

Strain rate dependent rheology of partially molten rocks

J.L. VIGNERESSE¹ & J.P. BURG²

¹CREGU, UMR CNRS 7566 G2R, BP 23, F-54501 Vandoeuvre Cedex France
jean-louis.vignerese@g2r.uhp-nancy.fr

²Geologisches Institut, ETH-Zentrum, Sonneggstrasse 5, CH-8006 Zurich, Switzerland
jpb@erdw.ethz.ch

ABSTRACT

Coupling or decoupling in the lithosphere is often related to the absence or the presence of a layer of partially molten rocks, although the rheology of such rocks remains unsolved. Theoretical arguments correlated with structural observations provide new insights on the rheology of partially molten rocks, namely migmatites and magma. These rocks are simplified to two-phase pseudofluids constituted of a quasi-solid matrix and a variable amount of melt. Previous experiments indicate that the matrix deforms plastically according to a power law. The melt is Newtonian and weakens at high shear strain rates. Because of the heterogeneous distribution of matrix and melt phases, their rheologies cannot be averaged to obtain the rock rheology. Four behaviours are identified. i) At high stress and strain rates, the viscosity contrast between melt and matrix is lowest. Both phases can accommodate strain at a comparable rate, allowing migmatite and magma bodies to deform as quasi-solid units. ii) At low strain rates, the viscosity contrast between melt and matrix is highest. Melt deforms and relaxes much faster than the matrix. The simultaneous coexistence of a weak and a strong phase is expressed in a 3D viscosity / strain rate / melt fraction diagram, in which a cusp-shaped surface represents viscosity. The cusp graphically shows that the viscosity of partially molten rocks may jump several orders of magnitude. These jumps, leading to sudden melt segregation, are timely erratic. iii) At low strain rates, strain partitioning may lead to internal instabilities and segregation between melt and restitic phases, as observed in the leucosome/melanosome separation. iv) Cyclic processes follow hysteresis loops and trigger strain localisation.

Abridged title Rheology of a two-phase material

Keywords: rheology, migmatites, instabilities

Accepted to GSL Special Publication Vertical and Horizontal Decoupling in the Lithosphere
Grocott, J., McCaffrey, K., Taylor, G. & Tikoff, B. (Eds)

Revised version 29/09/03

Lines 569 Words 6000 Characters 32 000 Figures 6

First author's address Jean Louis Vignerese
CREGU BP 23
54501 Vandoeuvre Cedex, France
Tel 333 8368 4737 Fax 333 8368 4701
mail jean-louis.vignerese@g2r.uhp-nancy.fr

INTRODUCTION

Vertical or horizontal decoupling in the lithosphere supposes an interface whose rheology restricts stress transmission. This may occur along a discontinuity, as a fault in the brittle crust, or weak shear zones in the ductile crust. Weakness is commonly attributed to a compositional change including soft minerals (Jordan, 1987), or the onset of melting, the molten rocks providing the decoupling interface (Dewey, 1988; Block & Royden, 1990; see recent review by Vanderhaeghe & Teyssier, 2001). At a smaller scale, coupling and decoupling are coeval in migmatites, which were partially molten crustal rocks (Mehnert, 1968; Ashworth, 1985; Brown, 1994). The presence of melt induces strain partitioning and decoupling between the melt and its matrix (Vigneresse & Tikoff, 1999). In contrast, large-scale structures of a migmatite body are concordant with those of the surrounding rocks, manifesting some kind of coupling.

The rheology of Partially Molten Rocks (PMR) has been approached from a theoretical point of view, importing into earth sciences observations and experiments from other disciplines such as soil sciences, food engineering, polymer rheology and chemical engineering. Crystallising magma consists of solid crystals suspended in a fluid melt. Migmatites also; they both can rheologically be considered as two-phase materials at the time of crystallisation and melting, respectively.

The present paper identifies rheological behaviours and physical effects to be taken into account for investigating magma segregation and extraction. We first review results concerning the rheology of two-phase materials. PMR are considered to be viscous, with viscosity values rapidly changing from that of the strong to that of the weak phase (Arzi, 1978; Barboza & Bergantz, 1998; Renner *et al.*, 2000). With such considerations, melting and crystallisation present symmetrical rheological properties, which is not supported by microstructural observation (Vigneresse *et al.*, 1996; Rosenberg, 2001). To explore the many aspects of PMR rheology, we extend a previous model that included non-linear interactions between melting, strain partitioning and rheology (Burg & Vigneresse, 2002) and obtain catastrophic events and memory effects due to hysteretic behaviour of PMR.

We first present the intrinsic rheological responses of each phase. We then briefly discuss the limits of averaging formulation. We attempt to reach a global formulation, which is highly strain rate dependent. The ensuing metastable states describe local instabilities. We finally discuss geological implications but point out that these findings are only in a preliminary, mostly conceptual stage.

