Rheology of Three-Phase Magmas

Mattia Pistone [1], Luca Caricchi [2], Peter Ulmer [1], Eric Reusser [1], Federica Marone [3], Luigi Burlini [1]

(1) ETH - Zurich, Earth Sciences, Zurich, Switzerland (mattia.pistone@erdw.ethz.ch) (2) University of Bristol, Earth Sciences, Bristol, United Kingdom (3) Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland

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1. AIM OF THE STUDY:

This study constrains the rheology of three-phase magmas, composed of quartz crystals (ϕ = 0.24, 0.44, 0.55, 0.65), CO_2-rich gas bubbles (β = 0.09, 0.10, 0.12) and silicate melt.

2. EXPERIMENTAL METHODOLOGY:

Hydrous haplogranitic three-phase magmas were deformed in simple shear at high temperature (723-1023 K) and pressure (200 MPa) conditions using a Paterson-type rock deformation apparatus (Paterson & Olgaard, 2000) at strain rate ranging between $1{\cdot}10^{-5}$ s^{-1} and $4{\cdot}10^{-3}$ s^{-1}.

3. RHEOLOGICAL AND MICROSTRUCTURAL RESULTS:

The rheology is strongly strain-rate dependent (*Fig. 1*). Two dominant Non-Newtonian regimes are identified: shear thickening (increase of viscosity with increasing strain rate) in crystal-poor magmas (ϕ = 0.24-0.44; β = 0.12); shear thinning (decrease of viscosity with increasing strain rate) in crystal-rich systems (ϕ = 0.55-0.65; β = 0.09-0.10). Shear thickening is the expression of bubble coalescence, generation of gas planes and outgassing. Shear thinning is associated with discrete redistribution of suspended crystals, their size reduction and formation of shear bands (*Fig. 2*).

4. PROPOSED FLOW MECHANICS:

Magmas are complex mixtures of silicate melt, crystals and gas bubbles. The rheology of three-phase magmas can be explained with the concepts of critical soil mechanics (Rutter et al., 2006; Caricchi et al., 2007; *Fig. 3*). Local dilation (decrease of local pressure) induces bubble coalescence in crystal-poor systems and shear banding in crystal-rich systems. At critical state (dilation is counterbalanced by compaction or increase of local pressure) gas escapes in crystal-poor magmas and shear bands accommodates most of deformation in crystal-rich magmas.

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This work is dedicated to Luigi Burlini, mentor and friend.

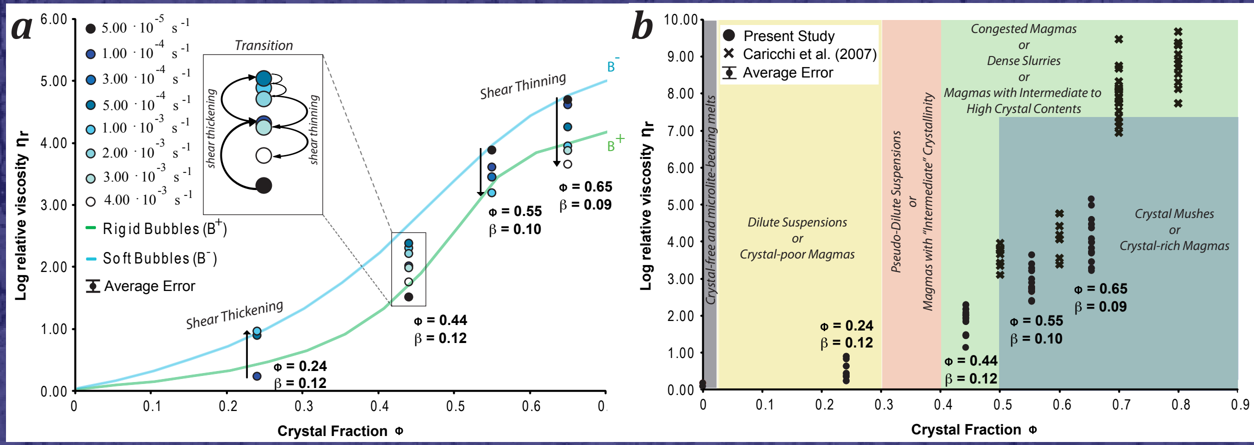

Figure 1: **Crystal fraction (ϕ) vs. log relative viscosity (η_r):**
a) Representative experiments exhibiting shear thickening at low crystal fraction (ϕ= 0.24; β = 0.12), shear thinning at high crystallinity (ϕ = 0.55-0.65; β = 0.09-0.10) and both regimes at intermediate crystal content (ϕ = 0.44; β = 0.12).
b) Comparison of the results from this study with the study of Caricchi et al. (2007) conducted in bubble-free crystal-bearing system.

