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Structural geology meets micromechanics: A self-consistent model for the multiscale deformation and fabric development in Earth's ductile lithosphere

Dazhi Jiang [a], [b], *

[a] Department of Earth Sciences, Western University, London, Ontario N6A 5B7, Canada
[b] State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China

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ABSTRACT

Earth's lithosphere is made of rheologically heterogeneous elements of a wide range of characteristic lengths. A micromechanics-based self-consistent MultiOrder Power-Law Approach is presented to account for lithospheric deformations and the accompanying multiscale fabric development. The approach is principally based on the extended Eshelby theory for the motion of a power-law viscous ellipsoid in a power-law viscous matrix and the idea of embedding inhomogeneities within inhomogeneities. The extended theory provides a general means for investigating deformation partitioning in heterogeneous rocks. The "inhomogeneities within inhomogeneities" method allows multi-hierarchical levels of flow field partitioning and hence multiscale deformations to be investigated. Partitioned flow fields are used to investigate fabric development. Being based fully on micromechanics, the approach generates model predictions of both kinematic quantities (strain, strain rates, and vorticity) and stress histories. The former can be directly compared with field and laboratory structural observations while the latter can help to understand the physics of natural deformations.

The self-consistent and multiscale approach is applied to a natural example of the Cascade Lake shear zone in the east Sierra Nevada of California. The modeling shows that the fabrics are most consistent with a steeply-dipping transpression zone with a convergence angle of 20° and a strike-slip displacement about 26 km. Further, the strength evolution of the model zone confirms that a transpression zone is a weakening system with respect to the simple shearing component and a hardening one for the pure-shearing component. This is consistent with slip partitioning in obliquely convergent plate boundaries: boundary-normal convergence tends to spread over a broad area whereas boundary-parallel shear tends to localize in major strike-slip zones.

1. Introduction

The application of continuum mechanics has led to significant advances in structural geology since Ramsay (1967) as reflected in many landmark textbooks (e.g., Hobbs et al., 1976; Means, 1979; Twiss and Moores, 1992; Johnson and Fletcher, 1994; Passchier and Trouw, 1996; Pollard and Fletcher, 2005) and a large number of research papers in the earth and planetary science literature. Applying continuum mechanics to structural studies is also a common theme of many recent international geoscience meetings such as the 2011 Geological Society of America Penrose Conference on "Deformation localization in rocks: new advances" held in Cap de Creus, Spain (Druguet et al., 2013) and a Topical Session on "Deformation processes in lithospheric high-strain zones" at the 2012 Geological Society of America Annual Meeting in Charlotte, USA (this volume). Nearly five decades of accumulated work have also clearly suggested that the classical continuum theory cannot effectively address the heterogeneous deformation in Earth's lithosphere where rheological heterogeneities spanning a wide range of characteristic length scales must be considered. This inability is due to the fact that the classical approach does not contain material parameters with length dimensions that can capture the characteristic scales of rheological heterogeneities. Because of this limitation, a sound approach to bridge multiscale structural studies remains elusive and structural geology studies on relatively small-scale features are still somehow disconnected from large-scale

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* Department of Earth Sciences, Western University, London, Ontario N6A 5B7, Canada.
E-mail address: djiang3@uwo.ca.

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tectonic synthesis. In this paper, I will review and further develop a micromechanical approach which has the potential of connecting multiscale deformations.

1.1. *Challenge to the classical continuum mechanics approach*

The classical continuum mechanics approach is robust in analyzing structures of a single or limited range of characteristic length scales. Continuum models of varying levels of rigor from purely geometric to fully mechanics-based exist for nearly every specific structure. A few examples include the folding theories for single and multi-layers (e.g., Johnson and Fletcher, 1994; Schmalholz and Podladchikov, 2000; Hudleston and Treagus, 2010), theories for the formation of pinch-and-swell structures (Smith, 1977; Schmalholz et al., 2008; Schmalholz and Fletcher, 2011), the geometrical/kinematic model for small ductile shear zones (Ramsay and Graham, 1970; Ramberg, 1975), the Taylor-Bishop-Hill model (e.g., Lister and Paterson, 1979; Lister and Hobbs, 1980) and the viscoplastic self-consistent (VPSC) model (Molinari et al., 1987; Lebensohn and Tomé, 1993) for the development of lattice preferred orientation fabrics in crystalline rocks. These theoretical models each apply to structures with a certain characteristic length scale appropriate for the structure in question and are thus referred to as single-scale models (Jiang and Bentley, 2012). Existing kinematic models (see a review by Davis and Titus, 2011) and the mechanical model of Robin and Cruden (1994) for tabular deformation zones are all single-scale models. However, such is the nature of many structural and tectonic studies that one must analyze structures for a wide range of characteristic lengths in a single problem. In such cases, the classical continuum approach is quite ineffective because rheological heterogeneities, ubiquitous in the lithosphere over a wide range of observational scales, cause significant flow-field partitioning (Lister and Williams, 1983). Consequently, in a large region such as in a tectonic-scale transpression zone, ‘local’ partitioned flow fields are relevant to small-scale features like stretching lineations, kinematic indicators, and crystallographic preferred orientation fabrics. In this scenario, single-scale models cannot relate these structures to the ‘bulk’ tectonic scale deformation boundary conditions and processes.

