

Instabilities development in partially molten rocks

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ABSTRACT

Partially molten rocks (PMR) are characterized by specific and contrasting behaviours. For instance, large-scale and smaller scale structures are consistently oriented in a migmatitic body with those of the surroundings, indicating that the migmatites were deformed as a whole. By contrast, ubiquitous strain partitioning and melt distribution are widely present in the same migmatitic body, reflecting highly heterogeneous strain and intrinsic rheological instabilities. A continuous transition from a liquid-like to a solid-like rheology, as many averaging processes implicitly assume, cannot explain this two-fold information. We develop a full analysis, considering the stress and strain rate, and the relative proportion of melt and solid phases. Temperature varies from T_{solidus} to T_{liquidus} in a PMR. We also assume that the transition to melting is not dual to crystallization. However, we prefer using the viscosity rather than the stress, since the former is better constrained from experiments. The viscosity of the matrix, which deforms according to a power law, shows shear thinning, whereas that of the melt remains constant. The viscosity contrast between the two phases thus varies with strain rate. The lower the strain rate, the higher is the viscosity contrast, hence instabilities development is controlled by the rheology. The path followed during a transition also controls the intermediate state, and may lead to instabilities, resulting from mechanical reasons or from the respective amount in each phase. In the last case, the concentration in one phase induces instabilities. A surface describing viscosity in a 3D diagram (strain rate-amount of phase-viscosity) is constructed, that presents a cusp shape for low strain rates. The diagram depicts two types of behaviour and a critical state. At high strain, the viscosity contrast between melt and matrix is lowest. The rock behaves as a near-homogeneous body and a continuous description of its rheology may be estimated. Instabilities lead to fabric development resulting from crystals alignment. At low strain rate, three domains are separated by a critical state. When the proportion of one phase is very small, the material behaves as the other end-member. For intermediate proportions, the cusp indicates three possible viscosity values. Two are metastable, whereas the third is virtual. Hence, the viscosity of the mixture jumps back and forth from the viscosity of one phase to that of the other. A similar process occurs for temperature, since the cusp in the viscosity profile has also implications in a diagram linking temperature and stress. Different behaviours result, depending on whether the deformation takes place under a fixed content in each phase, a common stress, a common strain rate or common temperature. We list several implications for partially molten rocks that may explain fabric development, contact melting between crystals, strain localisation, mineral banding, shear heating, welding, stick-slip-like melt extraction, magma fragmentation or formation of strong or fragile glass. A phase diagram that incorporates temperature, stress and concentration is constructed for PMR that bears much similitude with those issued for other soft materials.

KEY WORDS: *rheology, two-phase material, migmatites.*

RIASSUNTO

Sviluppo di instabilità in rocce parzialmente fuse.