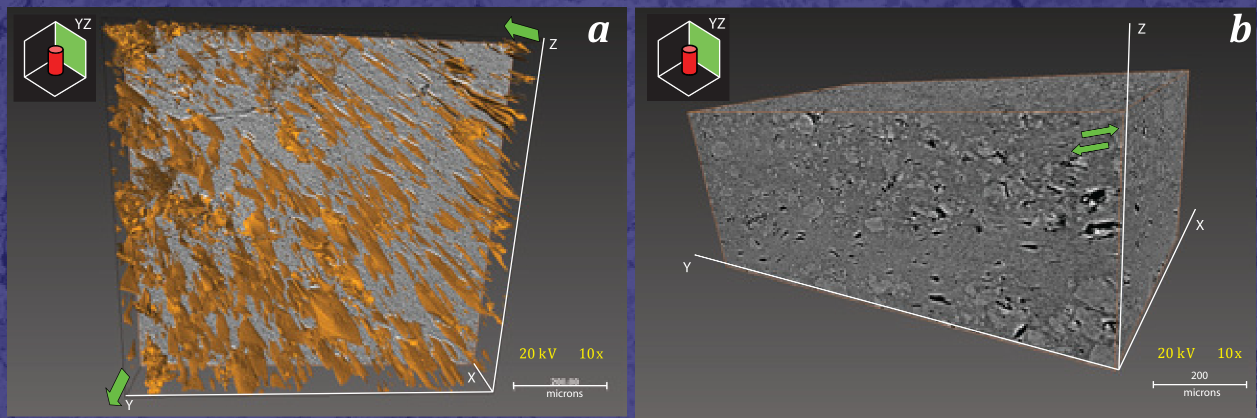

Figure 2: **3D renderings of deformed magmas at high temperature and high pressure:**
a) Crystal-poor magma (ϕ = 0.24; β = 0.12) deformed at 773 K and 200 MPa up to 3.64 in total strain
b) Crystal-rich magma (ϕ = 0.55; β = 0.10) deformed at 873 K and 200 MPa up to 6.91 in total strain.
3D renderings were obtained using synchrotron-based X-ray tomographic microscopy at the TOMCAT beam-line at Swiss Light Source (PSI, Villigen, Switzerland).

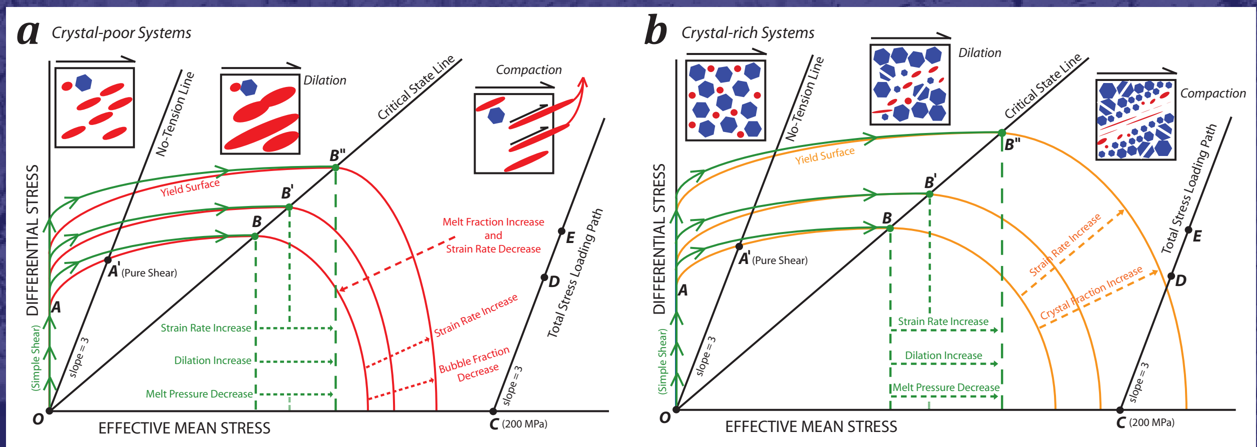

Figure 3: **Differential stress vs. effective mean stress** (redrawn from Rutter et al., 2006, and Caricchi et al., 2007):
a) Crystal-rich and bubble-bearing systems as analogue for crystal-rich systems (ϕ = 0.55-0.65; β = 0.09-0.10). The path OA represents the elastic loading trajectory for torsion experiments. At A (simple shear; A′ is the yield point for pure shear experiments, not performed in the present study), the loading path intersects the yielding surface where irreversible deformation of the sample starts. Increasing crystal fractions or applied strain rates expand the yielding surface; an increase of strain rate shifts the onset of flow from B to B′ and B″).
b) Crystal-poor and bubble-bearing systems as analogue for crystal-poor systems (ϕ = 0.24-0.44; β = 0.12). Both, relative increase of the melt fraction and reduction of the effective local strain rate, shrink the yield surface.

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