RHEOLOGY OF TWO-PHASE MATERIALS

Basic Rheological laws

Rheology is the science of deformation and flow (e.g. Adler *et al.*, 1990). In elastic materials, strain disappears as stress is removed. In viscous materials the strain rate ($\dot{\epsilon}$) depends in a complex manner on the applied stress (σ). In a Newtonian fluid, the relationship between shear stress and shear strain rate is linear. Linearity is a constant viscosity (η):

$$\dot{\epsilon} = \sigma / \eta \quad (1)$$

Very high temperature rocks produce magma that behaves as a low viscosity (10^4 to 10^{10} Pa.s) Newtonian body (Shaw, 1972; Holtz *et al.*, 1996; Clemens & Petford, 1999).

The strain rate of rocks deforming by creep is related to stress σ according to a power law:

$$\dot{\epsilon} = A \sigma^n \exp(-Q/RT) \quad (2)$$

in which A is a grain size sensitive constant, Q is the activation energy and n the coefficient of the power law, which are experimentally determined. R is the perfect gas constant and T the absolute temperature. In most rocks, the power coefficient (n) is close to 3 (Kirby & Kronenberg, 1987).

In PMR, a weak (the melt) and a strong phase (the matrix) simultaneously coexist. The solid matrix deforms plastically following a flow law close to equation 2. In contrast, the melt is Newtonian at low shear rate (Spera *et al.*, 1988; Kohlstedt *et al.*, 2000) and shows shear weakening when $\dot{\epsilon} > 10^{-4.5} \text{ s}^{-1}$ (Webb & Dingwell, 1990; Dingwell *et al.*, 1996). In our model, the maximum strain rate is set to 1 s^{-1} , equivalent to seismic strain, an estimated upper bound for strain rate values (Scholz, 1990; Reimold, 1995). In all cases, strain concentrates into the melt (Vigneresse & Tikoff, 1999). Complex non-linear interactions occur, inducing feedback loops between melt production, strain response, and material rheology and instabilities are function of the melt fraction (Burg & Vigneresse, 2002). In order to investigate in more details the rheology of melt + matrix systems, we map the stress / strain rate field in which PMR plot.

Equations 1 and 2 are better formulated in logarithmic coordinates, thus allowing direct comparison of the two laws:

$$\log \dot{\epsilon} = \log \sigma - \log \eta \quad \text{for the melt} \quad (3)$$

and

$$\log \dot{\epsilon} = n \log \sigma + C(T) \quad \text{for the matrix} \quad (4)$$

In this formulation, $\log \eta = 7$ would refer to the 10^7 Pa.s, the Newtonian viscosity of a granitic melt (Spera *et al.*, 1988; Clemens & Petford 1999). The $C(T)$ member in equation (4) includes the coefficient A of Eq. (2) and a temperature-dependent term that includes the activation energy Q . We use experimental data with $\log A = -4.89$, and $Q = 243$ kJ/mole (Wilks & Carter, 1990). We take 800 °C, the approximate temperature for starting dehydration melting of biotite (Patiño Douce *et al.*, 1995). $C(T)$ is then set to a constant value $= -32$. In the range of strain rates $10^{-4.5} < \dot{\epsilon} < 10^0$ s⁻¹, we let viscosity decrease with strain rate (Dingwell *et al.*, 1996). In that range of strain rates, a power law in which $n = 2$ best matches experimental data. Those adopted values must be considered as average assessments. Departures due to changes in the melt composition or in temperature (± 100 °C), do not strongly change the parameters. They vary by about ± 1 logarithmic unit in viscosity, a factor of ten. In all cases it does not alter the shape of the stress / strain rate diagram (Fig. 1).

In figure 1, the melt and the matrix curves intersect at a point of coordinates (12.5, 5.5) if no shear weakening occurs. With shear weakening, the point is located at (15, 12). Both intersections occur at stress and strain rate magnitudes out of significance in geological conditions. However intersection means that for corresponding parameters, the viscosity of the matrix is similar to that of the melt. Bracketing geological stress between 0.1 and 100 MPa (5 to 8 in log coordinates), the two lines do not coincide and delimit an irregular pentagon, which is the area that contains the rheology of natural PMR in a log-log diagram. In Cartesian coordinates, this area turns into a triangle because the strain rate remains very low ($10^{-17} - 10^0$ s⁻¹) compared to the stress range ($10^5 - 10^8$ Pa). Within this triangle, the couple $(\sigma, \dot{\epsilon})$ varies non-linearly with the melt content. Hence, we must now investigate effects of the melt proportion.

Rheology of a two-phase pseudofluid

The rheology of PMR implies introducing the proportion of solid phase, i.e. the solid fraction (Φ) relative to melt. Φ ranges from 0 in the fluid-like case to 1 in the solid-like case.

The simplest formulation of a bulk rheology consists in estimating either the average strain rate or the average stress that simultaneously applies to both phases. They form the extreme ideal formulation of a mixture. Owing to the large viscosity contrast, averaging is not particularly useful for PMR.

