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Single layer folding in simple shear

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ABSTRACT

Despite the common occurrence of simple shear deformation, laboratory and numerical simulations of folding have so far been almost exclusively in pure shear. Here we present a series of finite-element simulations of single layer folding in simple shear up to high shear strains ($\gamma \leq 4$, and up to 75% shortening of the folding layer). In the simulations we vary the viscosity contrast between layer and its surroundings (25–100), the stress exponent (1 or 3) and the kinematics of deformation (pure- versus simple shear). In simple shear fold trains do not show a clear asymmetry, axial planes form perpendicular to the developing fold train and rotate along with the fold train. Differences in geometries between folds formed in simple and pure shear folds are thus difficult to distinguish visually, with simple shear folds slightly more irregular and with more variable axial plane orientation than in pure shear. Asymmetric refraction of an axial planar cleavage is a clearer indication of folding in simple shear. The main effect of an increase in stress exponent is an increase in effective viscosity contrast, with only a secondary effect on fold geometry. Naturally folded aplite dykes in a granodiorite are found in a shear zone in Roses, NE Spain. Comparison of the folded dykes with our numerical simulations indicates a viscosity contrast of around 25 and a stress exponent of 3. The natural folds confirm that at this moderate viscosity contrast, a significant amount of shortening (20–30%) is achieved by layer thickening instead of folding.

1. Introduction

Folds are very common and usually conspicuous structures in rocks that are therefore widely used to unravel rock deformation. They are classical indicators of shortening direction and amount (Treagus, 1982; Hudleston, 1986; Ramsay and Huber, 1987; Hudleston and Lan, 1993; Hudleston and Treagus, 2010 and references therein). However, folds potentially contain much more relevant information, for example on the kinematics of deformation or rock properties. Viscosity or competence contrast between a folding layer and its matrix is usually assumed to have a first order control on fold geometry, as this contrast determines the initial wavelength and amplification rate of developing folds (Biot, 1961; Ramberg, 1961; Ghosh, 1966; Sherwin and Chapple, 1968; Fletcher, 1974, 1977; Smith, 1975; Johnson and Fletcher, 1994; Schmalholz and Podladchikov, 2001). Apart from studies that focussed on fold amplification from initial perturbations, many studies also investigated the question whether fold geometry may reveal the rheology of folding layers and their matrix. Most studies have focused on power-law rheology, where strain rate is proportional to stress to the power n (Fletcher, 1974; Smith, 1975, 1977; Abassi and Mancktelow, 1992; Mühlhaus et al., 1994; Hudleston and Lan, 1994; Lan and Hudleston, 1995; Kenis et al., 2005; Hudleston and Treagus, 2010). One problem in cases where $n \neq 1$ is that there is no single or constant viscosity contrast. This issue will be addressed further below. Other factors that may influence fold geometry are strain-dependent rheology (Lan and Hudleston, 1991; Tackley, 1998; Huismans and Beaumont, 2003; Schmalholz et al., 2005), mechanical anisotropy (Hudleston et al., 1996; Toimil and Griera, 2007; Kocher et al., 2008) or, recently, thermal effects (Hobbs et al., 2008; but see discussion by Treagus and Hudleston, 2009).

The kinematics of deformation can potentially also be deduced from the analysis of folds. Folds are common structures in many ductile shear zones, where they commonly show a strong asymmetry that can be used as a shear sense indicator (Hudleston, 1977; Quinquis et al., 1978; Ramsay et al., 1983; Passchier and Williams, 1996; Alsop and Holdsworth, 2006; Carreras et al., 2005). Strongly asymmetric folds are common at very high strains in non-coaxial deformation, where their formation has been explained with passive shearing of existing folds (Ghosh, 1966; Cobbold and

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Quinquis, 1980; Hudleston and Lan, 1993), although active buckling probably plays a role as well (Bons and Urai, 1996; Alsop and Carreras, 2007). Other studies, however, indicate that non-coaxial deformation does not necessarily produce asymmetric fold shapes (Ghosh, 1966) and that asymmetries arise during the final stages of fold amplification (Schmid, 2002). Several studies have pointed out that the asymmetry of cleavage patterns associated with folding is a better indicator of non-coaxial folding than the fold shape itself (Manz and Wickham, 1978). These authors observed that strain is not necessarily symmetrically distributed about fold axial planes, and that asymmetries between the two limbs arise in single layer simple shear experiments. In linear viscous simple shear models, Viola and Mancktelow (2005), however, did not observe a marked asymmetry in fold shape, but a clear difference in refraction of a developing cleavage. A complicating factor here is that layers originally oblique to the maximum shortening direction could potentially also develop asymmetric folds even in coaxial deformation (Treagus, 1973; Anthony and Wickham, 1978; Viola and Mancktelow, 2005).

