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Shear-induced porosity bands in a compacting porous medium with damage rheology

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ABSTRACT

Shear-induced porosity bands have been observed experimentally and have been the subject of a number of theoretical and numerical analyses in which a number of rheological laws governing the partial melt system have been proposed. These bands have been suggested to be important in Earth's interior in focussing melt to Earth's mid-ocean ridges, in reducing the effective viscosity of the asthenosphere, and in affecting seismic and electrical properties. Recently, a linear analysis of the formation of melt bands has been presented in which the viscosity of the solid matrix depends on the grain size and a parameter characterizing the roughness of the grain-liquid interface For some parameter values, this "damage" rheology mimics the effect of very strongly strain-rate dependent viscosity which can produce low angle bands, similar to those seen in experiments. In the present paper, I show full nonlinear simulations of melt bands with damage rheology. In agreement with the linear analysis, low angle bands are possible when the grain size and grain roughness evolve rapidly compared with the deformation of the sample. The grain size field evolves to form bands where grain-size anticorrelates with porosity. The effective viscosity and electrical conductivity of bands are also investigated. For low angle bands, the effective viscosity relative to the mean viscosity decreases and the electrical conductivity anisotropy increases with strain, indicating significant strain and electrical conduction localization.

1. Introduction

An instability that results in localized porosity bands in compacting porous layers with shear viscosity that decreases with porosity was first predicted theoretically by Stevenson (1989). Porosity bands were later seen in experiments involving the shear of partially molten rock samples (Holtzman et al., 2003; Holtzman and Kohlstedt, 2007, King et al., 2010). These bands have also been simulated numerically (Katz et al., 2006; Butler, 2009, 2010, 2012; Katz and Takei, 2013, Alisic et al., 2014). Such bands may exist in Earth's upper mantle where they may be significant for focussing melt to mid-ocean ridges (Katz et al., 2006; Gebhardt and Butler, 2016), in reducing the effective viscosity of the asthenosphere (Holtzman et al., 2012), in increasing the observed seismic anisotropy (Holtzman and Kendal, 2010) and may possibly affect the electrical conductivity and its anisotropy (Caricchi et al., 2011).

While the numerical and theoretical models have many similarities with the experimental bands, some experimental observations remain difficult to explain. In particular, experimental bands are always observed to occur at roughly 20° to the shear plane. Linearized compaction equations predict that bands in only porosity dependent viscosity will have their largest growth rate when they are oriented at 45° to the shear plane (Spiegelman, 2003). Strain-rate dependent (Katz et al., 2006; Butler, 2009, 2010) and anisotropic (Takei and Holtzman, 2009; Butler, 2012; Katz and Takei, 2013) viscosities have been shown to result in low angle bands under some circumstances. King et al. (2010) showed that some of their experiments were carried out with a Newtonian viscosity, ruling out the strain-rate dependent mechanism in some cases. The degree of strain-rate dependence required to make low angle bands is also greater than is generally expected for mantle materials (Hirth and Kohlstedt, 2003).

In a recent paper, Rudge and Bercovici (2015) (hereafter RB (2015)) presented linear instability results for the formation of porosity bands when the matrix viscosity is subject to damage. Damage theory, in which rheology depends on evolving grain size, has been developed in a series of papers (Bercovici et al., 2001; Bercovici and Ricard, 2003, 2005, 2012). The RB(2015) theory included a dependence of the matrix viscosity on the grain-liquid interface roughness as well as on the grain size. Time evolution equations were introduced in which the interface roughness increased with time due to coarsening but could be reduced by mechanical deformation or damage. A further time evolution equation was introduced for the grain size which could increase due to growth and in which the growth rate could be reduced by the effects of pinning. The pinning increased with the grain size

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but was reduced by the interface roughness. Thus damage could reduce the interface roughness which could directly reduce the viscosity by decreasing slip surface friction and indirectly through pinning. The RB(2015) theory is valid for diffusion creep which, in the absence of effects due to damage, exhibits a linear relationship between stress and strain-rate.

While RB(2015) predicted the growth rate as a function of angle for the various parameters characterizing the damage theory and the predicted time evolution, they did not investigate the nonlinear, long time evolution. Also, the evolution of the interface roughness and grain size (an experimentally determinable quantity) were not investigated. In the experimental investigations of Holtzman and Kohlstedt (2007), evidence was reported of both increased grain growth and reduction rates in regions of greater melt which would be expected to lead to a greater diversity of grain sizes within the melt rich bands. A comparison of grain sizes in the melt rich and melt poor bands in an experimental study has not yet been published.

Holtzman et al. (2003) and Holtzman et al. (2012) showed that as shear progresses and strain becomes localized within the bands, the effective viscosity of samples is reduced. Holtzman et al. (2005) argued that the reduction in effective viscosity by band structures may significantly affect the effective rheology of the upper mantle. Katz and Takei (2013) calculated the ratio of the integrated shear stress with time to that at the initial time in simulations with prescribed background simple shear flows. They showed that the effective viscosity only differed significantly from its initial value near the end of their simulations and that the effective viscosity actually increased with strain.

