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The emergence of asymmetric normal fault systems under symmetric boundary conditions

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ABSTRACT

Many normal fault systems and, on a smaller scale, fracture boudinage often exhibit asymmetry with one fault dip direction dominating. It is a common belief that the formation of domino and shear band boudinage with a monoclinic symmetry requires a component of layer parallel shearing. Moreover, domains of parallel faults are frequently used to infer the presence of a décollement. Using Distinct Element Method (DEM) modelling we show, that asymmetric fault systems can emerge under symmetric boundary conditions. A statistical analysis of DEM models suggests that the fault dip directions and system polarities can be explained using a random process if the strength contrast between the brittle layer and the surrounding material is high. The models indicate that domino and shear band boudinage are unreliable shear-sense indicators. Moreover, the presence of a décollement should not be inferred on the basis of a domain of parallel faults alone.

1. Introduction

Many normal fault systems and, on a smaller scale, fracture boudinage structures are described as being asymmetric or symmetric (e.g., McClay, 1990; Goscombe et al., 2004). If many, or all, faults have the same dip direction, then the system is strongly asymmetric, with a high proportion of extension on faults dipping in one direction. Conversely, if approximately equal amounts of extension are accommodated on oppositely-dipping faults, the system is described as symmetric (Fig. 1b). In the present study, the terms 'asymmetric' and 'symmetric' are used in the same sense, so that an asymmetric fault array consists of parallel or domino-style faults whereas a symmetric array consists of conjugate normal faults. (Note that fault-bounded blocks, or boudins, may, of course, individually exhibit a monoclinic or orthorhombic symmetry. However, symmetry in the latter sense should not be confused with that used here.)

Numerous field studies, physical experiments and numerical models shed light on the conditions favouring the formation of asymmetric normal fault systems (e.g., McClay, 1990; Mandl, 2000). Physical (e.g. sandbox) experiments, for example, have shown that normal faults with the same dip direction form within a brittle layer due to a basal shear couple, which can be imposed by (i) a topographic taper (Mandl, 1988, 2000), (ii) an inclination of a uniformly stretching base (McClay and Ellis, 1987; Vendeville et al., 1987), (iii) a non-uniformly stretching horizontal base (Mandl, 1988; Ishikawa and Otsuki, 1995), or (iv) drag due to flow of a viscous substratum (Vendeville et al., 1987; Brun et al., 1994). Irrespective of the origin of the basal shear couple, the sense of slip of the parallel faults is synthetic to the shear stress at the base (Mandl, 2000). In contrast, if slip on an array of parallel faults is accommodating external (i.e., layer parallel) shearing then the sense of fault slip is antithetic to the overall shear sense across the fault system, a mechanism referred to as bookshelf or domino faulting (Mandl, 1987, Fig. 1c; note that, strictly speaking, the sense of slip depends on the orientation of the faults relative to the instantaneous stretching axes). Consequently, domains of parallel faults are often used to infer the presence of a common décollement or interpreted to have formed due to external shearing. In fact, some researchers suggested that the sense of slip on parallel faults in relation to the overall shear sense across the fault system provides a clue to the strength profile of the faulted stratigraphy (Stewart and Argent, 2000). Moreover, it is a common belief that the formation of foliation parallel domino and shear band boudinage with a monoclinic symmetry requires a component of layer parallel shearing (Passchier and Druguet, 2002; Dabrowski and Grasemann, 2014, Fig. 1d), whereas torn (i.e., orthorhombic) boudins reflect coaxial flow (Goscombe et al., 2004, Fig. 1a). The reliability of asymmetric boudinage as a shear sense indicator is however

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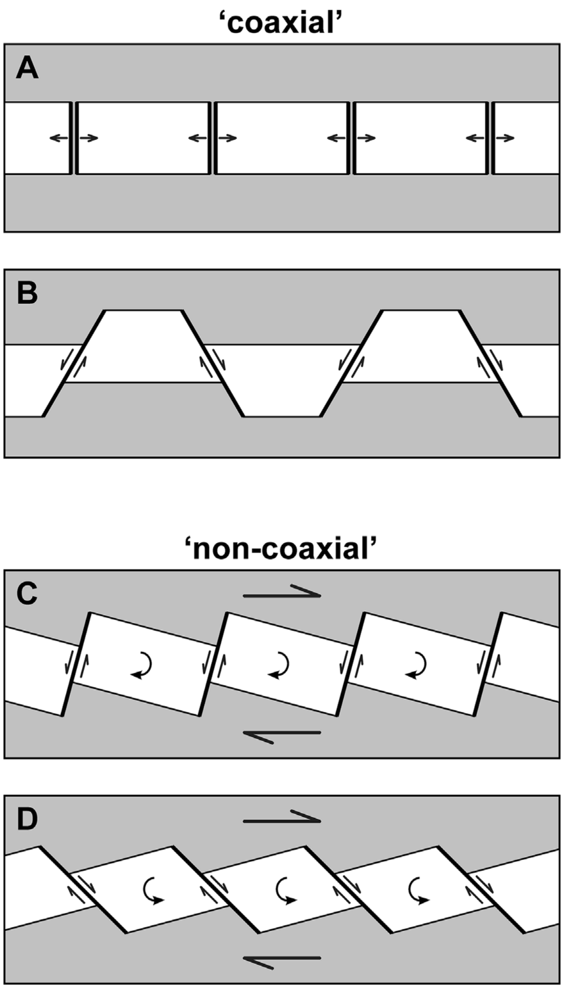

