



PERGAMON

Journal of Structural Geology 25 (2003) 813–818

**JOURNAL OF
STRUCTURAL
GEOLOGY**

www.elsevier.com/locate/jstrugeo

Some comments on the rheologically critical melt percentage

Yoshi-Taka Takeda^{a,*}, Masaaki Obata^b

^a*Department of Earth Sciences, Toyama University, Toyama 930-8555, Japan*

^b*Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*

Accepted 7 June 2002

Abstract

The concept of rheologically critical melt percentage (RCMP) originally proposed by Arzi [Tectonophysics 44 (1978) 173–184] for partially molten granitic rocks is re-examined. It is shown that there is no experimental support to show the presence of RCMP. The published experimental data suggest that the effective viscosity of partially molten granitic rocks is reduced rapidly and continuously with increasing melt fraction. It is also shown that the experimental data may be modeled by means of the upper bound behavior (the Voigt bound) of two-phase material by assuming a melt localization, which implies that there is no partitioning of strain between the solid and the melt.

© 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Rheologically critical melt percentage (RCMP); Partially molten granitic rocks; Effective viscosity

1. Introduction

The rheological behavior of partially molten rocks is an important subject for understanding the rheology of the lower crust. It is also important for understanding the origin of granitic magmas because deformation is believed to play an important role in segregation of acidic, viscous melt from partially molten rocks (e.g. Wickham, 1987; Brown et al., 1995). Although it is generally conceived that the strength of rocks should decrease as melting advances, there have been some controversies among researchers about details of the rheological behavior of the partially molten rocks. Some researchers consider that the strength of partially molten rocks does not see a significant decrease until a certain degree of partial melting (melt fraction) is achieved. The presence of such a ‘critical’ melt fraction for partially molten rocks was first proposed by Arzi (1978) through a theoretical consideration and with some preliminary deformation experiments of partially molten granitic rocks. The critical melt fraction, which was marked by a rapid decrease in rock strength, was termed ‘rheologically critical melt percentage’ (RCMP). This idea was substantiated by a series of more thorough experiments by van der Molen and Paterson (1979), who renamed this critical value ‘critical melt fraction’ (CMF). RCMP and CMF essentially refer to the same concept and we shall use RCMP in this

paper. This concept became very popular in geological literature and has been influential to the geological community (McLellan, 1984; Wickham, 1987; Blumenfeld and Bouchez, 1988; Rutter and Wyllie, 1988; Buck and Su, 1989; Obata et al., 1994; Brown et al., 1995; Renner et al., 2000; Rosenberg, 2001).

The rheological behavior of partially molten rocks is also dealt with in the context of melt segregation and, in particular, granitic magma generation problems. Segregation of partial melt is an important process for the formation of magmas in general. Unlike segregation of basaltic melts in the upper mantle, segregation of acidic melts was considered to be a very sluggish process because acidic melts are highly viscous and therefore cannot easily be segregated by a compaction and percolation process driven by the gravity and density contrast alone (McKenzie, 1984). Therefore, rock deformation driven by tectonic stress is thought to play an important role in the melt segregation for the generation of granitic magma (e.g. Wickham, 1987; Sawyer, 1994; Brown and Rushmer, 1997). This is where the melt segregation problem and rheology of partially molten rocks are considered linked together. If there is a critical behavior in the rheology of partially molten rocks as Arzi suggested, it will be difficult for a small percentage of melt to be segregated even at highly-stressed states, unless rocks are fractured thereby forming fast paths for melt transport, because of the finite rock strength. However, there is ample field evidence, mostly from migmatite terranes in

* Corresponding author.