Le rocce parzialmente fuse (PMR) sono caratterizzate da comportamenti specifici e contrastati. Ad esempio in un corpo di migmatiti le strutture a grande e piccola scala sono orientate coerentemente con quelle delle rocce circostanti e ciò indica che le migmatiti sono state deformate come un unico insieme. Al contrario, le ubiquitarie ripartizione della distorsione e distribuzione del fuso sono diffuse nello stesso corpo migmatitico e riflettono l'elevata eterogeneità della distorsione e delle instabilità reologiche intrinseche. Una transizione continua da una reologia di tipo-liquido a una reologia di tipo-solido, così come implicitamente si assume per molti processi mediati, non può spiegare questa duplice informazione. Sviluppiamo qui un'analisi completa considerando lo sforzo e la velocità di deformazione e le relative proporzioni di fuso e fasi solide. In una PMR la temperatura varia da T_{solidus} a T_{liquidus} . Noi assumiamo anche che la transizione verso la fusione non riproduce quella alla cristallizzazione. Comunque noi preferiamo usare la viscosità anziché lo sforzo, poiché la prima è definita meglio dagli esperimenti. La viscosità della matrice che si deforma secondo una legge esponenziale manifesta un assottigliamento per taglio, mentre quella del fuso rimane costante. Il contrasto di viscosità tra le due fasi varia quindi con la velocità della distorsione. Più bassa è la velocità di distorsione, più si eleva il contrasto di viscosità, quindi lo sviluppo delle instabilità è controllato dalla reologia. Il percorso seguito durante una transizione controlla pure lo stato intermedio e può portare all'instabilità, come risultato di cause meccaniche oppure di diversa quantità relativa delle fasi. Nell'ultimo caso, la concentrazione di una delle fasi induce l'instabilità. Viene qui costruita una superficie che descrive la viscosità in un diagramma tridimensionale (velocità di distorsione-quantità della fase-viscosità) e che presenta una forma a cuspide a basse velocità di distorsione. Sul diagramma sono rappresentati due tipi di comportamento e uno stato critico. Ad alta distorsione, il contrasto di viscosità tra fuso e matrice è più basso. La roccia si comporta come un corpo quasi omogeneo e può essere approssimata una descrizione continua della sua reologia. Le instabilità portano allo sviluppo di un fabric che risulta dall'allineamento dei cristalli. A bassa velocità di distorsione, tre domini sono separati da uno stato critico. Quando la proporzione di una fase è molto piccola il materiale si comporta come l'altra fase. Per proporzioni intermedie, la cuspide indica tre possibili valori della viscosità. Due sono metastabili mentre il terzo è virtuale. Quindi, la viscosità della miscela retrocede o avanza dalla viscosità di una fase a quella dell'altra. Un simile processo si verifica per la temperatura, poiché la cuspide nel profilo di viscosità manifesta anche implicazioni in un diagramma che collega la temperatura e gli sforzi. Ne risultano differenti comportamenti, a seconda che la deformazione si sviluppi a proporzione delle fasi fissa, stesso stato di sforzi, stessa velocità di distorsione o stessa temperatura. Si propone la lista delle numerose implicazioni per le rocce parzialmente fuse che possono spiegare lo sviluppo del fabric, la fusione ai margini dei cristalli, la localizzazione della distorsione, l'alternanza di composizione mineralogica, il riscaldamento per shear, la riscaldamento dei granuli, estrazione del fuso per scivolamento e bloccaggio (stick-slip), la frammentazione del magma o la formazione di vetro resistente o fragile. Si presenta qui un diagramma di fase per PMR che incorpora temperatura, sforzo e concentrazione che possiede un grande somiglianza con quelli noti per altri materiali deboli.

TERMINI CHIAVE: *reologia, materiali bifasici, migmatiti.*

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Most materials that constitute our direct environment are composed of several phases that all behave differently when submitted to stress. Rheology and continuum mechanics are usually the field of investigation for such behaviour. However, the basic hypotheses assume that the material presents continuous, or not too contrasted, properties between phases. Thus can be the case in solid rocks, where the minerals react similarly to a bulk stress. It is no more the case when one phase is solid, or highly viscous, and when the other phase is a liquid or a gas. For instance, sand usually flows under the wind, resulting in booming dunes whereas those keep a bulk pile shape. Conversely, mud saturated with water flows and spreads. Lavas adopt a similar behaviour. When a high temperature, they flow over kilometres, without any real structural control, except those imposed by the surrounding topography. Conversely, internal structures develop that can be used to infer flow directions and internal stress pattern. Such situations are hard to describe with usual methods, and any kind of averaging from the laws governing the end-members usually fail to describe instabilities that soon develop. Those are specifically observed into partially molten rocks, here referred to as PMR.

The present paper started from field observations on migmatites and crystallizing magmas. Migmatites are rocks that were partially molten rocks before they crystallized in their actual state (MENHERT, 1968; ASHWORTH, 1985). In contrast, fabrics in magma record the shear flow of the melt during emplacement (PATERSON *et alii*, 1998). PMRs can accordingly be envisioned as two-phase materials. One phase is solid (the rock that melts or crystals in magma); it is hereafter referred to as matrix. Melt is the other phase, here, essentially referring to felsic melts, though general term of granitic melt should not be restricted to any specific composition.

We develop a description of the PMR rheology that takes into consideration.

- 1) The amount of the solid phase (Φ), ranging from 0 to 1. It is similar to a volume.
- 2) The intrinsic viscosity η of each phase, intimately linked with the strain rate ($\dot{\gamma}$).
- 3) The applied stress (σ).
- 4) The temperature (T) interval between solidus and liquidus.

The choice of the viscosity is for convenience, because it is better constrained by experiments than stress or strain rate. In consequence, after selection of stress as the intrinsic variable, a full description could be represented into a 3D diagram with coordinates stress, temperature and volume.

The constraints taken into account relate to field observations. They consist in:

- 1) The changing viscosity contrast with strain rate.
- 2) The non-linear aspect of melting rate.
- 3) The different evolution of viscosity with temperature for melt and matrix
- 4) The difference between melting and crystallization.
- 5) The bulk motion «en bloc» at the scale of a magmatic body and the small-scale heterogeneous motion with instabilities.

