Barraud, J., Gardien, V., Allemand, P and Grandjean, P. 2001. Strain-dependence of the melt migration in partially molten crustal rocks. In: Rawling, T. and Aillères, L. 2001. Animations in Geology, Journal of the Virtual Explorer, 4, 1-3.

Strain-dependence of the melt migration in partially molten crustal rocks

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Abstract: Progressive horizontal shortening of a partially molten layer of microcrystalline paraffin wax is shown in the form of a movie. During the folding, the melt segregates into foliation-parallel veins. The distribution of the melt becomes heterogeneous and varies at each increment of deformation because veins may subsequently disappeared. A dilatancy-pumping mechanism is clearly observable. It allows the pervasive horizontal migration of the melt from the layer to the outside of the layer. The melt extraction occurs by pulses in a periodic manner.

Introduction

At the metric scale, the geometric relationships between deformation and melt migration in migmatitic crustal rocks is now well-established (Brown and Solar, 1998; Vanderhaeghe, 1999; Weinberg, 1999). The melt moves through an interconnected network of low-pressure sites such as hinges of folds, foliation-parallel veins or shear bands. However, little is known about the mechanism of melt extraction and about the amount of strain needed for an efficient extraction of the melt from the partially molten rocks. High-grade metamorphic rocks are often intensively deformed and show a pervasive foliation. However, the amount of strain recorded in condition of partial melting may be relatively low. Feedback relations between the presence of melt and the deformation are numerous (Brown and Solar, 1998) and concern mainly the creation of dilatant sites by heterogeneous deformation and the strain localization by the melt. This implies that the melt migration is strain-dependent. In order to investigate these feedback relations, analog experiments with paraffin waxes have been conducted.

Analogue materials and scaling of the experiment

We used a red microcrystalline wax, which is a complex mixture of hydrocarbons with a large range of molecular weights. At the temperature of the experiment (60±2°C), the wax is a two-phase material, consisting of a liquid phase and a solid viscous phase, the melt fraction being between 15 and 20%. Prior to deformation, the liquid is homogeneously distributed in the wax layer. In order to reproduce the strong mechanical planar anisotropy of foliated rocks, the wax layer is made of 9 superposed unwelded thin layers that are 3-4 mm thick. This stack is 33 mm thick and is embedded between two white layers of softer paraffin wax, whose thickness is 25 mm. This white paraffin wax melts at 69±1°C and so should not be molten at the temperature of the experiment (60±2°C). However, the lower layer undergoes a large volume reduction during the shortening (see the movie). This suggests that this melting point is pressure-dependent and strain-dependent. The role of these soft layers is to offer to the wax layer a viscous medium that transmits stresses. This role is achieved for the upper layer but the lower layer acts rather as a decollement level.

The uppermost layer of sand (thickness = 4 cm) increases the vertical stresses in the wax layers and improves the similarity between our model and the nature. The scaling of our experiment is based on relevant ratios linking geometric, cinematic and dynamic quantities (Barraud et al., 2001). The value of the vertical stress enters in the ratio Ψ between the vertical force due to gravity (i.e. the weight of the column of height *h*) and the viscous force:

$$\Psi = \frac{\rho g h l^2}{\eta V l} = \frac{\rho g h l}{\eta V}$$

where ρ is the density of the rocks above a given point at

Table 1. Physical parameters controlling the melt migration processes in nature and in the model.

	Length (m)	Depth (m)	Shortening velocity ($m\ y^{-1}$)	Density of the solid ρ_s ($kg\ m^{-3}$)	Density of the liquid ρ_m ($kg\ m^{-3}$)	Viscosity of the solid η_s (Pa s)	Viscosity of the liquid η_m (Pa s)
Nature	0.2-20	$30\text{-}40\times10^3$	0.001-0.1	2800-3000	2400-2500	10^{16}-10^{18}	10^4-10^6
Model	0.2	0.1	18	950	800	10^8	10^{-2}-10^{-3}

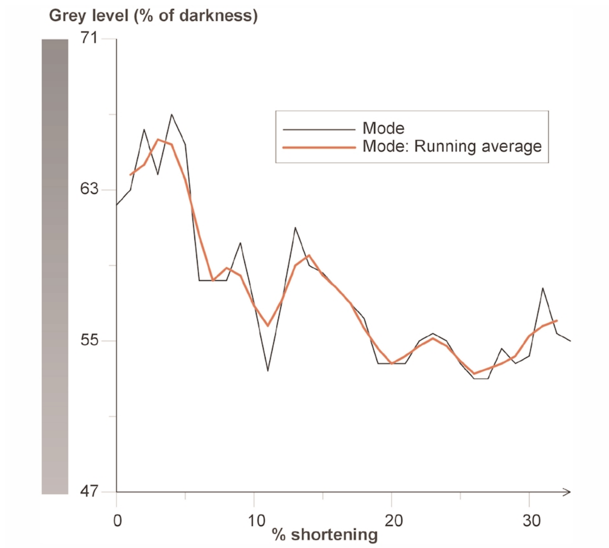
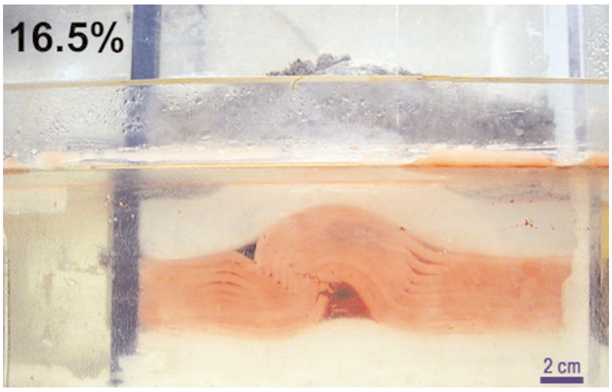


Figure 1. Mode of the grey-levels histogram of the wax layer during progressive deformation. The mode is a measure of the quantity of melt visible on the edge of the model. Pure melt and melt-depleted wax have a darkness of 100% and 25%, respectively. The darker is the layer, the higher is the melt fraction. The running average is computed on 3 consecutive values. The graph shows a net decrease during the run but with periodic variations that correspond to successive pulses of melt extraction.