E-mail address: ytakeda@ems.toyama-u.ac.jp (Y.T. Takeda).

the world, that indicates melt segregation can occur at levels of incipient partial melting and that deformation and melt segregation occur concomitantly and cooperatively (Brown and Rushmer, 1997). Geochemical analysis of leucocratic granitic bodies indicates that segregation of granitic melts did occur at small degrees of partial melting to form sizable masses of leucocratic granite (e.g. Le Fort, 1981; Holtz, 1989; Sawyer, 1991). On the other hand, no clear field evidence that supports the presence of RCMP in nature has ever been reported. Therefore, many geologists question the presence of an RCMP for crustal material despite the theoretical consideration and published experimental results (e.g. Brown and Rushmer, 1997; Vigneresse and Tikko, 1999).

With such historical background and considerations in mind, we have re-examined the original experimental data (van der Molen and Paterson, 1979; Rutter and Neumann, 1995) on which the concept of RCMP was founded and we found that there is no sound basis in their original data that supports the presence of RCMP. We then try to interpret the published experimental data in terms of a simple model for the rheology of two-phase composite material and show that they could be interpreted by the Voigt model by considering the effect of melt localization and thermal softening of solid particles without introducing the concept of RCMP.

2. Rheologically critical melt percentage

Arzi's concept of the RCMP was primarily based on the Roscoe's model for a suspension (Arzi, 1978). Roscoe's formulation (Roscoe, 1952) for the relative viscosity of a suspension fluid was $\eta_R = (1.35f - 0.35)^{-2.5}$, where η_R is the relative viscosity (that is, the ratio of the bulk viscosity of the suspension fluid to the viscosity of a particle-free, pure fluid) and f is the volume fraction of suspended particles. This was an extension of Einstein's model for dilute suspensions in which interaction of particles is negligible (Einstein, 1906, 1911). In this formulation, the relative viscosity of the suspension rapidly increases as the volume fraction of suspended particles increases until the bulk viscosity becomes infinite around 74% of particle fraction (i.e. 26% liquid fraction). Arzi (1978) applied this model for partially molten rocks and related this critical value to the RCMP for partially molten rocks. He considered the RCMP as a transition point from a solid framework-interlocking structure to a fluid state, in which solid particles are suspended. The drastic decrease of rock strength was considered to occur at the critical melt fraction because of the structural change in the partially molten rocks.

The solid to liquid transition in partially molten rocks and the liquid to solid transition in crystallizing magmas are not rheologically reversed processes (e.g. Vigneresse et al., 1996). Solids (crystals) in crystallizing magmas are generally assumed to be rigid, undeformable particles and,

thus, deformation is assumed to be entirely accommodated in silicate melt in partially crystallizing magmas. On the other hand, because partially molten rocks generally occur in the Earth's depths at high temperatures and high pressures, solid crystals may be deformed. Hence, for partially molten rocks, it is essential to treat the solid phase as a deformable medium, as well as the melt phase. In Roscoe's model rigid particles are suspended in viscous fluid. Accordingly, the model can treat the liquid to solid transition. Roscoe's model applies to the rheology of crystal-bearing melt (Lejeune and Richelt, 1995). It is obvious that infinite viscosity at a critical fraction in Roscoe's model results from locking by rigid particles. Consequently, Arzi's RCMP that is based on the Roscoe's model should be roughly applicable to crystallizing magmas but not necessarily to partially molten rocks. Therefore, the Roscoe model cannot be used to justify the concept of RCMP for partially molten rocks.

Among many deformation experiments of partially molten granitic rocks (Arzi, 1978; van der Molen and Paterson, 1979; Paquet and Francois, 1980; Auer et al., 1981; Paquet et al., 1981; Dell' Angelo and Tullis, 1988; Rushmer, 1995; Rutter and Neumann, 1995), the early work of van der Molen and Paterson (1979) was widely viewed to contain a direct experimental proof of the concept of RCMP. van der Molen and Paterson (1979) performed a series of deformation experiments for partially molten granitic rocks with melt fractions up to 25% at 800 °C and a confining pressure of 300 MPa at a constant strain rate of 10^{-6} s^{-1} . They defined strictly the RCMP (or CMF) as the point of maximum rate of decrease in rock-strength with increasing melt fraction. Further, they concluded that the RCMP is approximately 30–35% for granitic rocks on the basis of their experiments. It should be noted that they found a rapid drop of effective viscosity (i.e. the ratio of rock strength to experimentally controlled strain rate) on a logarithmic scale (Fig. 14 in van der Molen and Paterson, 1979). If the same data are plotted in a linear scale, however, a completely different picture emerges, as in Fig. 1. It is clearly shown that the strength of partially molten rocks decreases rapidly and almost linearly from the very beginning of partial melting with increasing melt fraction. Hence, according to the original definition of RCMP (or CMF), that is, "the point of maximum rate of decrease in strength", the RCMP becomes 0%, in which case the concept of RCMP is not necessary at all.