The present paper combines information about parameters identified in previous studies with important review papers about silicate melts (MYSEN &

RICHER, 2005), granite rheology (PETFORD, 2003), pastes (COUSSOT, 2007), polymers (DE GENNES, 1979), foam (KRAYNIK, 1979), dense suspensions (STICKEL & POWEL, 2005), analogue deformation (ROSENBERG, 2001), friction (PERSSON, 2000), granular flow (JAEGER *et alii*, 1996) and wet granular flow (MITARAI & NORI, 2006). Previously, we focused on identifying:

- 1) The evidence of two thresholds during melting and crystallization (VIGNERESSE *et alii*, 1996).
- 2) The non-duality between melting and crystallization (VIGNERESSE *et alii*, 1996).
- 3) The importance of strain partitioning between phases (VIGNERESSE & TIKOFF, 1999).
- 4) The non-linear behaviour of the melting rate and melt distribution (BURG & VIGNERESSE, 2002).
- 5) The rheological contrast between melt and matrix (BURG & VIGNERESSE, 2002).
- 6) The presentation and solution of a double system of equations for melt extraction (RABINOWICZ & VIGNERESSE, 2005).
- 7) The necessity of including pure and simple shear for melt extraction (RABINOWICZ & VIGNERESSE, 2004; VIGNERESSE & BURG, 2005).
- 8) The discontinuous melt extraction rate (VIGNERESSE & BURG, 2005, RABINOWICZ & VIGNERESSE, 2004).
- 9) The cusped shape of the viscosity as a function of strain rate (VIGNERESSE & BURG, 2004).
- 10) The discontinuities the cusp shape induces on a stress-phase diagram (VIGNERESSE *et alii*, 2007).
- 11) The role of nonlinear melting in the melt production, i.e. on the phase proportion (VIGNERESSE *et alii*, 2007).
- 12) The importance of mapping those parameters for identifying instabilities development (VIGNERESSE *et alii*, 2007).

RHEOLOGY OF THE TWO END-MEMBERS OF A PMR

Rheology commonly describes the relation between shear stress (σ) and shear strain (γ), whereas time dependent effects imply a strain rate ($\dot{\gamma}$) response to stress. We use a shear strain rather than a plane strain (ϵ) since most magmatic flows develop under shear.

Melt and its matrix are the two end-members of the system. The melt behaves as a Newtonian body for moderate to low strain rates. A constant viscosity relates linearly strain rate to stress. Within the temperature range of melting (650-900°C), calc-alkaline granitic melts present viscosity value around 10^6 Pa.s (CLEMENS & PETFORD, 1999). It exponentially decreases with temperature, in function of the activation energy E, with a typical value about 300 kJ/mole (MAALØE, 1985). Around 800°C, viscosity decreases by 2.5-3.0 orders of magnitude for an increase of 100°C.

In contrast, crustal rocks brought at the same temperature range (650-900°C) deform in a ductile manner. We adopt the case of dislocation creep of a single crystal, with a power law exponent of 3 (NICOLAS & POIRIER, 1976). Experimentally obtained values for amphibolites, with values $\log A = -4.9$ and $Q = 243$ kJ/mole (KIRBY & KRONENBERG, 1987), are used as a proxy for the restitic matrix of PMR, yielding a melt of granitic composition. The effective viscosity is estimated from the local tangent to the stress-strain rate curve.

Under those assumptions, the preceding numerical values provides the equations for the melt

$$\log \eta = 6 \quad (1)$$

and for the matrix

$$\log \eta = 10.66 - 2/3 \log \gamma^\circ \quad (2)$$

The rheology of mixed melt and matrix (PMR) cannot be simply defined as the combination of those two end-members, depending on their relative proportion (fig. 1). During crystallisation, the solid particles interact with each other, leading to the Einstein-Roscoe law (EINSTEIN, 1906; ROSCOE, 1952; ARZI, 1978):

$$\eta = \eta_0 (1 - \Phi/\Phi_{\max})^{-ne} \quad (3)$$

in which η_0 is the initial melt viscosity, Φ_{\max} is the maximum packing assemblage, and ne an experimentally determined coefficient (LEJEUNE & RICHET, 1995). It has been experimentally validated up to 0.40 of solid phase, less than maximum packing, about 0.75 (ROGERS *et alii*, 1994). Particle interactions become important at higher concentrations, changing the exponent into $-ne \cdot \Phi_{\max}$. This reduces the exponent value from 2.5 to about 1.8 (KRIEGER & DOUGHERTY, 1959). However, the viscosity increases by 4 to 5 orders of magnitude near maximum packing. Indeed, the mixture becomes thixotropic (BARNES, 1997) with departures from non-linearity in case of crystallization and pseudo-plastic in case of melting. Nevertheless, the viscosity contrast between melt and matrix ranges from 10 to 14 orders of magnitude (BURG & VIGNERESSE, 2002) when restricting the stress values in between 0.1 and 100 MPa.