Apart from theoretical and field studies (e.g. Biot, 1961; Flinn, 1962; Sherwin and Chapple, 1968; Treagus, 1973, 1981; Fletcher, 1977; Ramsay and Huber, 1987; James and Watkinson, 1994; Schmalholz and Podladchikov, 2000; Ormond and Hudleston, 2003), most of our current knowledge of fold mechanics is derived from experiments (e.g. Ghosh, 1966; Hudleston, 1973; Cobbold, 1975; Shimamoto and Hara, 1976; Manz and Wickham, 1978; Abassi and Mancktelow, 1992; Bons and Urai, 1996; Tikoff and Peterson, 1998) and numerical simulations (e.g. Chapple, 1968; Dieterich, 1970; Parrish, 1973; Stephansson and Berner, 1971; Parrish et al., 1976; Shimamoto and Hara, 1976; Hudleston and Stephansson, 1973; Anthony and Wickham, 1978; Casey and Huggenberger, 1985; Hudleston and Lan, 1994; Lan and Hudleston, 1995; Zhang et al., 1996, 2000; Mancktelow, 1999; Viola and Mancktelow, 2005; Frehner and Schmalholz, 2006; Schmid and Podladchikov, 2006; Schmalholz, 2008; Hobbs et al., 2008; Kocher et al., 2008; etc.). By far most of the studies deal with folding of single or multiple layers in pure shear parallel to the maximum shortening direction. Only a few have considered general shear or folding of a layer oblique to the maximum shortening direction (Anthony and Wickham, 1978; Schmid, 2002; Viola and Mancktelow, 2005). Considering that simple shear deformation is likely to be common in the crust, a numerical study on folding in true simple shear is long overdue.

In this paper, we present a series of numerical simulations of folding in simple and pure shear of viscous single layers. Layers are initially oriented oblique to the shear plane in the case of simple shear simulations, and parallel to the compression x-direction for pure shear models. This study aims to determine the difference, if any, in fold patterns between the two kinematic end-members.

2. Methods and experimental setup

2.1. The numerical model

Simulations were carried out with the software packages ELLE (Jessell et al., 2001, 2005; 2009; Bons et al., 2008) and the finite-element module BASIL (Barr and Houseman, 1996; Bons et al., 1997; Houseman et al., 2008 and references therein). ELLE is an open-source modelling platform used to simulate the development of (micro-) structures during tectonic and/or metamorphic processes. In ELLE, the model is defined by a contiguous set of polygons that are defined by nodes that link straight segments (Fig. 1). The spatial resolution of the model is constant as additional nodes are inserted or removed when boundaries are stretched or shortened. The spacing of nodes (set between 0.005 and 0.011, at a model size of 1 × 1) not only determines the resolution of the shape of the folding layer, but also determines the resolution of the triangulation for the finite-element routine (see below). A series of tests with different node spacings (between 0.00125 and 0.005 to 0.00275–0.011) was carried out to ensure that it did not influence the results.

Properties can be assigned to polygons. In this case, the only property assigned to a polygon is its viscosity (see definition below), which is constant within a polygon and remains unchanged throughout the simulation (no strain hardening or softening is considered). We define a single, more competent layer with a constant viscosity, which is embedded in a matrix with a lower viscosity. To track the finite deformation field we use a passive marker grid.

In our simulations the model is a unit cell that it is repeated infinitely in all directions. For this, ELLE uses both horizontally and vertically wrapping boundaries. A polygon that is truncated by the right boundary thus continues on the left side. For simple shear deformation, an initially square model remains square, which significantly reduces the boundary effects that would arise if the model were to shear into a parallelogram. In pure shear simulations boundaries are also periodic, but the unit cell does not remain square.

All simulations presented here are for the folding of a single competent layer in a homogeneous isotropic matrix. The layer is originally inclined with respect to the shear plane in simple shear. The initial layer thickness is 0.025 for all simulations, 1 being the size of the simulation bounding box in simple shear. It should be noticed though, that due to the wrapping boundaries, the initial model in simple shear effectively consists of multiple layers that finally shear into a single vertical layer (see Fig. 1a).

The simulations presented below address two main questions: (i) What is the difference in fold geometry between pure shear and simple shear? and (ii) What is the difference between folding in linear ($n = 1$) and non-linear ($n = 3$) materials? For this we varied (a) the viscosity contrast ($m = 25, 50, 100$), (b) the stress exponent ($n = 1, 3$), (c) the boundary conditions and (d) the amount of finite shortening (Table 1):

- Horizontal dextral simple shear up to a shear strain of $\gamma = 2$ and $\gamma = 4$, with a square unit cell of dimensions 1 × 1. For $\gamma = 2$, the folding layer was initially inclined 27° and shortened 59%, while for $\gamma = 4$, it was inclined 14.0° and shortened 75%. At the end of the simulation, the layer is oriented normal to the shear plane.
- Vertical pure-shear shortening by 59% (starting as a $\sqrt{5}$ by $1/\sqrt{5}$ rectangle) and 75% (starting as a $\sqrt{17}$ by $1/\sqrt{17}$ rectangle) to end up with a square model of dimensions 1 × 1. The layer is oriented parallel to the maximum compression x-direction for all deformation stages.

2.2. Finite-element method

BASIL is a 2D finite element (FEM) package that calculates non-linear viscous deformation in plane strain (Houseman et al., 2008). BASIL is used to compute viscous strain rates and the associated stress fields. An incompressible, viscous constitutive law is assumed for both folding layer and matrix. Here the deviatoric stress tensor (τ_{ij}) is related to the strain rate tensor ($\dot{\varepsilon}_{ij}$) with:

$$\tau_{ij} = 2\eta\dot{\varepsilon}_{ij} = \eta\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \quad (1)$$