The arithmetic and geometric averaging equations are the simplest formulations (Guéguen & Palciauskas, 1992). A system composed of two materials with viscosity η_1 and η_2 has an arithmetic (or Voigt) mean viscosity η_a :

$$\eta_a = \Phi \eta_1 + (1 - \Phi) \eta_2 \quad (5)$$

and a geometric (or Reuss) mean viscosity η_g ,

$$1/\eta_g = \Phi / \eta_1 + (1 - \Phi) / \eta_2 \quad (6)$$

Adopting Eq. 5 or Eq. 6 is not trivial and has implications on the theoretical behaviour of each phase because both descriptions correspond to specific boundary conditions. The arithmetic description corresponds to the same strain rate applied to both phases. In an elasto-viscous PMR, the arithmetic mean viscosity cannot fit the fluid response if the elastic component is significant. It should be selected for a solid-like behaviour in which small deformations are damped. This is the case in a crystallising magma. Conversely, the geometric formulation supposes that the same stress applies to both phases responding as a fluid to a steady or a stationary state. The fluid-like behaviour allows accommodating large strain with partial elastic recovery. It applies to melting migmatites.

The rheological equation of a crystallising magma can thus be written:

$$\sigma_a = \Phi \sigma_1 + (1 - \Phi) \sigma_2 \quad (7)$$

which can be also written

$$\sigma_a = \Phi (\dot{\epsilon})^{1/n} \{ A \exp(Q/RT) \}^{1/n} + (1 - \Phi) \eta \dot{\epsilon} \quad (8)$$

which features the general equation of Herschel-Bulkley (Adler *et al.*, 1990).

For melting migmatites, the rheological equation is:

$$\dot{\epsilon}_g = \Phi \dot{\epsilon}_1 + (1 - \Phi) \dot{\epsilon}_2 \quad (9)$$

or

$$\dot{\epsilon}_g = \Phi A \sigma^n \exp(-Q/RT) + (1 - \Phi) \sigma/\eta \quad (10)$$

which also features the general equation for thixotropy (Adler *et al.*, 1990; Barnes, 1997).

Suffixes 1 and 2 correspond to melt and matrix, respectively. The corresponding viscosity values are plotted with respect to the solid fraction (Fig. 2). The viscosity contrast between the two phases is varied from 10^1 to 10^9 Pa.s to emphasise differences between the two averaging methods. The arithmetic mean favours the largest values of the average at the expenses of small ones. Conversely, the geometric average is damped by the small values of the average. In other words, the arithmetic average favours the strong phase, whilst the geometrical average gives much weight to the weak phase. We conclude that there is no correct way to address the problem of a heterogeneously varying phase proportion. Any model of averaging rheological properties, whether arithmetic or geometric, fails to adequately represent the rheology of PMR.

Averaging formulations involve either stress or strain rate boundary conditions that apply simultaneously to both phases. Hence, a unique formulation cannot indifferently describe melting and crystallisation that proceed from different boundary conditions. A second consequence of averaging methods is that the resulting equations for bulk flow involve that both, melt and matrix flow. The flowing material is a pseudo-fluid. This may be the case when the viscosity contrast is restricted to 1-3 orders of magnitude. In the case of PMR, the viscosity contrast is huge, up to 15 orders of magnitude, and varies with the imposed strain rate. A limit to the flow would be a Darcy flow, in which the matrix is fixed, which is obviously not a correct model for PMR. Therefore, we suggest another way to examine the rheology of a two-phase material

Rheology of a two-phase material

Representing the PMR rheology implies introducing the amount of the solid fraction as the third dimension in a diagram (σ , $\dot{\epsilon}$, Φ). The applied stress is difficult to estimate. Therefore, we prefer to display the rheology in a diagram scaled with viscosity (Fig. 3). Several considerations are prerequisite.

- 1) The PMR viscosity is constrained by experimental measurements (Lejeune & Richet, 1995; Renner *et al.*, 2000) and numerical applications (Vigneresse *et al.*, 1996; Barboza & Bergantz, 1998). They demonstrate the increase of viscosity with particle concentration, and thresholds that apply.
- 2) A 3D diagram must take into account the non-linear effects discussed earlier (Burg & Vigneresse, 2002).
- 3) The bulk melt content is unsatisfactory to define a PMR. We must consider the coexistence of two phases with contrasted rheology.
- 4) The 3D representation should also coincide with the known viscosity dependence on the solid fraction (Lejeune & Richet, 1995) and the solid-like behaviour of concentrated suspensions (Rogers *et al.*, 1994).

- 5) The model should simultaneously describe small and large-scale behaviour of PMR, which refer to the small and the large relaxation time of melt and matrix, respectively.

The irregular pentagon of Fig. 1 turns in the 3D diagram into a cusped viscosity-plane integrating the coexistence of the two phases (Fig. 3). In consequence, the strain response to stress, or viscosity determination, is not a single parameter. It strongly varies with applied stress, shear rate or solid fraction. This first-order conclusion strongly contrasts with an equivalent viscosity that would apply for a given solid fraction, independently of strain rate (Arzi, 1978).