PMR SPECIFICITIES

A PMR combines three possibilities to develop instabilities. One is mechanical or rheological, owing to the large viscosity contrast between melt and matrix. The second is driven by the respective amount of each phase. The third is chemical and relates to temperature, especially during the interval between melting and crystallization. A 3D diagram combining stress, temperature and the volume of one phase is suggested that would provide a complete mapping of the complex PMR rheology.

However, before constructing this diagram, one should take into account the specific points that characterize PMR rheology. Those are the existence of two thresholds during the transition between the end-members (VIGNERESSE *et alii*, 1996), strain partitioning (VIGNERESSE & TIKOFF, 1999) and feedback loops that develop due to nonlinear processes (BURG & VIGNERESSE, 2002). The link between the rheology of a strong matrix and that of a concentrated suspension, drawn from Einstein-Roscoe equation (RENNER *et alii*, 2000; ROSENBERG, 2001) is seriously questioned since it does not allow any instability to develop (BURG & VIGNERESSE, 2002).

The range of threshold values for melting and crystallization overlaps. Thus, a definite rheology cannot be ascertained in that domain, that sees overlapping of two behaviours, each being related to one end-member.

In addition, this domain, with two metastable states varies in size depending on the strain rate or stress acting on the system. Instabilities develop during melting or crystallization, when the slope of the flow curve relating

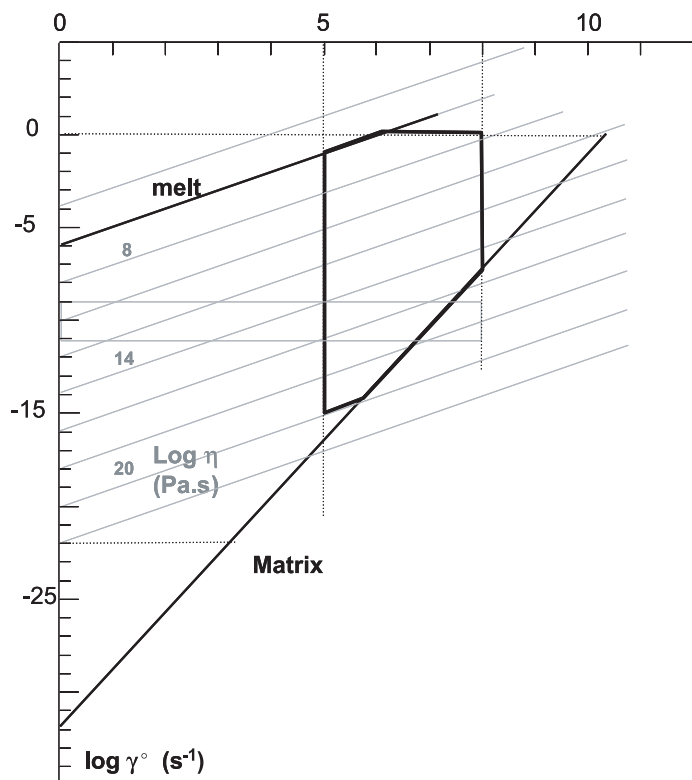


Fig. 1 - Log-log stress-strain rate diagram showing the behaviour of the melt and its matrix. Viscosity values are indicated in grey.

- Diagramma bilogarithmico sforzi-velocità di ditorione, che mostra il comportamento del fuso e della sua matrice. I valori di viscosità sono indicati in grigio.

the transition from one phase to the other has become negative (SPENLEY *et alii*, 1993). In case of a system under common stress, fluid decomposes into a layered structure, with alternate layers of high and low strain rate. Conversely, in case of deformation under common stress, shear localisation develops (fig. 2).

The bulk rheology of a PMR should be examined in a 3D ($\sigma - \gamma^\circ - \Phi$) diagram. However, the pair $\sigma - \gamma^\circ$ is poorly determined from experiments, that often develop under constant and fast strain rate. Hence, they are limited by the total duration of the experiments. We prefer adopting a 3D ($\eta - \gamma^\circ - \Phi$) diagram because the pair $\eta - \gamma^\circ$ is experimentally constrained.