Fig. 1. Typical kinematic interpretations of symmetric and asymmetric fracture systems developing in a brittle layer surrounded by a weak matrix. In the present study, 'symmetric' means that approximately equal amounts of extension are accommodated on oppositely dipping faults, whereas 'asymmetric' implies that one dip direction dominates. (**A**) Torn (i.e., orthorhombic) boudins and (**B**) symmetric horst and graben structure (or symmetric shear fracture boudinage) are typically interpreted to form under coaxial strain boundary conditions, with the maximum stretching axis parallel to layering. **C**, bookshelf faulting (or domino boudinage) shown for a system in which the initial fault traces are normal to layering. Layer parallel shearing leads to the rotation of fault bounded blocks and fault slip which is opposite to the external shear direction. **D**, asymmetric fault system (or shear band boudinage) shown for an array in which the initial fault traces are inclined to layering. External shearing leads to a synthetic fault slip and to a block rotation which is opposite to the imposed shear. Slip along parallel faults and associated block rotation is hence often interpreted to form under layer-parallel shearing.

questionable (Hanmer and Passchier, 1991), especially in cases were the boudinage developed from foliation-oblique boudin trains or the flow geometry in the host rock (matrix) is unknown (Goscombe et al., 2004).

All of the aforementioned studies illustrate that asymmetric fault systems, at any scale, are the result of asymmetric boundary conditions (e.g., basal shear couple or external layer-parallel shearing). The phrase 'asymmetric boundary condition' is, again, used in a loose sense and infers an imposed non-coaxial background strain. Conversely, 'symmetric boundary condition' implies coaxial strain and that the instantaneous stretching axes are normal/parallel to mechanical layering (if present). As perhaps expected, symmetric boundary conditions usually lead to symmetric structures (Fig. 1a and b). However, a few studies illustrate that parallel-dipping fault arrays can, at least locally, form under symmetric boundary conditions. For example, sand or wet clay layers that are stretched uniformly at their base often exhibit domains of parallel faults (McClay and Ellis, 1987; Vendeville et al., 1987; Mandl, 2000; Schlische and Withjack, 2009). Mechanical explanations for the formation of asymmetric fault systems under symmetric boundary conditions are, in our opinion, not straightforward. For example, Mandl (2000) suggests that, after the formation of the first pair of conjugate faults, reactive shear stresses develop because extension within the brittle layer is (due to the presence of faults) no longer uniform even though basal extension continues to be uniform. These reactive shear stresses lead to the development of parallel infill faults. On the other hand, Schlische and Withjack (2009) explain the formation of domains of parallel faults by means of so-called stress-reduction zones (Ackermann and Schlische, 1997; Gupta and Scholz, 2000). According to this model, domains of parallel faults develop because the stress-reduction zones do not overlap. Another mechanical explanation for the formation of parallel-dipping faults under symmetric boundary condition is based on numerical models of two-layer systems (Nagel and Buck, 2006), which illustrate that certain viscous substratum thicknesses and viscosities lead to the preferential development of one fault dip direction due to channel flow.

Here we use the Distinct Element Method (DEM) to model the formation of normal fault systems under symmetric (coaxial strain) boundary conditions. The DEM is a valuable tool for modelling the formation of normal fault systems (Saltzer and Pollard, 1992; Egholm et al., 2007), the spacing of layer-confined rock joints (Schöpfer et al., 2011), the development of fracture boudinage (Abe and Urai, 2012; Abe et al., 2013; Komoróczi et al., 2013), or the evolution of crack-seal fracture networks (Virgo et al., 2014). These existing DEM studies, however, confirm the general consensus that symmetric (coaxial strain) boundary conditions lead to symmetric fracture systems, a notion that is also supported by continuum mechanical modelling (Harper et al., 2001; Schueller et al., 2005).

The set-up of the DEM models presented in this study is similar to the laboratory rock experiments by Griggs and Handin (1960) and the DEM models by Abe and Urai (2012): a central brittle layer surrounded by a weak matrix is subjected to layer parallel extension. In contrast to these earlier studies, we systematically varied the properties (stiffness, friction) of the frictional-plastic matrix material and ran multiple realisations, i.e. models run under identical boundary conditions and statistical material properties, to examine conditions required to produce asymmetric normal fault systems. The DEM models illustrate that asymmetric fault systems can develop under symmetric boundary conditions when the strength contrast between the brittle layer and the surrounding matrix is high. A statistical analysis of system polarities suggests that a probable cause for the formation of parallel-dipping faults is simply chance, meaning that fault dip directions are random.

2. Distinct Element Method (DEM)

We use the Particle Flow Code in two dimensions (*PFC-2D*; Itasca Consulting Group, 2008) which implements the Distinct Element Method (DEM) for circular particles (Potyondy and Cundall, 2004; Potyondy, 2014). In the present study, particles interact via a linear force-displacement law with slip, so that the maximum permissible contact shear force at any contact is the product of the normal contact force and the contact friction coefficient (μ_c). Cohesion is modelled by adding linear elastic bonds to particle-particle contacts (so-called parallel-bonds; see Potyondy and Cundall, 2004). These bonds break if either their normal or shear strength is exceeded, corresponding to fracture. Model boundaries are represented by rigid, frictionless platens to which velocities are applied. Usage of a servo-algorithm allows continuous adjustment of platen velocities so that a constant stress boundary condition is achieved. Dissipation of kinetic energy is modelled by damping particle accelerations (damping constant = 0.7) resulting in quasi-static conditions.