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Reconciling the formation of shear-induced melt bands in numerical and laboratory experiments: The effects of surface tension and a porosity-weakening bulk viscosity

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Understanding the time scales and mechanisms of melt transport in the mantle and melt focusing to mid-ocean ridges is an important problem in the Earth sciences. In particular, many challenges arise (1) due to the nonlinear nature of this problem, which can lead to feedback mechanisms and strong shear localization, and (2) due to large uncertainties in the material properties of partially molten rocks. While laboratory experiments are an important tool to better understand these processes, theoretical and numerical studies are required to explain the behaviour observed in the experiments and to extrapolate and apply the laboratory results to the time and length scales of the Earth's mantle.

One important localization mechanism is the formation of melt bands in partially molten rocks.
Laboratory experiments show that when partially molten rock is deformed under simple shear or torsion, a network of melt-enriched bands develops, acting as shear zones in the rock. The melt band formation can be explained by the porosity-weakening rheology of rocks, which have a lower viscosity in regions with higher melt fraction, leading to a low pressure in the melt and consequently the flow of melt into these high-porosity regions from areas of lower porosity.

However, many of the features that emerge in the laboratory experiments are not well understood. So far, numerical studies with the goal of reproducing these laboratory experiments have not been able to explain why the spacing between melt-rich bands is much larger than their width. In addition, numerical models often break down shortly after melt bands have started to form, because melt continues to localize in the high-porosity shear bands, eventually exceeding the disaggregation threshold. In the laboratory experiments, the maximum melt fraction in the bands stabilizes after the initial phase of growth.

Here, we address this problem using a series of numerical models that include surface tension effects and systematically test the effect of porosity-weakening of the rock's compaction viscosity. We show that a compaction viscosity that increases with decreasing porosity leads to an asymmetry between the band width and band spacing, and that this asymmetry is stronger the stronger the bulk viscosity depends on the porosity. In addition, we demonstrate that the effects of surface tension can limit the localization of melt bands and stabilize the maximum porosity in the bands before the disaggregation threshold is reached. This explains why in the laboratory experiments, the porosity in the melt bands remains stable after their formation up to large strains.

Our results suggest that under experimental conditions, surface tension effects influence the localization of melt, and the porosity weakening is stronger for the bulk viscosity than for the shear viscosity. If this latter relation also applies to mantle rocks beneath mid-ocean ridges, it potentially affects both melt and plate boundary focusing.

Our implementation of this problem is freely available as a plugin for the community code ASPECT.