Movie 1: Progressive horizontal shortening of a partially molten layer of microcrystalline paraffin wax.

depth *h*, *g* the gravitational acceleration constant, *l* the characteristic length of the studied system, *V* the shortening velocity and η the viscosity of the solid. This ratio must be equal in model and in nature for the structures to be dynamically similar (Ramberg, 1981). The table 1 shows the values of the parameters in the model and in nature. The ratio Ψ in our model equals 3. The diversity of the settings implies that Ψ varies in the range 10^{-2}-10^{4} in nature. If one calculates every possible value of Ψ with the parameters of table 1, the most frequent values are between 10 and 100. This indicates that the scaling is correct. The ratio Ψ for the model should be higher, i.e. the vertical stress should be increased. However, the melt pressure has not been taken into account. By reducing the effective stresses, it diminishes the importance of the lithostatic pressure. Two other ratios, ρ_s/ρ_m and η_s/η_m, where subscripts *s* and *m* refers to the solid rock and to the melt, respectively, are important for a correct scaling (Table 1). The viscosity contrast between melt and solid is high enough (10 orders of magnitude), so that melt-enhanced phenomena such as strain localization are reproduced. The density of the molten wax is lower than the density of the solid wax. The gravity processes are therefore correctly scaled. That is the reason why our experiments show that the pressure gradients due to the heterogeneous deformation are more important to drive the melt segregation than the buoyancy forces.

Description of the movie

The movie, composed of 33 pictures taken every hour (i.e., every 2.5 mm of shortening), shows the four layers of the model and the warm water that was surrounding it. The water level fluctuated because of the evaporation and subsequent refilling of the tank. The movie shows the growth of an upright fold in which many melt-filled veins open and close. The first step of the deformation (0-5% of shortening) corresponded to a slight homogeneous thickening of the layer. Next, a buckling instability developed and foliation-parallel veins opened in the limbs (5-7% of shortening). With rotation of limbs and elevation of the hinge zone, a saddle reef was created and the veins opened more and more. These dilatant sites were filled with the dark red melt. Next, the left limb rotated rapidly and when its dip became higher than 30° (shortening > 8.1%), the aperture of the veins decreased. The melt is therefore expulsed horizontally and perpendicularly to the shortening direction, towards the outside of the model. The melt could migrate along the sides of the box and accumulate at the surface of the surrounding water under the form of a red film.

The next stages of the deformation consisted in a succession of similar processes of opening and closure of melt-filled pockets. The convex sides of the folds were affected by radial cracks, showing the effect of a strong stretching that the ductility of the wax was unable to accommodate. The large saddle reef structure was collapsing between 18 and 24% of shortening. This was associated with an increase of the volume of expulsed melt, together with opening of veins in the axial plane of the fold. The movie ends with the lock-up of the anticline and the beginning of vertical stretching.

Discussion and conclusion

This experiment provides evidences for a mechanism of extraction of the melt from a partially molten material. This mechanism resembles to dialtancy pumping: as the aperture of veins increases and decreases, pressure gradients oscillate within the layer. The melt migrates in a passive manner through the wax layer and goes ultimately out of the fold, in the surrounding water that is the region of lowest pressure. It follows that melt extraction occurs in a series of pulses. Two evidences show this fact. First, the movie shows periodically a dark red spot, generally centred on the hinge zone and which diameter varies between 1 and 4 cm.

This is a lens of melt coming from the layer's interior and migrating along the vertical sides of the box. Secondly, as the colouring agent is more soluble in the melt, the darkness of the wax reflects its melt fraction. Whitened zones are depleted in melt and are generally around the melt-filled veins. This confirms that the melt moves down the pressure gradients through the microscopic porosity of the wax. The histogram of the grey levels of the pixels constituting the wax layer has been computed for each images of the movie. The mode of each histogram is then calculated and plotted as a function of the amount of shortening (Fig. 1). A running average is used to smooth the data because their accuracy is not better than 10%. A clear periodic signal is confirmed and its period is about 5-7 hours. A bulk decrease of the grey level appears also. It corresponds to the 10% of weight loss that the wax layer underwent. As the melt fraction was at the beginning between 15 and 20%, about 50% of the available melt has been extracted.

To conclude, the experiment shows that horizontal shortening of a horizontal anisotropic partially molten layer results in the periodic extraction of the melt that migrates along the foliation. Melt pathways are created by heterogeneous strain but are transient and may disappeared with subsequent deformation. The hinge zone of a fold is both a zone of accumulation (saddle reef structures) and a transient melt-pathway. This dilatancy-pumping is suggested to be an efficient mechanism of melt extraction in migmatites.

Acknowledgements

J.B. thanks Jean-Louis Vigneresse for his suggestion of a layered wax layer.

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