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Author(s):
Moulas, Evangelos; Burg, Jean-Pierre; Podladchikov, Yuri Y.

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The role of viscosity heterogeneities in the development of pressure variations

Moulas, E.\textsuperscript{1}, Burg, J.-P.\textsuperscript{1} and Podladchikov, Y.\textsuperscript{2}

\textsuperscript{1}Department of Earth Sciences – ETH Zurich, Switzerland
\textsuperscript{2}Institut des Sciences de la Terre, Université de Lausanne, Lausanne, Switzerland

Natural rocks are to a large extend heterogeneous. Despite the presence of heterogeneities on various scales, continuum approaches that treat rocks as homogeneous have proven to be first-order satisfactory (Turcotte and Schubert, 2014). On the large scale (meter to kilometer scale) however, variations in rock effective shear stress (e.g. due to different viscosities) may have a noticeable effect in the mechanical response of the deforming systems. Rocks at high-temperature conditions flow in a viscous manner. The stress field is perturbed as a result of the force balance when viscosity heterogeneities are present. Perturbation of the stress field implies that the mean stress, the effective shear stress and the stress orientation may vary locally.

Figure 1. Modified after Moulas et al. (2014). Second stress invariant ($\tau_{II}$) from lithostatic pressure ($\sigma_{0}$) during lithospheric shortening (after Schmalholz and Podladchikov, 2013). $X/h_c$ and $Y/h_c$ represent the width and the height of the model (a,c) normalized to the initial thickness of the crust ($h_c$). The models in (b) and (d) are dimensionless and can be applied on various scales. All stress components in (a) and (c) have been normalized to the lithostatic pressure at the Moho ($\sigma_c$). Comparison of similar dynamic parameters from our analytical solutions (b, d). Note that in two dimensions the second stress invariant ($\tau_{II}$) and the effective shear stress ($\tau$) are equal. $P$ represents the pressure deviation from the far-field pressure. All stress components in (b) and (d) have been normalized to the far-field effective shear stress ($\tau_{ffs}$). The viscous inclusion has an aspect ratio of 3, it is inclined $60^\circ$ from the horizontal and it is 10 times less viscous than the surrounding matrix.
In order to investigate the effect that the viscosity variations have on the stress field, we employ Kolosov-Muskhelishvili’s method for the all-viscous flow (Kolosov, 1909; Muskhelishvili, 1953; Schmid and Podladchikov, 2003). This method provides an analytical solution for the viscous flow around a circular/elliptical inclusion that has a different viscosity than the matrix. Despite the fact that Kolosov-Muskhelishvili’s method was originally created for the solution of all-elastic problems, it is mathematically identical to the solution for the all-viscous deformation if the shear modulus is replaced by viscosity and strain is replaced by strain rate (Goodier, 1936). As shown in Moulas et al. (2014), the approximation of a viscous shear zone by a viscous elliptical inclusion under general shear is able to capture the first-order patterns of the stress and pressure perturbations in regions of viscosity heterogeneity (detail in Fig. 1). This comparison reveals that zones of lower viscosity and effective shear stress may develop significant pressure variations as a result of force balance (Moulas et al., 2014; Schmalholz et al., 2014; Schmalholz and Podladchikov, 2013). The later observation is not valid only for circular and elliptical shapes as it has been shown for the separation of blocky boudins in plane strain (Mancktelow, 2008).

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