More recently, Rutter and Neumann (1995) performed deformation experiments for partially molten granitic rocks at 800–1100 °C temperature and 250 MPa confining pressure at a constant strain rate, $8 \times 10^{-5} \text{ s}^{-1}$, in which no critical behavior was observed but a moderate reduction of strength (flow stress) of the partially molten rocks was observed with increasing melt fraction (Fig. 2). In detail, in their experiment the strength decreases nearly linearly in a logarithmic scale, which indicates a nearly exponential decrease of strength with increasing melt fraction. A similar

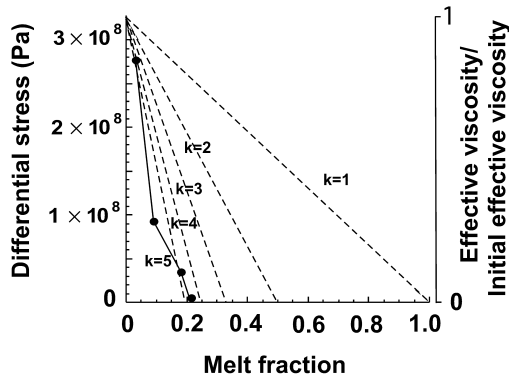


Fig. 1. Strength of partially molten granitic rocks replotted from original data of van der Molen and Paterson (1979). Note that ordinate is on a linear scale. Broken lines represent theoretical variation of strength of partially molten rocks estimated for various k -values in Eq. (4). The k -value is a measure for enhancement of melt fraction in shear zone (see text for explanation).

behavior was also observed by Rushmer (1995). It should be noted here that there is an important difference between van der Molen and Paterson (1979) and Rutter and Neumann (1995) in their way of controlling the melt fraction. While the former controlled the melt fraction by varying the amount of water at a constant temperature, the latter authors raised temperature to increase the melt fraction (Rutter and Neumann, 1995). Apparent differences between the two experimental results are likely to be due to this difference in experimental procedure as further discussed below.

An important conclusion to be emphasized is that neither of the studies support or suggest the presence of substantial weakening at the RCMP. In the following we give interpretations for these experimental data in terms of the two-phase flow model.

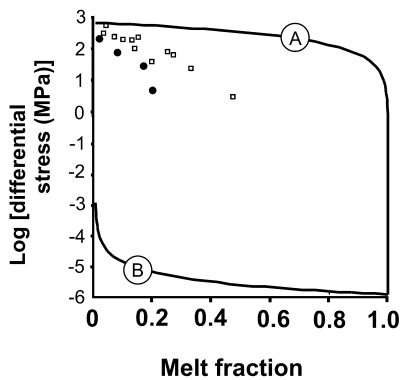


Fig. 2. Comparisons of experimental data of van der Molen and Paterson (1979) (solid circles) and Rutter and Neumann (1995) (open circles) with two theoretical curves for the Voigt bound (A) and the Reuss bound (B). Theoretical curves are calculated assuming a differential stress of about 10^{-6} MPa for the melt and a differential stress of about 6×10^{-2} MPa for the solid.

