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Simulating faults and plate boundaries with a transversely isotropic plasticity model

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ABSTRACT

In mantle convection simulations, dynamically evolving plate boundaries have, for the most part, been represented using an visco-plastic flow law. These systems develop fine-scale, localized, weak shear band structures which are reminiscent of faults but it is a significant challenge to resolve the large- and the emergent, small-scale-behavior. We address this issue of resolution by taking into account the observation that a rock element with embedded, planar, failure surfaces responds as a non-linear, transversely isotropic material with a weak orientation defined by the plane of the failure surface. This approach partly accounts for the large-scale behavior of fine-scale systems of shear bands which we are not in a position to resolve explicitly. We evaluate the capacity of this continuum approach to model plate boundaries, specifically in the context of subduction models where the plate boundary interface has often been represented as a planar discontinuity. We show that the inclusion of the transversely isotropic plasticity model for the plate boundary promotes asymmetric subduction from initiation. A realistic evolution of the plate boundary interface and associated stresses is crucial to understanding inter-plate coupling, convergent margin driven topography, and earthquakes.

1. Introduction

Tectonic stresses within the shallow regions of the lithosphere result in the formation of faults, the largest of which are the plate boundaries themselves. Both fault zones and the plate boundaries are extremely narrow regions compared to the size of the plates (Kreemer et al., 2003). This immediately presents a challenge for numerical modeling since the wide separation in scales is difficult to represent in any finite, discrete model. Broadly speaking, this challenge can be approached in two different ways: either by explicitly addressing the two scales with distinct discrete representations (e.g. treating plate boundaries as lower-dimensional surfaces in a two-dimensional or three-dimensional continuum (Zhong and Gurnis, 1995, 1996)), or by finding a single-scale, non-linear, rheological model which naturally gives rise to multiple scales of deformation and computing the models at high resolution (e.g., Bercovici, 1993 and subsequent work). The approach we present in this paper is a hybrid of these two approaches: primarily a rheological model, but one which assumes an embedded discontinuity exists below the limit of resolution.

There are several rheological approaches to implementing both (a) narrow, weak, rapidly deforming plate boundaries and (b) laterally extensive, strong, and slowly deforming plate interiors. For example, power law viscous flow laws have been used to generate plate boundaries (e.g., Christensen and Harder, 1991; Weinstein and Olsen, 1992), followed by the more sophisticated temperature dependent viscosity and depth dependent yielding implementations (e.g., Moresi and Solomatov, 1998; Trompert and Hansen, 1998), as well as thermo-elastic and thermal-rheological approaches that include the effects of water (Regenauer-Lieb et al., 2001). The longevity and reactivation of plate boundaries and fault zones on Earth provides us with evidence that plate boundaries and fault zones have some history dependence (Moresi et al., 2000; Gurnis et al., 2000; Jadamec et al., 2013). To address this problem, many models of the Earth's lithosphere and mantle have a time dependent damage parameter included, such as strain weakening or defect creation (e.g., Bercovici, 1998; Tackley, 2000; Lenardic et al., 2000; Auth et al., 2003; Ogawa, 2003; Bercovici and Ricard, 2014). The damage parameter induces severe weakening so that the plate boundaries or deformation zones are long lasting and may be reactivated more easily than undamaged material. The incorporation of these approaches

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reproduce many Earth-like plate boundary features in models. However, certain features remain difficult to reproduce, including asymmetric subduction.

In all of the rheological models outlined above, the effects of yielding are implemented through a reduction in viscosity. We note that this means that this limits any changes to the stress field at yielding to be a uniform scaling of all components, that there can be no rotation of the stress field at yielding, and that the yield criterion can only be expressed in terms of the scalar invariants of the stress tensor. We refer to this approach as a Byerlee yield model since it addresses the depth-dependent (frictional) strength of the lithosphere without dealing with details of individual structures (cf. Byerlee, 1967). The stress-limit caused by frictional sliding on a planar surface cannot be expressed within this rheological framework; it is necessary to set limits on the shear stress and the normal stress in the failure plane independently. Moresi and Mühlhaus (2006), Moresi et al. (2007) and Mühlhaus et al. (2010) showed that this can be modeled in a continuum formulation by using a non-linear, transversely isotropic flow law identical in form to that used previously to model buckling of a layered medium (Moresi and Mühlhaus, 2006).