Rheologies for low ($\Phi < 10\%$) and high ($\Phi > 60\%$) solid fractions are both easy to estimate. Such PMR behave almost as the solid and fluid end members, with non-linear modifications of the effective viscosity according to the Einstein-Roscoe model of suspensions (reviews in Adler *et al.*, 1990; Liu & Masliyah, 1996; Vigneresse *et al.*, 1996). For intermediate solid fractions (10 - 40 %), complexity due to non-linear interactions occurs (Burg & Vigneresse, 2002).

We first examine the case of low strain rates. The viscosity contrast between melt and matrix is highest (Fig. 3). The relaxation time of the melt is much shorter than for the matrix. This difference generates an instability expressed by the cusp shape of the surface representing viscosity (Fig. 3). The coexistence of the two phases over a range of percentage ($.20 < \Phi < .75$) results in a metastable state. For a given solid fraction, three viscosity values are theoretically possible. The highest and the lowest correspond to stable states and reflect the viscosity of matrix and melt, respectively. The third, intermediate one is unstable. It reflects the response of a PMR to stress and may fluctuate from the viscosity of the matrix to melt viscosity. The fluctuation is rapid, similar to catastrophes as formulated in mathematics (Zeeman, 1976; Thom, 1990; Wassermann *et al.*, 1992).

At higher strain rates, the viscosity contrast between melt and matrix is few orders of magnitude (Fig. 1). The relaxation times of both phases allow accommodation of their relative motions and there is no instability.

The difference in relaxation times between melt and matrix has a second consequence expressed by hysteresis in a stress-strain rate-solid fraction diagram (Fig. 3). The metastable state develops over $0.20 < \Phi < 0.75$, as stated above. However it also develops for a fixed percentage of one phase, but at varying strain rate values. For example at 70% of melt, and low strain rate (Fig. 3), the sequentially loaded and unloaded PMR may suffer cyclic deformation, but the strong phase has no time to completely relax. Strain adds up at each cycle, resulting in large localisation of strain in the weak phase, like it has been

experimented on water-saturated sand and clay (Bardet, 1995; 1996). In a similar way, experiments on partially saturated sediments, which have a non-linear rheology, report a drastic increase of strain amplitude while the material is submitted to low frequency stress cycling (Guyer *et al.*, 1995; Tutuncu *et al.*, 1998).

GEOLOGICAL IMPLICATIONS

The levels of stress and strain rate differ when considering the bulk behavior of a PMR or only local melt segregation. In the following, we foresee and discuss some geological implications of our model.

Bulk response of PMR to tectonic stresses (high strain rate)

PMR is of regional extent ($10^3 - 10^5$ m) and the ambient stresses are tectonic. We first address melting metatexites, which are low melt (10-20 %) migmatites. They commonly form under 400 – 800 MPa and 750 – 800°C (Brown, 1994). Metamorphic pressures correspond to the 10 - 25 km depth of the brittle/ductile transition where fracturing occurs at 0.8 to 4 times the vertical load (Byerlee, 1978): 100 – 400 MPa at 10 – 12 km depth, depending on whether tectonics are extensive or compressive. Accordingly, we may assume an ambient differential stress of about 10^8 Pa (8 in the log-log diagram, Fig. 1). The corresponding strain rate is in a range of 1 to -3 in log scale, with viscosity of 10^7 Pa.s for the melt and 10^{10} Pa.s for the matrix. The corresponding viscosity contrast is 10^3 (Fig. 4).

The response to ambient tectonic stress is thus mostly the solid-state behavior of the matrix. One may thus expect to observe structures that are similar to those of the surrounding non-molten rocks (Nzenti *et al.*, 1988; Brun & Balé, 1990).

High tectonic stresses may impose correspondingly high strain rates to a granitic body with 40 – 50 % crystals. Although the magma is still rich in melt, it may react as a solid, up to fracturing (Dingwell, 1997). At moderate strain rate, plastic deformation locally re-orientates the crystalline fabrics, inducing proto-faults as described in the Mono Creek massif (Saint Blanquat *et al.*, 1998).

The bulk reaction of a two-phase system to high stress level is common in geology. At very fast strain rates, as during earthquakes, saturated sediments that are ordinary very soft and without cohesion, behave en masse during soil liquefaction (Ishihara, 1993).

Bulk response of PMR to low strain rates

PMR has similar regional extent than previously ($10^3 - 10^5$ m), but the deformation rate of 10^{-16} s⁻¹ is below the usual strain rates in geology (Pfiffner & Ramsay, 1982). This situation applies to the lower continental crust, in which some weakness may form, either from grain size reduction, leading to strain localisation, or partial melting that may induce

magmatism. Such situations are inferred in lower crustal sections presently brought at the surface as in Kohistan (Arbaret *et al.*, 2000), or deduced from geophysical studies as under the Andes (Schilling *et al.*, 1997), the Pyrenees (Partzsch *et al.*, 2000) and the Tibetan Plateau (Hauck *et al.*, 199). The amount of weak phase does not need to be high. Estimates of 4 % melting are provided in the Pyrenees and the Tibetan Plateau (Partzsch *et al.*, 2000). Nevertheless, connection of any melt is assumed from electrical conductivity, which suffices for strain partitioning. In such cases, decoupling can be assumed to develop at very low strain rate.