3. Reinterpretation of published experimental data on partially molten granitic rocks

Partially molten rocks may be treated as a two-phase material in which a solid phase and a melt phase are mixed together. Qualitatively speaking, the effective viscosity (or the bulk flow strength) of the two-phase material must be reduced with increasing fraction of melt—the less viscous phase. The question is how fast this reduction of strength occurs. Upper and lower bounds for the effective bulk viscosity of the two-phase material, μ_{bulk} , can be determined assuming an iso-strain rate state (the Voigt bound) and an iso-stress state (the Reuss bound), respectively (e.g. Hill, 1965) as follows:

$$\mu_{\text{bulk}} = \mu_1 \phi_1 + \mu_2 \phi_2, \text{ (iso-strain rate)} \tag{1}$$

$$\mu_{\text{bulk}} = \left(\frac{\phi_1}{\mu_1} + \frac{\phi_2}{\mu_2} \right)^{-1}, \text{ (iso-stress)} \tag{2}$$

The viscosities and fractions of the less and more viscous phases are denoted by μ_1 and ϕ_1 , and μ_2 and ϕ_2 , respectively. The behavior of real materials should lie somewhere between the two bounds.

The experimental results of van der Molen and Paterson (1979) and Rutter and Neumann (1995) are plotted on the same diagram and the two theoretical bounds, A and B, are drawn for comparison in Fig. 2. The Reuss bound (B) predicts an abrupt drop of strength for the first few percent of melt fraction increase; whereas the Voigt bound (A) does not show such a decrease.

The experimental values lie indeed between the two bounds and it can be seen that the experimental results are closer to the Voigt bound than to the Reuss bound. We will show that the Voigt bound is a better approximation for partially molten granitic rocks for less than 50% melting.

3.1. Effect of melt and strain localization

It was noted above that in Fig. 1, the experiment of van der Molen and Paterson (1979) shows the rock strength decreasing linearly with the melt fraction. In this respect, the experimental results are closer to the Voigt behavior (Eq. (1)) than to the Reuss behavior. However, the observed rate of decrease is greater than the predicted (curve A in Fig. 2). We interpret that this discrepancy may be due to a melt localization in a shear zone that was observed in some experimental run charges of van der Molen and Paterson (1979). We shall show below how this discrepancy may be resolved by considering both melt and strain localization.

Because the viscosity of the melt is orders of magnitude lower than that of the solid, Eq. (1) may be approximated, by neglecting the melt viscosity term, by:

$$\mu_{\text{bulk}} = (1 - \phi_{\text{melt}})\mu_{\text{solid}} \tag{3}$$

where ϕ_{melt} is the average melt fraction of the specimen. When deformation is localized into narrow regions such as

shear zones in which melt fraction is higher than the average value, as observed by van der Molen and Paterson, Eq. (3) should be replaced by:

$$\mu_{\text{bulk}} = (1 - k\phi_{\text{melt}})\mu_{\text{solid}} \quad (4)$$

where k is a factor of melt concentration in the shear zone. If the melt fraction in the shear zone is greater than the average melt fraction, then k becomes greater than unity. This assumes that deformation is accommodated by the shear zone in which melt is concentrated and both solid and melt phases are deformed homogeneously. Fig. 1 shows the effective viscosity for various k values. It is evident that a significant melt concentration into shear zones can result in a linear and rapid reduction of the effective viscosity.

3.2. Effect of thermal softening

It was emphasized that temperature was raised to increase the degree of partial melting in Rutter and Neumann (1995). It will be shown below that the apparent exponential decrease of the rock strength can be explained by considering the effect of thermal softening of the solid phase. In order to examine the effect of thermal softening, Eq. (3) is re-written as:

$$\mu_{\text{bulk}} = (1 - \phi_{\text{melt}})\mu_{\text{solid}}^0 \exp\left(\frac{E}{R(T_0 + \Delta T)} - \frac{E}{RT_0}\right) \quad (5)$$

where μ_{solid}^0 is a viscosity of the solid phase at a reference temperature T_0 , E is the activation energy of the creep in the solid, R is the gas constant and ΔT is the temperature change. If the melt fraction varies linearly with temperature, Eq. (5) can be rewritten as:

$$\frac{\mu_{\text{bulk}}}{\mu_{\text{solid}}^0} = (1 - \phi_{\text{melt}}) \exp\left(\frac{E}{R(T_0 + g\phi_{\text{melt}})} - \frac{E}{RT_0}\right) \quad (6)$$

where g is a linear coefficient, the ratio between the temperature increase and the melt volume fraction increase. The initial temperature of the experiments of Rutter and Neumann (1995) is $T_0 = (800 + 273)$ K. Further, the ratio of the temperature increase to the melt fraction increase, g , may be estimated from the experiments of Rutter and Neumann (1995); $g \approx 800$. Using these values, Eq. (6) was fitted to the observed effective viscosities for different activation energies (Fig. 3). As seen in the figure, a best fit was obtained for the activation energy of 100–150 kJ mol⁻¹. Microstructural observations of the deformed specimens of Rutter and Neumann (1995) showed that brittle deformation was dominating in their experiment. Although purely brittle deformation is not likely to be a thermally activated process as assumed above, fluid-assisted cracking, such as stress corrosion cracking, may be a thermally activated process owing to chemical interactions between the fluid and the solid. It is likely that silicate melt also aids stress corrosion cracking (e.g. Rubin, 1998). Although experimental work on silicate melt-aided stress corrosion cracking is lacking, stress corrosion cracking of

silicate minerals has been investigated in the presence of water. For example, the activation energy for stress corrosion of quartz is about 100 kJ mol⁻¹ (Atkinson, 1984). This value is comparable with the above evaluated activation energy for the experiment of Rutter and Neumann. Thus, the effect of thermal softening of the solid phase, by means of stress corrosion cracking, can explain the experimental result of Rutter and Neumann (1995).

Some localization of melt in shear zones was also noted by Rutter and Neumann (1995). Therefore, we examine the effect of localization as well as the effect of thermal softening. The result is also shown in Fig. 3, in which bulk viscosity curves calculated for melt localization are superimposed on the non-localized case. It is seen that the experimental results can still be explained unless local melt concentration is significant.

4. Discussion and conclusions

It was shown above that in the experiment of van der Molen and Paterson (1979) the effective viscosity of partially molten granitic rocks decreases sharply and continuously with increasing melt fraction and we have concluded that the idea of RCMP was not experimentally justified.

We have presented an interpretation that the published experimental results can be explained in terms of the Voigt model, which assumes no partitioning of strain rate between solid and melt. The result of van der Molen and Paterson (1979) may be explained by considering the localization of deformation accompanied by the melt localization and that of Rutter and Neumann (1995) may be explained by incorporating a thermal softening effect of the solid phase.

There are some other factors we have not yet considered that might affect the strength (or the effective viscosity) of partially molten granitic rocks. For example, melt pore pressure may increase as melting rapidly advances, which may induce a pervasive microfracturing and thereby cause a significant reduction of rock (i.e. compaction softening; Renner et al., 2000). On the contrary to the compaction softening, a quick formation of dilatant cracks (or very slow melting relative to the fracturing rate) would result in a reduction of melt pore pressure, thereby causing an enhancement of rock strength (i.e. dilatancy hardening; Renner et al., 2000). Renner et al. (2000) interpreted the apparent high strength of the partially molten rocks observed in the experiments of van der Molen and Paterson (1979) in terms of the dilatancy hardening. However, as described above, we pointed out that, in the experiment of van der Molen and Paterson (1979), the strength of partially molten rocks decreases continuously and almost linearly without a critical behavior. Accordingly, it is not needed to invoke such effects. Further, we do not think that the effects of the melt pore pressure can explain the difference in