Magnetotelluric studies (e.g., Naif et al., 2013) have shown evidence of low electrical resistivity regions in the upper mantle and of resistivity anisotropy that may be caused by melt arranged in band structures. However, it has been argued that electrical anisotropy may be better explained by the presence of water (Dai and Karato, 2014). Caricchi et al. (2011) and Zhang et al. (2014) have carried out experiments measuring electrical conductivity in partially molten deformed samples. While these samples showed stress-oriented melt pockets at the grain scale, they did not show macroscopic bands. In the present study, the electrical conductivity of deforming compacting systems will be calculated in two space dimensions.

This paper has three main purposes. One is to investigate whether the predictions of linear theory for the formation of melt-bands in a compacting porous medium with damage rheology remain true when finite amplitude and hence nonlinear effects are present. A second purpose is to determine if there is a relationship between grain size and porosity in shear bands, a topic that was not investigated by RB(2015). Finally, the large amplitude deformation simulations will be used to look at effects of melt bands on effective viscosity and electrical conductivity.

In what follows, I will briefly review the damage rheology theory of RB(2015) and the relevant linear theory. I will then describe the implementation of the grain-size and interface roughness evolution equations in a numerical model of compaction in a simple shear geometry and then present results for the time evolution of the porosity, grain size and roughness fields. The evolving effective viscosity and conductivity results will be shown in subsequent sections.

2. Theory

A dependence of the viscosity, η, on the length scale of the roughness of the interface, r, and on the grain size, R, in addition to the porosity, ϕ, is introduced as in RB(2015).

$$\eta = \exp(-\alpha(\phi - \phi_0)) r^n R^m. \tag{1}$$

The equation above is dimensionless. The dependence of viscosity on grain-size is well known (Turcotte and Schubert, 2002) and in diffusion creep, $m = 2$ for grain-volume creep and $m = 3$ for grain boundary creep. In dislocation creep, the viscosity is independent of grainsize. The dependence on grain interface roughness captures the effect of a reduction in friction as the interface roughness is reduced while the parameter α characterizes the reduction in viscosity with porosity.

The dimensionless equations governing r and R are

$$\frac{\partial r}{\partial t} + \mathbf{U} \cdot \nabla r = \Gamma_l \left[\frac{\lambda}{\lambda_0 r^{q-1}} - \frac{r^2 \Psi \lambda_0}{\lambda} \right] \tag{2}$$

and

$$\frac{\partial R}{\partial t} + \mathbf{U} \cdot \nabla R = \Gamma_g R^{1-p} \left[1 - \frac{\phi}{\phi_0} \frac{R^2}{r^2} \right]. \tag{3}$$

Here $\mathbf{U}$ represents the matrix velocity while Γ_l and Γ_g are rate constants for roughness and grain growth and the exponent p is given value 2. The function $\lambda = 3\phi(1-\phi)$ and $\lambda_0 = \lambda(\phi_0)$ (Bercovici and Ricard, 2012) while $\Psi = 4\eta \dot{\epsilon}_{II}{}^2$ represents the work done by viscous deformation where $\dot{\epsilon}_{II}$ represents the second invariant of the strain-rate tensor. The two terms on the right-hand side of Eq. (2) represent interface coarsening and the reduction of interface coarsening by damage while the two terms on the right-hand side of Eq. (3) represent grain growth and grain-growth reduction due to pinning.

I use the governing equations for compaction of McKenzie (1984) which include equations for conservation of mass of the solid phase

$$\frac{\partial \phi}{\partial t} = \nabla \cdot [(1-\phi)\mathbf{U}], \tag{4}$$

and of the combined liquid and solid

$$\nabla \cdot (\mathbf{U}(1-\phi) + \mathbf{u}\phi) = 0, \tag{5}$$

as well as equations for the liquid force balance,

$$\phi(\mathbf{u} - \mathbf{U}) = -k_\phi \nabla P \tag{6}$$

and aggregate force balance

$$\nabla[-P(\zeta_0 + 4/3) + (\zeta_0 - \frac{2}{3})\eta \nabla \cdot \mathbf{U}] + \nabla \cdot \eta(\nabla \mathbf{U} + \nabla \mathbf{U}^T) = 0. \tag{7}$$

In the equations above, $\mathbf{u}$ and $\mathbf{U}$ are the liquid and solid velocity fields while P is the fluid pressure and ζ_0 represents the ratio of the bulk to shear viscosity at the initial porosity, roughness and grain size. The bulk viscosity is assumed to be proportional to the shear viscosity as it evolves with ϕ, r and R.

The permeability is taken to have a power-law dependence on the porosity,

$$k_\phi = \left(\frac{\phi}{\phi_0} \right)^3. \tag{8}$$

Some simulations were undertaken in which permeability increased as the square of the grain-size and this was found to make very little difference.

In order to assure that the porosity always falls between 0 and 1, a transformation is defined such that

$$\phi = \frac{1}{2}(1 + \tanh(\phi_c)). \tag{9}$$

Eq. (4) is then rewritten

$$\frac{1}{2}\mathrm{sech}^2(\phi_c)\frac{\partial \phi_c}{\partial t} = \nabla \cdot [(1-\phi)\mathbf{U}]. \tag{10}$$