Melt segregation at outcrop scale

At the mesoscopic scale (1–10 m), low stress is added to the background field and results from local readjustments after en masse motion of melt and matrix. The large viscosity contrast between melt (10^7 Pa.s) and matrix (10^{13} Pa.s) impels a large strain rate contrast. Strain partitions into the melt and relaxes much faster than in the surrounding matrix. In consequence, the rheological contrast between melt and matrix accentuates at low strain rate, leading to instability, whatever the melt percentage.

If stress cycles occur while melt and matrix deform with the same strain rate, sudden jumps between the liquid-like and solid-like rheology, or vice versa, correspond to sudden expulsion of the melt. The low relaxation rate of the matrix makes the periods of melt segregation irregular and discontinuous in time. Irregular bursts of melt segregation have been obtained in numerical (Vigneresse & Burg, 2000; Rabinowicz *et al.*, 2001) and analogue (Rosenberg & Handy, 2000; Barraud *et al.*, 2001) modelling.

Conversely, deformation involving the same stress on melt and matrix leads to strain localisation (Fig. 6). Repeated loading and unloading increases and amplifies strain localisation, resulting in thin shear bands in which a small amount of melt may have focused deformation. With further deformation, the weaker shear bands may be reactivated, showing very large finite strain (see photos in Crawford *et al.*, 1998).

Melt segregation within a vein

At smaller scale (10^{-2} – 1 m), strain partitioning and strain rate are high in the melt because its relaxation time is short. We do not wish to enter the controversy about the actual proportion of molten and restitic phases and the effects of back-reactions changing this proportion (Kriegsman, 2001). We simply assume that the flowing melt is a suspension of crystals in a fluid.

In suspensions, the velocity gradient and strain partitioning produce a plug-like concentration of solid particles in the center of a channeled flow, known as the Bagnold effect (Bagnold, 1954; Komar, 1976). It is common in dykes and in crystal-rich lava flows

(Correa-Gomes et al., 2001). In contrast, a concentration of restitic minerals (melanosome) on both sides of channeled melt (leucosome) is commonly described in migmatites. The flat shape of restitic biotites is generally parallel to leucosomes and flow direction (McLellan, 1988). This orientation suggests that those minerals have passively rotated and side-melanosomes seem to correspond to outward concentration of solid particles, more or less symmetric with respect to the central flow plane.

Segregation towards the borders of the flow, as suggested by melanosome-bounded leucosomes in migmatites thus differs from solid phase segregation in dykes. It is due to both strain partitioning and chemical effects (Olmsted, 1999; Tanaka, 2000). Strain partitioning concentrates each phase along the flow direction and perpendicular to vorticity (Fig. 6). Exchange of elements between biotite and microcline (Olsen, 1977) added to the mechanical effect could explain why biotites concentrate along each side of the leucosome, with their flat face aligned parallel to the flow direction (McLellan, 1983). The concentration of restitic minerals on both sides of the leucosome would therefore be a consequence of instability under a common strain rate.

Viscosity determination PMR

A direct consequence of time or strain rate dependent rheology is the non-unique determination of an equivalent viscosity for a PMR, given its proportion of melt. More generally, a two-phase material cannot be represented by one single equivalent viscosity.

Extending the discussion a step further would be to link the viscosity determination to an underlying mechanism. Power-law rheology classically corresponds to dislocation creep (Kirby & Kronenberg, 1987). Diffusion creep corresponds to Newtonian flow. However, recent experiments show that a transition from dislocation creep to diffusion creep may develop when a small fraction of melt is added to an aggregate of solid grains (Kohlstedt *et al.*, 2000). A specific “granular flow” has been coined for this situation (Paterson, 2001). It manifests by a prompt switch from power law ($n = 3$) to linear ($n = 1$) rheology (Kohlstedt *et al.*, 2000), which is the situation our model describes.

CONCLUSIONS

We imported models from other disciplines to approach the rheology of partially molten rocks (melting migmatites and crystallising magmas). We point out that PMR is a material in which it is impossible to assign a given phase proportion at any point. Therefore, average laws fail to correctly represent PMR rheology. To alleviate the problem, we first mapped the PMR rheology within a stress-strain rate diagram in which we could incorporate the phase content. Results show hysteresis and catastrophic jumps of viscosity due to the

coexistence of a solid and a fluid phase. Several responses may develop, depending on whether the system responds under high or low strain rate or stress level.

We infer that a migmatite body and plutons deform as solid-like mechanical units under high tectonic stress level. At a smaller scale, and under low stress level, instabilities develop under steady strain rate or quasi-constant stress and produce strain localisation. Since instabilities involve hysteresis, cycling loading and unloading may lead to large strain concentrated in small regions. If the same strain rate is imposed on fluid and solid phases, melt segregation and increased vorticity cause veins transecting layering and flow-induced mineral separation such as restitic minerals aside leucosomes.

