Non-Newtonian rheological law for highly crystalline dome lavas

Yan Lavallée
Kai-Uwe Hess
Benoit Cordonnier
Donald Bruce Dingwell
Earth and Environment, Ludwig-Maximilians University Munich, Theresienstraße 41/III, D80333, Germany

ABSTRACT

Volcanic eruption models are hampered by the lack of multiphase magmatic flow laws. Most rheological models estimate the viscosity of multiphase lavas via the Einstein-Roscoe equation, but this simplification cannot be used for high crystallinity and it does not consider the non-Newtonian strain-rate dependence of viscosity. We carried out parallel plate experiments on natural samples to simulate multiphase lava deformation under various stresses and strain rates. Multiphase lavas exhibit an important component of shear thinning, and appear to invalidate the adequacy of Einstein-Roscoe–based formulations for highly crystalline lava rheology. The remarkable singular dependence of viscosity (η) on strain rate (γ) yields a novel universal rheology law at eruptive temperatures (T), i.e., $\log \eta = -0.993 + 8974/T - 0.543 \cdot \log \gamma$. Our work reveals the importance of considering microcracking and viscous dissipation at very high strain rate ($>10^{-3}$ s^{-1}), explaining the occurrence of seismic swarms along the conduit margins, and consequently supporting plug-like magma ascent models.

Keywords: suspension rheology, lava viscosity, non-Newtonian regime, strain-rate dependence, uniaxial deformation, parallel plate.

INTRODUCTION

Understanding the nature and efficiency of physico-chemical processes involved in effusive and explosive volcanism is fundamental to risk assessment and hazard mitigation. Such processes are unfortunately not easily observable in actual eruptions. In the past, risk assessment has chiefly relied on monitoring combined with numerical simulations. However, advances in experimentation on natural materials at relevant temperatures and pressures have contributed to quantification and modeling of magmatic behavior in conduits and domes during eruption (Alidibirov and Dingwell, 1996; Kennedy et al., 2005; Spieler et al., 2004; Tuffen et al., 2003). In addition, the description of single-phase melt rheological properties has vastly improved in the past decade (Giordano et al., 2006; Hui and Zhang, 2007). This combination of developments has advanced the physico-chemical basis of volcanic simulations in terms of mechanistic considerations and effective parameterizations (Gonnermann and Manga, 2003; Melnik and Sparks, 1999; Papale, 1999). Lavas, however, inevitably contain some crystals and bubbles, and the description of their influences on the rheology remains far from complete (McBirney and Murase, 1984; Petford, 2003). Observations from dome-building eruptions, in particular, reveal variable but very high levels of both vesicularity and crystallinity in erupting lavas.

A suspension rheology is generally understood as a fluid in which the addition of particles increases the viscosity nonlinearly according to the Einstein-Roscoe equation (Einstein, 1911; Roscoe, 1952). Problems with this expression nonetheless exist when extrapolating to particle concentrations >~50% as the mixture becomes non-Newtonian and therefore strain-rate dependent (Stevenson et al., 1996; Vigneresse and Tikoff, 1999). Suspension rheology studies of basaltic (Pinkerton and Norton, 1995; Ryerson et al., 1988), andesitic (Lejeune and Richet, 1995), and rhyolitic melts (Alidibirov et al., 1997; Murase et al., 1985; Stevenson et al., 1996) and synthetic melts (Bruckner and Deubener, 1997) at low to moderate stresses support this nonlinear increase of viscosity. The findings seem to be consistent with an onset of non-Newtonian flow behavior at crystallinity >~30%, and yield stresses of a few kilopascals (see discussion in Barnes, 1999). Rheological models of multiphase lavas are still badly hampered by a paucity of data and, as a consequence, the lack of an expression that describes the strain-rate dependence (Petford, 2003).

We investigated the rheology of natural melts subject to a wide range of stresses and strain rates. This study reveals important effects of strain rate on the apparent viscosity of lava and includes the generation of a general expression for the non-Newtonian regime of lavas with high crystal content.