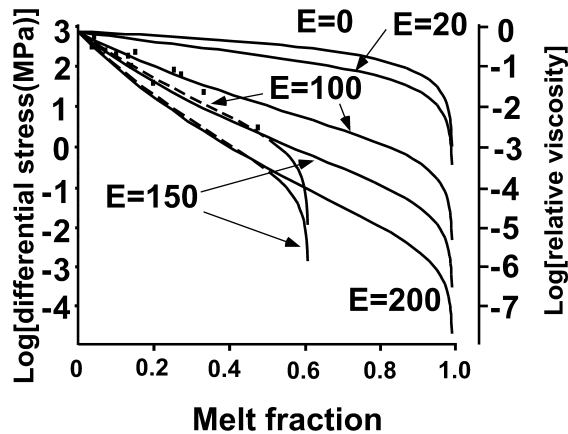


Fig. 3. Comparison of strength values observed by Rutter and Neumann (1995) with theoretical values. Solid squares represent the experimental observation. Solid curves show a variation of strength of partially molten rocks estimated for various activation energies (kJ mol^{-1}) for the creep in the solid. Two broken curves are drawn for the activation energies of 100 and 150 kJ mol^{-1} , respectively, and assuming a k -value of 1.6 (see Eq. (4)).

behavior between van der Molen and Paterson (1979) and Rutter and Neumann (1995).

Our interpretation of the published experimental results suggests that if partially molten rocks are subjected to homogeneous deformation without localization of melt, the effective viscosity would be reduced linearly with increasing melt fraction (that is, tracing path A of the Voigt bound in Fig. 2). We conclude that the past experimental data failed to detect RCMP because of the effect of both localization of melt and deformation and/or of a thermal softening of solids. It may be possible to say that the experiment of van der Molen and Paterson (1979) and of Rutter and Neumann (1995) only detected a load-bearing framework behavior, i.e. when weak phase (i.e. melt) is distributed only in a small amount of the interstices of the load-bearing framework, stress is primarily supported by the framework and the strain rate would become uniform (Arzi, 1978; Handy, 1994).

Consequently, we must ask whether the 'load-bearing framework' is really present or not in partially molten rocks in nature. If the load-bearing framework is present and, as melting advances, suddenly broken down beyond a certain degree of melt fraction, then RCMP may occur. Even if it is present, if it is gradually broken with increasing melt fraction, RCMP cannot be defined. In order to verify whether the RCMP is present or not, we must measure the partitioning of strain rate between the melt and the solid in the experiments in which both localization of melt and deformation are controllable.

Acknowledgments

We thank J. Renner and T. Rushmer for their critical review. We acknowledge grant in aid for scientific research

from the Ministry of Education of Japan for the second author.