Acknowledgements. This paper resulted from numerous and enriching discussions with many colleagues. It also came out from several discussion meeting at Zurich, for which Cregu founding is acknowledged. C. Rosenberg and F. Spera provided quite thoughtful comments.

References

- ADLER, P., NADIM, A. & BRENNER, H., 1990. Rheological models of suspensions. *Advances in Chemical Engineering* **15**, 1-67.
- ARBARET, L., BURG, J.P., ZEILINGER, G., CHAUDHRY, N., HUSSAIN, S. & DAWWOD, H., 2000. Pre-collisional anastomosing shear zones in the Kohistan arc, NW Pakistan. In: KAHN, M.A., TRELOAR, P.J., SEARLE, M.P. & JAN, M.Q. (Eds), *Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya*. Geological Society of London, Special Publication **170**, 295-311.
- ARZI, A.A., 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics* **44**, 173-184.
- ASHWORTH, J.R., 1985. *Migmatites*. Blackie & Sons, Glasgow, 302 p.
- BAGNOLD, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Royal Society of London Proceedings* **A225**, 49-63.
- BARBOZA, S.A. & BERGANTZ, G.W., 1998. Rheological transitions and the progress of melting of crustal rocks. *Earth and Planetary Science Letters* **158**, 19-29.
- BARDET, J.P., 1995. Scaled memory model for undrained behavior of anisotropic clays. *Journal of Geotechnical Engineering* **121**, 755-765.
- BARDET, J.P., 1996. Scaled memory description of hysteretic material behavior. *Journal of Applied Mechanics* **63**, 750-757.
- BARNES, H.A., 1997. Thixotropy – A review. *Journal of Non Newtonian Fluid Mechanics* **70**, 1-33.
- BARRAUD, J., GARDIEN, V., ALLEMAND, P. & GRANDJEAN, P., 2001. Analog modelling of melt segregation and migration during deformation. *Physics and Chemistry of the Earth* **A26**, 317-323.
- BLOCK, L. & ROYDEN, L.H., 1990. Core complex geometries and regional scale flow in the lower crust. *Tectonics* **9**, 557-567.
- BROWN, M., 1994. The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. *Earth Science Reviews* **36**, 83-130.
- BRUN, J.P. & BALE, P., 1990. Cadomian tectonics in northern Brittany. In: D'LEMONS, R.S., STRACHAN, R.A. & TOPLEY, C.G. (eds). *The Cadomian orogeny*. Geological Society Special Publication **51**, 95-114.
- BURG, J.P. & VIGNERESSE, J.L., 2002. Non-linear feedback loops in the rheology of cooling-crystallising felsic magma and heating-melting felsic rock. In: Drury, M., de Meer, S., Bresser de, J.H., Pennock, G., (Eds), *Deformation Mechanisms, Rheology and Tectonics* : Geological Society of London Special Publication (in press).
- BYERLEE, J.D., 1978. Friction of rocks. *Pure and Applied Geophysics* **116**, 615-626.
- CLEMENS, J.D. & PETFORD, N., 1999. Granitic melt viscosity and silicic magma dynamics in contrasting tectonic settings. *Journal of the Geological Society of London* **156**, 1057-1060.
- CORREA-GOMES, L.C., SOUZA FIILO, C.R., MARTINS, C.J.F.N. & OLIVEIRA, E.P., 2001. Development of symmetrical and asymmetrical fabrics in sheet-like igneous bodies: the role of magma flow and