We start with the state equations for the melt and its matrix (Eqs. 1 and 2). Owing to large variations in viscosity, the strain rate response to stress plots in a log-log diagram. A line with constant slope represents the melt, whereas another line represents the matrix. In between, the Einstein-Roscoe curve is not strain rate dependent. The two surfaces constructed from the two end-members overlap over a wide range of Φ (0.50 to 0.75). The connection between the two end-members takes the form of a cusp surface in the ($\eta - \gamma^\circ - \Phi$) diagram.

Temperature has a differential effect on the viscosity of melt and matrix, resulting from the activation energy values for those phases. They respectively plot as two lines with different slope on a semi-log diagram as a function of temperature. The viscosity for the transitional state must be computed for fixed values of strain rate from the 3D diagram ($\eta - \gamma^\circ - \Phi$).

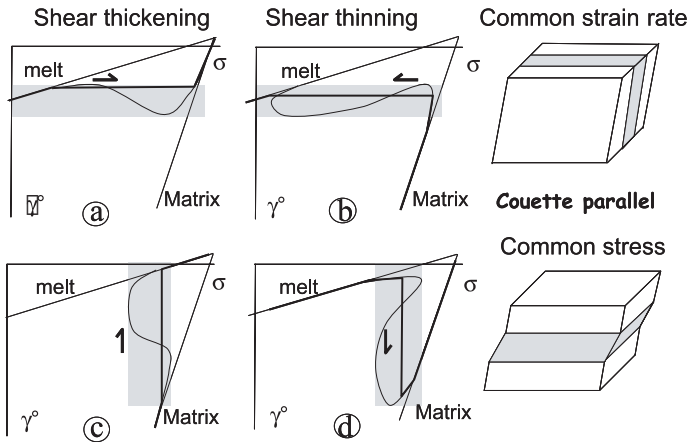


Fig. 2 - Instability occurrence depending on whether the path occurs under a common strain rate (a) and (b), leading to banding, or under a common stress (c) and (d), leading to strain partitioning.
 - Dipendenza dell'instabilità dall'instaurarsi del percorso in condizioni di velocità di distorsione comune (a) e (b), che genera un'alternanza di composizione, oppure in condizioni di stress comune (c) e (d) che genera ripartizione della distorsione.

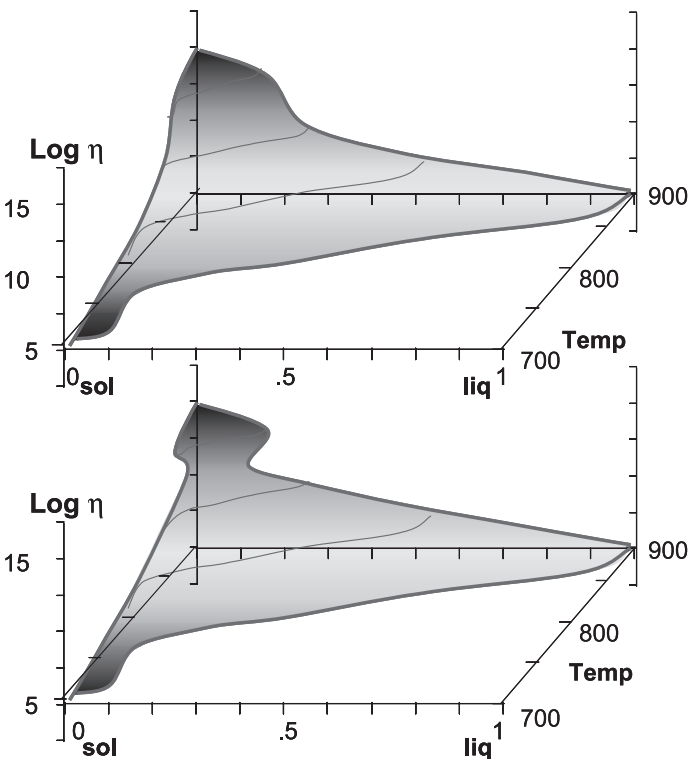


Fig. 3 - 3D diagram showing the occurrence of a cusp in the PMR rheology surface, as a function of decreasing viscosity and temperature.
 - Diagramma tridimensionale che mostra la comparsa di una cuspidè sulla superficie della reologia PMR in funzione della viscosità decrescente e della temperatura.