MEASUREMENT METHOD AND VISCOSITY DETERMINATION

We used a high-load, high-temperature uniaxial press to investigate the stress-strain-rate behavior of multiphase lava (see Hess et al., 2007). Cylindrical samples with a length to width aspect ratio of two (80 × 40 mm and 40 × 20 mm), and with a length at least 10 times that of the largest crystal, were prepared. This geometry minimized both edges and crystal-size scaling effects. The samples were inserted in the press and placed between two axial pistons surrounded by a three-zone furnace. The system was heated and equilibrated at high temperatures (940–1010 ± 1.5 °C), then various loads (1–60 MPa) were applied to the sample until a maximum of 33% strain was obtained. Length changes of the sample were recorded at a rate of 10 times/s and the apparent viscosity of the melt (η_b in Pa·s) was then calculated via an equation developed by Gent (1960) for parallel plate measurements. Our calibration work demonstrated that we resolve the viscosity in Pa·s with an accuracy of ±0.06 log unit (Hess et al., 2007).

Four active volcanoes were selected for this study: Unzen (Japan), Colima (Mexico), Bezymianny (Russia), and Anak Krakatau (Indonesia) (Table 1). The textures in the rocks were examined through microscopy, and the open porosity of every sample was measured before and after each experiment (Table 2). The samples for all volcanoes were highly degassed (≤0.1% ± 0.05%), and no volatiles were lost during the extensive heat treatment, as confirmed by weight loss tests before and after treatment. The rocks chosen for this study cover wide ranges of geochemistry, crystallinity, and vesicularity, and thus represent a significant portion of the range of lavas at active volcanic systems. We used

© 2007 The Geological Society of America. For permission to copy, contact Copyright Permissions, GSA, or editing@geosociety.org.

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/35/9/843/3534709/i0091-7613-35-9-843.pdf
by University of Oslo user

TABLE 1. NORMALIZED GEOCHEMICAL COMPOSITION OF 12 MEASUREMENTS ON GLASS PHASE OF EACH SAMPLE

Oxides	Unzen	Std. dev.	Colima	Std. dev.	Bezymianny	Std. dev.	Krakatau	Std. dev.
SiO_2	77.77	0.32	73.18	1.18	75.26	0.63	64.60	0.81
Al_2O_3	11.89	0.12	13.06	0.99	12.27	0.64	17.20	0.39
Na_2O	3.11	0.11	4.65	0.32	4.45	0.32	5.63	0.31
K_2O	4.65	0.12	3.73	0.39	3.72	0.51	1.74	0.18
MgO	0.08	0.01	0.37	0.20	0.19	0.05	0.65	0.53
CaO	0.68	0.19	1.40	0.59	1.30	0.41	5.14	0.69
TiO_2	0.39	0.05	0.74	0.07	0.50	0.07	0.70	0.15
FeO	0.84	0.13	2.58	0.31	2.17	0.26	3.92	0.70
MnO	0.60	0.02	0.07	0.07	0.06	0.04	0.06	0.03
P_2O_5	0.00	0.01	0.22	0.05	0.09	0.02	0.36	0.26
Melt viscosity[1]	$10^{9.79}$		$10^{8.58}$		10^{9}		107.25–8.8	
Bulk viscosity[2]	$10^{11.74}$		$10^{11.28}$					

Note: The analyses were done with an electron microprobe, using a 15kV, 20 nA scanning box mode (10^2 μm^2). Standards: Na, albite; K, orthoclase; v12, rhyolite. Std. Dev.—standard deviation. (1) Viscosity (Pa·s) of the melt phase estimated at 940 °C after the work of Giordano et al. (2006) and Hess and Dingwell (1996). (2) Viscosity (Pa s) of the bulk estimated via the Einstein-Roscoe equation for the melts with crystal content within the limit of the Einstein-Roscoe equation (see sample description). Here we considered the ideal packing of 0.6 and the adjustable parameter value of 2.5 suggested by Lejeune and Richet (1995).

them to test the hypothesis that a simple non-Newtonian rheological law is capable of dealing with this range of materials.