- wall-rock displacements in theoretical and natural cases. *Journal of Structural Geology* **23**, 1415-1428.
- CRAWFORD, M.L., KLEPEIS, K.A., GEHRELS, G. & ISACHSEN, C., 1998. Batholith emplacement at mid-crustal levels and its exhumation within an oblique convergent margin. *Tectonophysics* **312**, 57-78.
- DEWEY, J.F., 1988. Extensional collapse of orogens. *Tectonics* **7**, 1123-1139.
- DINGWELL, D.B., 1997. The brittle-ductile transition in high-level granitic magmas : Material constraints. *Journal of Petrology* **38**, 1635-1644.
- DINGWELL, D.B., HESS, K.U. & KNOCHÉ, R., 1996. Granite and granitic pegmatite melts: volumes and viscosities. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **87**, 65-72.
- GUEGUEN, Y. & PALCIAUSKAS, V., 1992. *Introduction à la physique des roches*. Hermann, Paris, 302p.
- GUYER, R.A., MCCALL, K.R. & BOITNOTT, G.N., 1995. Hysteresis, discrete memory, and nonlinear wave propagation in rock: A new paradigm. *Physical Review Letters* **74**, 3491-3494.
- HAUCK, M.L., NELSON, K.D., BROWN, L.D., ZHAO, W. & ROSS, A., 1998. Crustal structure of the Himalayan orogen at ~90° East longitude from INDEPTH Reflection Profiles. *Tectonics* **17**, 481-500.
- HOLTZ, F., SCAILLET, B., BEHRENS, H., SCHULZE, F. & PICHAVANT, M., 1996. Water content of felsic melts: applications to the rheological properties of granitic magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **87**, 57-64.
- ISHIHARA, K., 1993. Liquefaction and flow failure during earthquakes. *Géotechnique* **43**, 351-415.
- JORDAN, P.J., 1987. The deformation behaviour of bimineralic limestone-halite aggregates. *Tectonophysics* **135**, 185-197.
- KIRBY, S.H. & KRONENBERG, A.K., 1987. Rheology of the lithosphere: Selected topics. *Reviews of Geophysics* **25**, 1219-1244.
- KOHLSTEDT, D.L., BAI, Q., WANG, Z.C. & MAI, S., 2000. Rheology of partially molten rocks. In: BAGDASSAROV, N., LAPORTE, D. & THOMPSON, A.B. (Eds), *Physics and chemistry of partially molten rocks*. Kluwer, Dordrecht, 3-28.
- KOMAR, P.D., 1976. Phenocryst interactions and the velocity profile of magma flowing through dikes and sills. *Geological Society of America Bulletin* **87**, 1336-1342.
- KRIEGSMAN, L.M., 2001. Partial melting, partial melt extraction and partial back reaction in anatectic migmatites. *Lithos* **56**, 75-96.
- LEJEUNE, A.M. & RICHET, P., 1995. Rheology of crystal-bearing silicate melts: an experimental study of high viscosities. *Journal of Geophysical Research* **B100**, 4215-4229.
- LIU, S. & MASLIYAH, J.H., 1996. Rheology of suspensions. In: SCHRAMM, L.L. (Ed), *Suspensions Fundamentals and Applications in Petroleum Industry*. Advances in Chemical Series 251, American Chemical Society, Washington, 107-176.
- MCLELLAN, E.L., 1983. Contrasting textures in metamorphic and anatectic migmatites: an example from the Scottish Caledonides. *Journal of Metamorphic Geology* **1**, 241-262.
- MCLELLAN, E.L., 1988. Migmatite structures in the Central Gneiss Complex, Boca de Quadra, Alaska. *Journal of Metamorphic Geology* **6**, 517-542.
- MEHNERT, K.R., 1968. *Migmatites and the origin of granitic rocks*. Elsevier, Amsterdam, 393 p.

- NZENTI, J.P., BARBEY, P., MACAUDIÈRE, J. & SOBA, D., 1988. Origin and evolution of the late Precambrian high grade Yaoundé gneiss (Cameroon). *Precambrian Research* **38**, 91-109.
- OLMSTED, P.D., 1999. Two-state shear diagrams for complex fluids in shear flow. *Europhysics Letters* **48**, 339-345.
- OLSEN, S.N., 1977. Origin of the Baltimore gneiss migmatites at Piney Creek, Maryland. *Geological Society of America Bulletin* **88**, 1089-1101.
- PARTZSCH, G., SCHILLING, F.R. & ARNDT, J., 2000. The influence of partial melting on the electrical behavior of crustal rocks: Laboratory examinations, model calculations and geological interpretations. *Tectonophysics* **317**, 189-203.
- PATERSON, M.S., 2001. A granular flow theory for the deformation of partially molten rock. *Tectonophysics* **335**, 51-61
- PATIÑO DOUCE, A.E. & BEARD, J.S., 1995. Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *Journal of Petrology* **36**, 707-738.
- PIFFNER, O.A., & RAMSAY, J.G., 1982. Constraints on geologic strain rates: arguments from finite strain states of naturally deformed rocks. *Journal of Geophysical Research* **87**, 311-321.
- RABINOWICZ, M., GENTHON, P., CEULENEER, G. & HILAIRET, M., 2001. Compaction in a mantle mush with high melt concentrations and the generation of magma chambers. *Earth and Planetary Science Letters* **188**, 313-328.
- REIMOLD, W.U., 1995. Pseudotachylite in impact structures - generation by friction melting and shock brecciation?: A review and discussion. *Earth Science Reviews* **39**, 247-265.
- RENNER, J., EVANS, B. & HIRTH, G., 2000. On the rheologically critical melt fraction. *Earth and Planetary Science Letters* **181**, 585-594.
- ROGERS, C.D.F., DIJKSTRA, T.A. & SMALLEY, T.A. 1994. Particle packing from an Earth science viewpoint. *Earth-Science Reviews* **36**, 59-82.
- ROSENBERG, C.L. & HANDY, MR., 2001. Mechanisms and orientation of melt segregation paths during pure shearing of a partially molten rock analog (norcamphor-benzamide). *Journal of Structural Geology* **23**, 1917-1932.
- ROSENBERG, C.L., 2001. Deformation of partially-molten granite: A review and comparison of experimental and natural case studies. *International Journal of Earth Sciences* **90**, 60-76.
- SAINT BLANQUAT, M. DE, TIKOFF, B., TEYSSIER, C. & VIGNERESSE, J.L. 1998. Transpressional kinematics and magmatic arcs. In: HOLDSWORTH, R.E., STRACHAN, R.A. & DEWEY, J.F. (Eds), *Continental transpressional and transtensional tectonics*. Geological Society of London, Special Publication **135**, 327-340.
- SCHILLING, F.R., PARTZSCH, G., BRASSE, H. AND SCHWARZ, G., 1997. Partial melting below the magmatic arc in the central Andes deduced from geoelectromagnetic field experiments and laboratory data. *Physics of the Earth and Planetary Interiors* **103**, 17-31.
- SCHOLZ, C.H., 1990. *The mechanics of earthquakes and faulting*. Cambridge University Press, New York, 439 p.
- SHAW, H.R., 1972. Viscosities of magmatic liquids: an empirical method of prediction. *American Journal of Science* **272**, 870-893.