Many people have recognized this problem (e.g., Lister and Williams, 1979, 1983; Ishii, 1992; Jiang, 1994a,b; Jiang and White, 1995; Jiang and Williams, 1999; Hudleston, 1999; Goodwin and Tikoff, 2002; Jones et al., 2005). Geologists distinguish different scale quantities routinely using terms like ‘regional’ (or ‘bulk’) stress vs ‘local’ stress. They also frequently resort to the concept of flow partitioning to explain heterogeneities of natural structures and fabrics (e.g., Kilian et al., 2011; Carreras et al., 2013). It is perhaps safe to say that very few geologists would deny the significance of flow partitioning in lithospheric deformation. Yet, how to address the problem remains elusive. Apart from some simple analyses, usually based on geometric and kinematic grounds (e.g., Jiang, 1994a,b; Jiang and White, 1995; Jiang and Williams, 1999; Hudleston, 1999; Jones et al., 2004; Passchier et al., 2005) or simple mechanical considerations (e.g., Ishii, 1992) and some recent studies highlighting the significance of flow field heterogeneity in the vicinity of a rigid inclusion (e.g., Griera et al., 2011, 2013; Dabrowski and Schmid, 2011), there is still no rigorous and generally applicable means to handle flow partitioning. Because of this, “partitioning” remains a qualitative concept used in various contexts: Sometimes it is used to criticize simple-minded extrapolations from small-scale observations to big-scale processes. At other times, without much harm, “partitioning” is used as a convenient means to “explain” observations that do not fit the predictions of simple models. Most unfortunate is that some earth scientists have taken the ubiquitous “flow partitioning” in nature to support their notion, often expressed informally, that small-scale structures are too complicated to be useful. While this notion is not acceptable (Ramsay and Huber, 1987, p.vi), it demonstrates the need for a more rigorous consideration of heterogeneities at a variety of scales. Otherwise, the use of small structures to infer tectonic processes is hampered.

1.2. *A new micromechanics approach*

Micromechanics (Mura, 1987; Nemat-Nasser and Hori, 1999; Qu and Cherkaoui, 2006) is a new and fast-developing branch of continuum mechanics grown from the milestone work of Eshelby (1957, 1959, 1961) on the interaction between an elastic inhomogeneity and the surrounding infinite elastic matrix. His novel approach, now commonly referred to as Eshelby's inclusion/inhomogeneity solution (e.g., Mura, 1987, p.74; Qu and Cherkaoui, 2006, p.77; Li and Wang, 2008, p.94) or more simply the Eshelby (inclusion) formalism (e.g., Lebensohn and Tomé, 1993), was first extended to Newtonian viscous materials (Bilby et al., 1975; Bilby and Kolbuszewski, 1977) and then to non-Newtonian power-law viscous materials using various linearization schemes (Molinari et al., 1987; Lebensohn and Tomé, 1993; Ponte Castañeda, 1996; Masson et al., 2000). The extension to power-law materials led to the viscoplastic self-consistent (VPSC) formulations (Lebensohn and Tomé, 1993; Lebensohn et al., 2011) for simulating lattice preferred orientation fabrics in crystalline aggregates. Castelnau et al. (2010), in their multiscale investigation of the anisotropic rheology of olivine polycrystals and Earth's upper mantle dynamics, and Montagnat et al. (2013), in their recent simulation of ice deformation, gave a succinct review of the first-order, second-order, and full-field viscoplastic approaches. The VPSC theory and code have been used by many geoscientists to investigate texture development in crustal and mantle rocks (e.g., Wenk et al., 1989, 2009; Tommasi et al., 2000; Lebensohn et al., 2003; Keller and Stipp, 2011) for over two decades. More recently, Griera et al. (2011, 2013) have used the full-field viscoplastic formulation based on the fast Fourier transformation (Lebensohn, 2001) to simulate the rotation of rigid porphyroclasts and strain localization near the clasts.

It is realized recently that the extended Eshelby formalism for power-law viscous materials can be adopted to address the general problem of flow partitioning (Jiang and Bentley, 2012; Jiang, 2012, 2013). With the idea of “inhomogeneities within inhomogeneities”, one can use the extended Eshelby formalism to investigate multi-hierarchical levels of flow field partitioning in materials containing rheologically heterogeneous elements of varying characteristic lengths. This has led to the MultiOrder Power-Law Approach (MOPLA, Jiang and Bentley, 2012). *MultiOrder* means that the approach considers rheological elements of multiple characteristic lengths, from large (low-order) elements to small (fabric-defining, high-order) elements. And *Power-Law* reflects the fact that the model considers the non-Newtonian rheological behavior of natural rock deformation.

1.3. *Purpose and organization of the paper*

In this paper, I shall first review the theoretical background of this new micromechanical approach and the associated numerical methods. Secondly, I develop MOPLA of Jiang and Bentley (2012) to a more rigorous and self-consistent level that considers the rheological evolution with time as fabrics and hence rheological anisotropy develop in a progressively deforming rock mass. Finally, I apply this new self-consistent MOPLA to the Cascade Lake shear zone in the east Sierra Nevada of California (Bentley, 2004; Jiang and Bentley, 2012). The application serves to show how small-