RESULTS

More than 40 experiments were performed to describe the influence of stress, and resultant strain rate, on the apparent viscosity of the multiphase lavas. At low applied stresses (<15 MPa) the initial deformation was characterized by a rapid nonlinear increase in viscosity until a steady value was reached (Fig. 1). We associate this initial portion of apparent viscosity increase to the elastic responses of the press and sample upon application of stress. At intermediate stresses (~15–30 MPa) deformation occurred at a constant strain rate and the viscosity remained constant over the entire measurement (Fig. 1). An instantaneous viscosity decrease was observed for each applied stress increment. At higher stresses (>30 MPa) the viscosity temporally decreased upon deformation; a delayed decrease of ~0.15 log unit occurred under a constant stress applied. In this rheological regime, the degree of delayed viscosity decrease was accentuated with increasing stress, and temperature increases attributed to viscous heating began to be recorded by the thermocouple array (Fig. 1). During these highest-stress experiments, the viscosity sometimes abruptly plunged, and accompanying microcracking of the samples occurred. Cracking of supercooled melt results from high deformation rates that drive the system toward the brittle-ductile transition (Dingwell, 1996; Tuffen et al., 2003)

Post-experiment textural analyses provide important complementary insights into suspension rheology. Upon deformation, the samples bulged laterally and extensional microcracks developed in the periphery (Fig. 2A). In the glass phase these cracks generally extend from one crystal to the next, whereas in the crystal phase the cracks seem to focus primarily in the largest crystals. We also note a higher population of cracks inside the crystals for the experiments at higher strain rates. Even though cracks formed, some pores inside the melt closed and healed upon deformation; the end porosity values thus remained very similar to the initial porosity values, except for Krakatau samples in which the higher porosity lessened the occurrence of microcracking while allowing for more open pores to close (Table 2).

TABLE 2. PETROLOGICAL AND TEXTURAL CHARACTERISTICS OF ROCK SAMPLES

Volcanoes	Glass (%)	Crystal (%)	Microlite (%)	Initial porosity (%)	End porosity (%)
Unzen	50	30	20	6	6
Colima	45	40	15	9	8.5
Anak Krakatau	30	55	15	23	21
Bezymianny	20	70	10	8	8

Note: The proportions of crystals, microlites, and glass (on a pore-free count) are averaged for 10 visual analyses coupled to digital estimates obtained via the JMicroVision 1.22 software. We resolved their proportion within 10%. The porosity of the sample were calculated by the Archimedian method and measured by a pycnometer. These porosities reflect an average of all samples, which did not vary by more than 1%.

TABLE 3. LINEAR REGRESSIONS FOR VISCOSITY–STRAIN RATE DATA SETS

Volcanoes	*T* (°C)	a	b	Std. dev.
Colima	940	–0.518	8.297	0.063
Bezymianny	940	–0.543	8.584	0.038
Anak Krakatau	940	–0.545	8.597	0.036
Unzen	940	–0.565	8.735	0.057
Average	940	–0.543	8.553	
Colima	980	–0.519	7.905	0.000
Unzen	980	–0.493	8.653	0.042
Unzen	1010	–0.528	8.126	0.000

Note: *T* — temperature. Std. Dev.—standard deviation. The average of the linear regressions at 940 °C is displayed as the green line in Figure 4. The non-Arrhenian variations in temperature of the linear regressions (b values) were used as proxy to derive equation 3 and the blue and green lines of Figure 4.

Microscopic analysis also revealed a range of textures indicative of both viscous and elastic deformations. The alignments of crystals and melt into flow bands perpendicular to the applied stress evidenced the viscous response of the bulk in all samples and its dominant control on the obtained viscosity (Fig. 2B). Otherwise, samples deformed at high strain rates were further characterized by multiple microcracks through phenocrysts (Fig. 2B). In general these cracks were subparallel to the direction of stress, and restricted to the phenocrysts, which had undergone rotation into perpendicular flow bands. At very high strain rates, microcracks were more closely concentrated, and developed into longer fractures. The presence of large crystals sometimes deviated fracture propagation, which showed their influence in changing the stress distribution. The microtextural analysis showed the importance of crystal organization in the bulk of deformation and resultant non-Newtonian flow regime.