Under high strain situation, the transition from the solid to the weak phase is monotonous, giving place to a smooth viscosity variation. In contrast, the low strain rate case has to take into account the cusp that develops in the $(\eta - \Phi)$ diagram. Cusp occurs in between 30 and 60% of the solid phase. The transition in viscosity also adopts a

cuspidè shape within this range of temperature. Instabilities may develop depending on the followed path, i.e. constant stress or constant temperature, identically to the instabilities with strain rate.

All parameters are now settled to build a phase diagram that would determine the limits of PMR rheology, in function of the phase amount, viscosity and temperature. The strain rate should be introduced to determine the respective occurrence of instabilities. The basic ingredients to construct a 3D diagram $(\Phi - \eta - T)$ are the preceding diagrams (fig. 3). For a better readability, we use $\phi = 1 - \Phi$, the amount of liquid phase, and because it is better constrained, we use the viscosity instead of stress.

The three axes $(\phi - \eta - T)$ determine the range of occurrence of PMR. Whereas the amount of melt ranges from 0 to 1, the temperature ranges from T_{solidus} to T_{liquidus} , and the viscosity, which is plotted in a log scale ranges from the viscosity of the melt at T_{liquidus} to the value for the matrix at T_{solidus} . The resulting diagram adopts the shape of a quarter of quasi-cylindrical body, the concavity of which faces the origin. This shape results from the two limiting values in temperature and phase amount, whilst the concave pattern results from the melting curve. In case of cusp development, the quasi-cylindrical body also presents a cusped surface, toward the origin.

Such mapping is useful as much as it can prompt the design for new experiments through predicting the behaviour of a studied system. A first attempt has been to classify the instabilities in a two-phase material according to the shape of the flow curve. It corresponds to considering the concentration, spinodal decomposition, or strain rate, i.e. essentially adopting a mechanical, point of view (OLMSTED & LU, 1999).

GEOLOGICAL IMPLICATIONS

MAGMA EMPLACEMENT AND STRUCTURES

During felsic body emplacement, the strain rate is commonly higher than 10^{-12} s^{-1} , implying a stress level over 10 MPa (HARRIS *et alii*, 2000; VIGNERESSE, 2005; HAWKESWORTH *et alii*, 2004). The viscosity contrast between melt and matrix is the lowest, thus relaxation times for both phases have similar amplitude. The bulk material responds as a single-phase body with a bulk viscosity. Two situations can be observed that relate the strain rate and the ability of PMR to flow. Migmatitic bodies present the same structural trends as surrounding rocks (NZENTI *et alii*, 1988) documenting «en masse» deformation of the PMR massif.

Decreasing the strain rate implies increasing the viscosity contrast between melt and matrix. In a PMR, the rotation of the first formed crystals results in a fabric (BOUCHEZ, 1997; ARBARET *et alii*, 2000). When crystals interactions develop, it can lead to particle segregation, controlled by the concentration, as it has been described as Bagnold segregation (BAGNOLD, 1954). Conversely, when the strain rate locally exceeds the ability of a PMR to deform viscously, then it breaks into fragments like during brittle deformation (PAPALE, 1999), as observed during volcanic eruptions. Experiments on brittle fragmentation of magmatic melts suggest strain rates ranging from 50 to 150 s^{-1} (BÜTTNER *et alii*, 2006).

Mineral banding is one way to accommodate velocity continuity between phases, as described in flowing liquid crystals (BONN *et alii*, 1998). It manifests in PMR through schlieren and melt-rich segregation (CLARKE & CLARKE, 1998; WEINBERG *et alii*, 2001; CLARKE *et alii*, 2002). In this case, it manifests through crystal sorting by size or by composition. In obsidian, it also takes the form of alternating bands of different colour some tens of microns to decimeters in width (SWANSON *et alii*, 1989; SMITH, 2002). The occurrence of shear bands due to strain localisation in plastic material results from deformation concentration on planes. In PMR, the different viscosity between the two phases leads to strain partitioning (VIGNERESSE & TIKOFF, 1999). The discrete distribution of localised shear zones with only a few cm in width profoundly differs from the usual observation that ductile rocks should present diffuse deformation. In crystallizing magma, strain localisation develops within a non-yet consolidated framework of touching crystals, leading to formation of dilatant proto-faults (GUINEBERTEAU *et alii*, 1989; PONS *et alii*, 1995; SMITH, 2000).