The distinctions between direct viscosity and shear viscosity within a constitutive model have already been made (Christensen, 1987; Moresi and Mühlhaus, 2006; Pouilloux et al., 2007). However, we extend this approach and propose a transversely isotropic constitutive model in order to simulate the macro-scale behavior of faults and plate boundaries. This model allows for a weak plane along which there is a preferential direction of slip to represent the manner in which two volumes of rock or two tectonic plates slide past one another (Fig. 1b). We assume an isotropic, viscous medium undergoes a symmetry-breaking transformation at failure in accordance with standard plasticity approaches, but formulated from a kinematic viewpoint rather than a classical yield-stress-based flow rule. Where the symmetry breaking transformation occurs, the material behaves anisotropically. Drawing from the methods outlined in Mühlhaus et al. (2004), an invertible, three dimensional transversely isotropic constitutive formulation is presented, where individual shear components of the constitutive matrix can be modified independently.

The ease of implementation into mantle convection software is a feature of this formulation as we write out the transversely isotropic flow law from a canonical orientation aligned with the material fault planes and then rotate it to match the geometry of fault segments at each integration point. This approach is different from previous mesh-based global fabric models (Zhong and Gurnis, 1996), as it is more flexible due to the complexities arising from

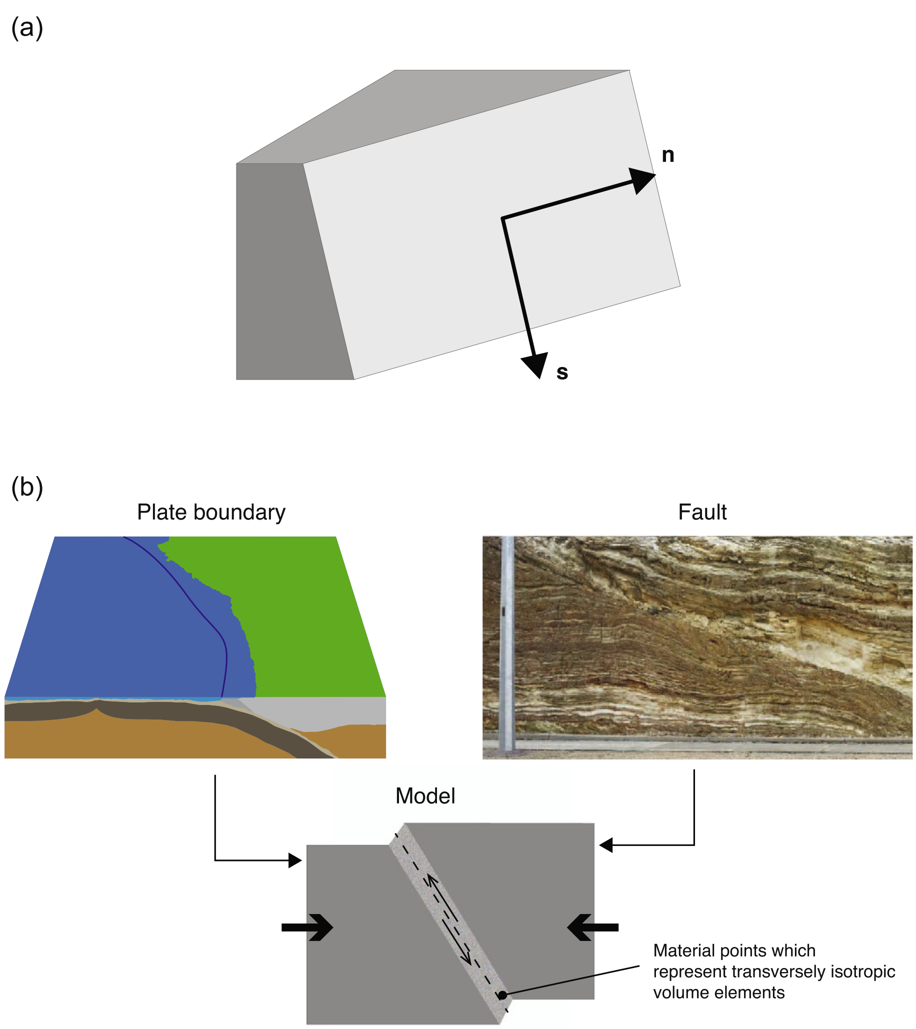

Fig. 1. Illustration of a volume element with an embedded fault plane and a model of a subduction zone plate boundary and faulted crust. (a) A three-dimensional depiction of volume element with an embedded fault plane, where the normal and shear vector are depicted. (b) Example of a large scale fault zone (plate boundary) and a small scale thrust fault (outcrop size Wenger, 2012) which is then shown to be simplified in a numerical model.