- SPERA, F.J., BORGIA, A., STRIMPLE, J. & FEIGENSON, M., 1988. Rheology of melts and magmatic suspensions. 1. Design and calibration of concentric cylinder viscometer with application to rhyolitic magma. *Journal of Geophysical Research* **B93**, 10273-20294.
- TANAKA, H., 2000. Viscoelastic phase separation. *Journal of Physics : Condensed Matter* **12**, R207-R264.
- THOM, R., 1990. *Apologie du logos*. Hachette, Paris, 672p.
- TUTUNCU, A.N., PODIO, A.L. & SHARMA, M.M., 1998. Nonlinear viscoelastic behavior of sedimentary rocks, Part II: Hysteresis effects and influence of type of fluid on elastic moduli. *Geophysics* **63**, 195-203.
- VANDERHAEGHE, O. & TEYSSIER, C., 2001. Partial melting and flow of orogens. *Tectonophysics* **342**, 451-472.
- VIGNERESSE, J.L. & BURG, J.P., 2000. Continuous versus discontinuous melt segregation in migmatites : insights from a cellular automaton model. *Terra Nova* **12**, 188-192.
- VIGNERESSE, J.L. & TIKOFF, B., 1999. Strain partitioning during partial melting and crystallising felsic magmas. *Tectonophysics* **312**, 117-132.
- VIGNERESSE, J.L., BARBEY, P. & CUNEY, M., 1996. Rheological transitions during partial melting and crystallisation with application to felsic magma segregation and transfer. *Journal of Petrology* **37**, 1579-1600.
- WASSERMANN, G.S., ARNOLD, V.I. & THOMAS, R. K., 1992. *Catastrophe Theory*. Springer Verlag, Heidelberg, 150 p.
- WEBB, S.L. & DINGWELL, D.B., 1990. Non-Newtonian rheology of igneous melts at high stresses and strain rates : experimental results for rhyolite, andesite, basalt and nephelinite. *Journal of Geophysical Research* **B95**, 15695-15701.
- WILKS, K.R. & CARTER, N.L., 1990. Rheology of some continental lower crustal rocks. *Tectonophysics* **182**, 57-77.
- ZEEMAN, E.C., 1976. The umbilic bracelet and the double-cusp catastrophe. Structural stability, the theory of catastrophes and applications in the sciences. *Lecture Notes in Mathematics* **525**, Springer-Verlag, Heidelberg, 328-366.

Figure captions

Fig. 1. Log-log stress-strain rate ($\sigma - \dot{\epsilon}$) diagram displaying the relation (Eq. 3) for a Newtonian melt ($n=1$), which turns to shear thinning for $\dot{\epsilon} > 10^{-4.5} \text{ s}^{-1}$, and the power law (Eq. 4) ($n=3$) for the matrix (see references in the text). Grey lines indicate the corresponding viscosity values.

Fig. 2. Viscosity contrast between the liquid and solid phases as a function of the solid fraction (Φ) for a PMR. Different values of the viscosity contrast ($10^2, 10^5, 10^8, 10^{11}$) are presented. For each, two curves correspond to the arithmetic (η_a) and geometric (η_g) averages, respectively. They define a system that develops at constant stress and constant strain rate respectively. The geometric average does not show many differences between a contrast of 10^2 and 10^{11} in the end member values.

Fig. 3. Diagram for strain rate – viscosity – solid fraction ($\dot{\epsilon} - \eta - \Phi$) that relates strain rate and viscosity according to the proportion of one phase.

Fig. 4. Same diagram as Figure 3, but on which we located: a) the specific cusp shape instability for vein segregation, b) the quasi continuous variation of viscosity that rules the deformation of the bulk massif at low strain rate, c) the instability due to viscosity variation leading to melanosome segregation from the leucosome, and finally d) the zone where hysteresis takes place.

Fig. 5. Instability developing at quasi-constant stress and leading to strain localisation.

Fig. 6. Catastrophic jumps in viscosity that take place at constant low strain rate, between places of different melt content. They lead to segregation of the melanosome either side of leucosomes, as it occurs during spinodal decomposition.