MELT SEGREGATION

Melt segregation at incipient melting results when both pure and shear stress apply on a PMR (RABINOWICZ & VIGNERESSE, 2004). A compaction length describes the resulting space and time discontinuities. Melt-rich bands form at low angles (within 20°C) when observed on analogue material (ROSENBERG & HANDY, 2000; BARRAUD *et alii*, 2004) and natural samples (KATZ *et alii*, 2006). They occur both during partial melting (MARCHILDON & BROWN, 2002) and crystallization (GOURLAY & DAHLE, 2007). Instabilities in time result in cyclic periods of segregation, driven by the amount of melt (RABINOWICZ & VIGNERESSE, 2004; VIGNERESSE & BURG, 2005).

Grain boundaries wetting by incipient melt is due to progressive depinning of the melt along the boundary surface, bearing relation to stick-slip motion observed during friction. Sliding motion is discontinuous and depends on the differential velocity between the two surfaces in contact leading to stick-slip motion (SCHOLZ, 1990; THOMPSON & ROBBINS, 1990). It results from a competition between nucleation and growth rate of the pinning zones on one hand and the sliding velocity on the other hand. Indeed, stick-slip vanishes as the velocity overcomes a critical value, just because pinning has no more chance to develop.

At the end of crystallisation, the high proportion of the solid phase drastically reduces the melt mobility, isolating small-scale closed systems. The strain rate variation within the solid phase is analogue to pressure dissolution, resulting in important stress gradient between touching crystals. The gradient relaxes by dissolving one crystal to the benefit of another one (GRINFELD, 1993), leading to crystal impingement (MEANS & PARK, 1994; PARK & MEANS, 1996) in analogue experiments or in natural examples described in a crystallizing gabbro (NICOLAS & ILDEFONSE, 1996; ROSENBERG, 2001). At a larger scale, similar observations have been realised in metamorphic aureoles induced by granitic intrusions (MARCHILDON & BROWN, 2002).

Sintering and high-pressure aggregation of particles into a solid bloc is observed in tuff welding (GRUNDER & RUSSELL, 2005). Competition between compaction and

viscous flow results in sintering, adhesion of molten fragments and deformation of glassy clasts (SMITH, 1960). Superplasticity is been widely observed as related either to micrograin or microstructural behaviour. It is interpreted as a transition between creep at low stresses and plastic flow near the yield stress. Viscous heating may lead to tachylites or pseudo-tachylites formation (SPRAY, 1995).

Dilatancy is a volume expansion in response to an applied stress, also synonymous with shear thickening, induced by the increasing viscosity of the crystallising magma. Nevertheless some dilatant veins also show internal brecciation (SMITH, 1996) indicating that still present melt overcame the brittle/ductile transition. Dilatant regions are a sink for the residual melt in a flowing magma has been widely recognised by a more abundant glassy material (SMITH, 2000).

MEMORY EFFECTS

Most of the instabilities above described present hysteresis, i.e. memory effect. It means that the transition from one state to the other is not dual to the reverse transition in terms of energy balance. Hysteresis is commonly described for induced magnetization (BERTOTTI, 1998), but also for plastic deformation (PRANDTL, 1928). Indeed, a plastic body retains some strain (BRIDGMAN, 1950) when stress returns to its initial state. It profoundly contrasts with elastic deformation during which the strained body returns to its initial state when the stress is no more applied.

Hysteresis is the manifestation of stored energy. The return to initial conditions requires additional forces. This is the case for plastic deformation, or magnetism through the magnetic coercive field. In the transition to melting, the additional energy takes the form of the latent heat. During crystallisation of viscous material, there is a continuous reduction in the mobility of elements, manifested by the viscosity increase. Energy is thus continuously released between the liquidus and the solidus, corresponding to the entropy step due to latent heat when considering the temperature. The correlation between latent heat and viscosity is linear (GARAI, 2004) for materials that show a good Arrhenius behaviour. This would correspond to a well-defined heat capacity gap between the liquid and the solid state, that is, to contrasted values of entropy of structural configuration (BOTTINGA, 1994). When this is not the case, as for instance in fragile glass material, the number of intermediate structural configurations is large allowing intermediate metastable states, hence departure to Arrhenian behaviour, and non-Arrhenian viscosity (ANGELL, 1995) and consequently larger hysteretic loop. Indeed, hysteretic flow curves have been observed for non-Newtonian flows (BONN *et alii*, 1998).