References

- Arzi, A.A., 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics* 44, 173–184.
- Atkinson, B.K., 1984. Subcritical crack growth in geological materials. *Journal of Geophysical Research* 89, 4077–4114.
- Auer, F., Berkhemer, H., Oehlschlegel, G., 1981. Steady state creep of fine grain granite at partial melting. *Journal of Geophysics* 49, 89–92.
- Blumenfeld, P., Bouchez, J.L., 1988. Shear criteria in granite and migmatite deformed in the magmatic and solid states. *Journal of Structural Geology* 10, 361–372.
- Brown, M., Rushmer, T., 1997. The role of deformation in the movement of granitic melt: views from the laboratory and the field. In: Holness, M.B., (Ed.), *Deformation-enhanced Fluid Transport in the Earth's Crust and Mantle*, Chapman & Hall, London, pp. 111–144.
- Brown, M., Averkin, Y.A., McLellan, E., Sawyer, E.W., 1995. Melt segregation in migmatites. *Journal of Geophysical Research* 100, 15655–15679.
- Buck, W.R., Su, W., 1989. Focused mantle upwelling below mid-ocean ridges due to feedback between viscosity and melting. *Geophysical Research Letters* 16, 641–644.
- Dell' Angelo, L.N., Tullis, J., 1988. Experimental deformation on partially molten granitic aggregates. *Journal of Metamorphic Geology* 6, 495–515.
- Einstein, A., 1906. Eine neue bestimmung der molekuldimensionen. *Annales de Physique* 19, 289–306.
- Einstein, A., 1911. Berichtigung zu meiner arbeit: eine neue bestimmung der molekuldimensionen. *Annales de Physique* 34, 591–592.
- Handy, M.R., 1994. Flow law for rocks containing two non-linear viscous phases: a phenomenological approach. *Journal of Structural Geology* 16, 287–301.
- Hill, R., 1965. Continuum micro-mechanics of elastoplastic polycrystals. *Journal of the Mechanics and Physics of Solids* 13, 89–101.
- Holtz, F., 1989. Importance of melt fraction and source rock composition in crustal genesis—the example of two granitic suites of northern Portugal. *Lithos* 24, 21–35.
- Le Fort, P., 1981. Manaslu leucogranite: a collision signature of the Himalayas. A model for its genesis and emplacement. *Journal of Geophysical Research* 86, 10545–10568.
- Lejeune, A.-M., Richelt, P., 1995. Rheology of crystal-bearing silicate melt: an experimental study at high viscosities. *Journal of Geophysical Research* 100, 4215–4229.
- McKenzie, D., 1984. The generation and compaction of partially molten rock. *Journal of Petrology* 25, 713–765.
- McLellan, E., 1984. Deformation behavior of migmatites and problems of structural analysis in migmatite terrains. *Geological Magazine* 121, 339–345.
- van der Molen, I., Paterson, M.S., 1979. Experimental deformation of partially-melted granite. *Contributions to Mineralogy and Petrology* 70, 299–318.
- Obata, M., Yoshimura, Y., Nagakawa, K., Odawara, S., Osanai, Y., 1994. Crustal anatexis and melt segregations in the Higo metamorphic terrane, west-central kyushu, Kumamoto, Japan. *Lithos* 32, 135–147.
- Paquet, J., Francois, P., 1980. Experimental deformation of partially melted granitic rocks at 600–900 °C and 250 MPa confining pressure. *Tectonophysics* 68, 131–146.
- Paquet, J., Francois, P., Nedelec, A., 1981. Effect of partial melting on rock deformation: experimental and natural evidences on rocks of granitic compositions. *Tectonophysics* 78, 545–565.
- Renner, J., Evans, B., Hirth, G., 2000. On the rheologically critically melt fraction. *Earth and Planetary Science Letters* 181, 585–594.

- Roscoe, R., 1952. The viscosity of suspensions of rigid spheres. *British Journal of Applied Physics* 3, 267–269.
- Rosenberg, C.L., 2001. Deformation of partially molten granite: a review and comparison of experimental and natural case studies. *International Earth Sciences* 90, 60–76.
- Rubin, A.M., 1998. Dike ascent in partially molten rock. *Journal of Geophysical Research* 103, 20901–20919.
- Rushmer, T., 1995. An experimental deformation study of partially molten amphibolite: application to low-melt fraction segregation. *Journal of Geophysical Research* 100, 15681–15695.
- Rutter, E.H., Neumann, H.K., 1995. Experimental deformation of partially molten Westerly granite under fluid-absent conditions, with implications for the extraction of granitic magmas. *Journal of Geophysical Research* 100, 15697–15715.
- Rutter, M., Wyllie, P.J., 1988. Melting of vapour-absent tonalite at 10 kbar to simulate dehydration–melting in the deep crust. *Nature* 331, 159–160.
- Sawyer, E.W., 1991. Disequilibrium melting and the rate of melt-residuum separation during migmatization of mafic rocks from the Grenville Front, Quebec. *Journal of Petrology* 32, 701–738.
- Sawyer, E.W., 1994. Melt segregation in the continental crust. *Geology* 22, 1019–1022.
- Wickham, S.M., 1987. The segregation and emplacement of granitic magma. *Journal of Geological Society, London* 144, 281–297.
- Vigneresse, J.L., Tikko, B., 1999. Strain partitioning during partial melting and crystallizing felsic magmas. *Tectonophysics* 312, 117–132.
- Vigneresse, J.L., Barbey, P., Cuney, M., 1996. Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer. *Journal of Petrology* 37, 1579–1600.