the upper and middle crust (until 400°C) and completely delocalized in the lower crust (deformation of type III). For extensional or convergent models using a weak mantle that does not control the deformation, this will result in localized deformation in the crust. For a crust only made of wet quartz, localization will occur only in the upper crust (until 140°C) (deformation of type I), while the rest of the crust (middle and lower) will behave in a ductile manner favoring a strong delocalization of the deformation in extension or contraction (deformation type III). Our results suggest that the integration of a heterogeneous composition will have several consequences on lithospheric scale models. First of all, an intermediate type of deformation will appear at midcrustal level favoring the formation of anastomosing structures (deformation of type II). In an extensional setting, the preservation of undeformed lenses of material in anastomosing patterns will eventually lead to boudinage structure at meter scales.
(Figure 1b) or continental ribbons at lithospheric scale as observed along the Iberian-Newfoundland margin. Analytical and numerical studies using layer cake experiments [Emmerman and Turcotte, 1984; Neurath and Smith, 1982; Ramberg, 1955; Schmalholz and Maeder, 2012; Schmalholz et al., 2008; Smith, 1977] discuss the formation of boudinage structures depending on the viscosity ratio between the layers and the value of the power stress exponent. Our results suggest that integration of polymineralic or anisotropic material in the layer would considerably affect these results and could favor the formation of boudins for small-viscosity ratios and small power law exponents without any material softening or feedback mechanisms (e.g., shear heating). To explain the initiation of ductile shear zones or the development of foliation in midlower crustal depth controlling rifting processes [Lavier and Manatschal, 2006; Vauchez and Tommasi, 2003], Montési [2007, 2013] proposed a constitutive model to estimate the averaged rock strength of polyphase aggregate when layering is partially developed. Based on this analytical approach, he concludes that a change of weak phase abundance without a change of fabrics (from dispersed to layered) is unlikely to produce enough weakening to localize the deformation. Our study refutes this assessment by demonstrating that the addition of a small amount of a weaker phase in a ductile matrix will immediately favor the localization of the deformation. We did not test the effect of the change of fabrics in our study, but we demonstrated that the interaction between phases with different strengths plays an important role in terms of localization and that this effect cannot be taken into account by defining an averaged bulk strength for the aggregate. Furthermore, this study infers that the localization of the deformation in the semiductile micromechanical domain could be a potential explanation for the detection of earthquakes or microseismicity in deeper parts of the crust or mantle that are expected to be ductile and aseismic [Fagereng and Sibson, 2010; Hill et al., 1990; Maggi et al., 2000; Shelly et al., 2009].

4.4. Remaining Questions

Finally, an important remaining question concerns the effect of syntectonic variations in temperature, pressure, and fluid activity on the localization of the deformation. Our experiments and observations of the evolution of the strain rate through time show that for deformation of type II and type III, all branches of the anastomosing structure are created at the beginning of the experiment and remain active during the entire shear experiment. The strain rate might vary through time in the different branches but will never disappear entirely, suggesting that, during the deformation process, the shear zone is neither widening nor narrowing but keeps a constant width. However, macroscopic and microscopic observations of natural shear zones suggest that dynamic localization of the deformation occurs, highlighting the effect of external parameters. Figure 7 infers that syntectonic variations in temperature will affect the localization of the deformation. Figure 8 illustrates an example of a tectonic exhumation of a polymineralic rock in the footwall of a normal fault or exhumining detachment system illustrating that the exhumation can result in changes in the deformation processes. The decreasing temperatures during the exhumation can lead to a shift of deformation type from type II or type III to type I. This change in deformation type will lead to a localization of the deformation along a single shear zone (Figure 8). Furthermore, dynamic recrystallization of mineral phases and fluid-rock interactions leading to mineral transformation can result in weakening, which might enhance localization of the deformation. While we account for the weakening of the brittle shear zones by introducing strain softening in the models, we do not account for the weakening of ductile shear zones. Gueydan et al. [2003, 2014] studied the effect of reaction softening by a pressure-sensitive criterion (reduction in flow stress by feldspar to mica reaction) and demonstrated that this ductile weakening mechanism could be the destabilizing factor for strain localization at midcrustal depth. However, as previously discussed, by averaging the bulk strength of the aggregate during phases change processes, they neglect the interaction factor between phases. It appears therefore that both approaches should be combined and that grain-size-dependent creep flow or dynamic mineral transformation should be integrated in our model to study the effect of weakening on the deformation of semiductile polymineralic materials.

Acknowledgments

We thank the reviewers Frederic Gueydan and two anonymous reviewers, the Associate Editor Mark D. Behn, and the Editor Michael Walter for their constructive and positive comments that significantly improved the paper. This study is supported by the ExxonMobil through the Center of Excellence In Basin Analysis project. Computations were made using the program DYNEARTHSOL developed by E. Choi, E. Tan, and L.L. Lavier available for download at http://bitbucket.org/an2/dynearthsol2. We also thank C. Thieulot for helping in the visualization of the results, L. Wallace for the helpful comments, and N. Hayman for the fruitful discussions. This is UTIG paper UTIG2843.

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