The memory effect or hysteresis in PMR is observed during successive phases of heating and cooling silicate melts above their liquidus temperature (YUE, 2004). The repeated heating and cooling phase lead to a gradual transition from non-equilibrium to equilibrium states. An ordered structure is observed up to 70°C above T_{liquidus} . The conversion from multi-crystalline phases to a single phase indicates that the liquid remembers the structures previously formed (YUE, 2004). Indeed, glassmakers use

cycles of rapid heating and cooling to transform a fragile crystalline phase into a stronger one (CONRADT, 2004).

In our suggested model, hysteresis should be understood as a dissipation mechanism unable to return to its initial state without the addition of extra energy. However, repeated cycles of straining could lead to unexpected large strain, especially when the material has not the time to completely relax and return toward a state near its initial conditions. This is obviously the case when seismic waves, which are successive cycles of compression and extension, interact with a two-phase material. Nonlinear effects develop that indicate no return to initial conditions before the material is strained again. It usually leads to soil liquefaction when seismic waves propagate through saturated sediments (ISHIHARA, 1993).

The preferential reusing of a vein by new magma is also a sign of hysteresis. Tubes offer a pathway for lava to flow over large distances (PETERSON *et alii*, 1994; CALVARI & PINKERTON, 1994).

Finally, the reusing of already formed plastic shear zones is also a consequence of the memory effect. Grain reduction in a shear band or weakened material due to a former heating are potential sites to localise strain for a future deformation cycle. In that sense shear heating (SCHOLZ, 1980) could provide natural conditions for rapidly deforming magma-present material.

IMPLICATIONS FOR EXPERIMENTAL DEFORMATION

The present paper offers an explanation for the development of much instability observed in natural conditions. However, it should be better regarded as a short review on the conditions under which those instabilities are produced. It is a former guide for designing experimental or numerical studies in order to address such instabilities.

One problem with experiments performed on natural rocks of analogue materials is the duration of the experiment. It directly points to the effect of strain rate. Adopting the time scale for a one year experiment, a long time indeed when considering the stability of one experiment, implies a strain rate of at least $3.2 \cdot 10^{-8} \text{ s}^{-1}$. Each additional order of magnitude implies a factor of 10, that would result in a maximum strain rate of 10^{-10} s^{-1} obtained during a single experimentalist's life.

One possibility to overpass this difficulty would be to change the material for some analogue material, resulting in the application of more reasonable strain rate. Adopting a common value of 10^{-5} s^{-1} , which is in use in many experimental press systems, limits in turn the viscosity contrast between a two-phases material.

The idea of the paper started from a different point of view. Provided experiments are not able to address the development of instabilities in terms of viscosity, strain rate and stress, it should be possible to design some specific experiment that would be designed to address only one type of instability, depending on the temperature, viscosity and relative percentage of each phase (fig. 3).

CONCLUSIONS

Partially molten rocks (PMR) are commonly described as inhomogeneous, with a locally variable and unpre-

dictable amount of melt. They also show local heterogeneities in strain distribution, with a neat predominance of non-coaxial deformation and shear. In contrast, at a large scale, their internal structures are concordant with those of the surrounding. PMR are by evidence a place where instabilities develop. Examining the rheology of PMR, we suggest three types of instabilities, one related to mechanical reasons, as shear zone localization or stick-slip motion, one linked with the concentration of solid phase, as banding or dilatant zones and a third one linked to temperature occurs when melting rate overcomes the rate of melt extraction.

Our model of two-phase rheology presented through a 3D diagram ($\gamma^\circ - \Phi - \eta$) shows a transition between a low strain rate regime during which the transition from one phase to the other is continuous in terms of rheology. It corresponds to a bulk motion of magma as a solid body, as exemplified during magma crystallisation or when migmatitic bodies are tectonically deformed. In contrast, at low strain rate, a cusp develops within the surface that represents the effective viscosity. It is the place of successive jumps between the rheology of each phase. It is naturally also the place where instabilities develop, depending on whether they develop under common shear rate or common stress. Crystal impingement during crystallisation reflects the progressive jamming. Melt extraction is also unstable, leading to competition between discontinuous melt production and melt extraction. All those instabilities strongly depend on the path adopted to go from one rheology to the other, resulting in strain localisation or phase banding. At moderate strain rate, crystals orientate toward an equilibrium position, giving place to a fabric in the magma.

The construction of a phase diagram allows designing specific experiments for better understanding the onset of those instabilities. It is essentially controlled by the amount of phase, the available stress and the temperature.

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