SINGULAR NON-NEWTONIAN DESCRIPTION OF STRAIN RATE

The nonlinearity between the applied stresses and resulting strain rates reveals that lava suspensions are pseudo-plastic fluids with a strong shear thinning component and without any observable yield strength (Fig. 3). The

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/35/9/843/3534709/i0091-7613-35-9-843.pdf
by University of Oslo user

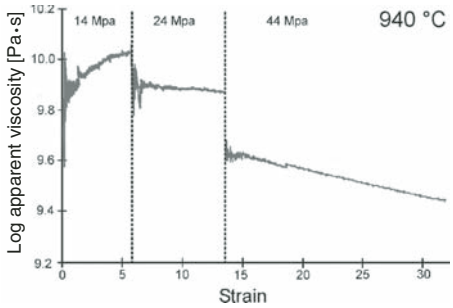


Figure 1. Typical viscosity profile for experiment at 940 ºC in which incremental stresses were applied. At 14 MPa, viscosity nonlinearly increased with deformation due to elastic responses of the sample and the piston. At 24 MPa, viscosity was constant throughout, but note the instantaneous decrease with respect to viscosity at lower stress. A similar instantaneous drop occurred at 44 MPa, but here cracking and viscous heating lowered the apparent viscosity throughout the measurement.

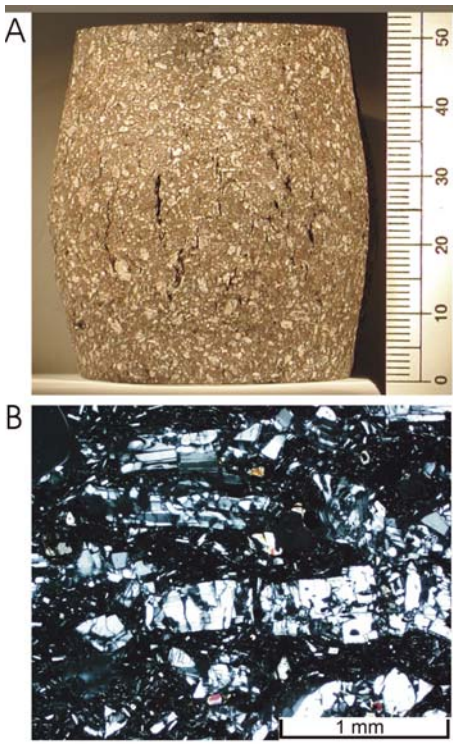


Figure 2. Post-experiment textures. A: Bulging and minor lateral extensional cracking in a Colima sample deformed at 30 MPa. B: Crystal reorientation and alignment typical of ductile response of the suspension, and crystal breakage due to brittle response of the suspension at high strain rates (vertically applied stress).

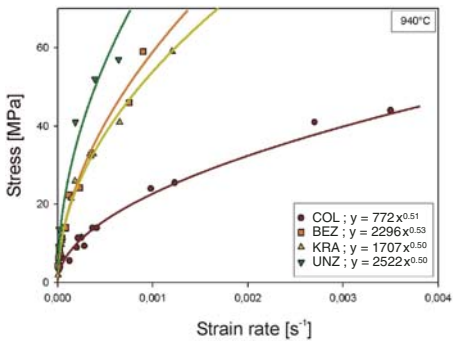


Figure 3. Stress-strain-rate profile of experiments at 940 °C. Suspension lavas behave as pseudo-plastic fluids with strong component of shear thinning of 0.510. COL—Colima; BEZ—Bezymianny; KRA—Anak Krakatau; UNZ—Unzen.

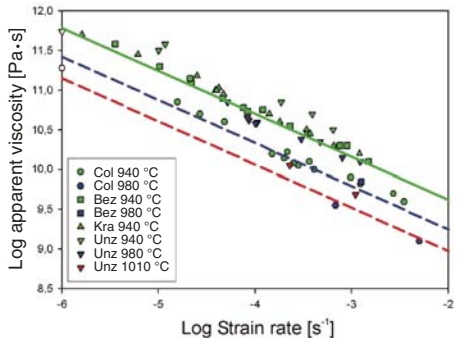


Figure 4. Viscosity–strain-rate profiles for all experiments. Green line was modeled by averaging best fit curves for each volcano at 940 °C (Table 3). Blue and red dash lines display curves obtained through our general non-Newtonian rheological law (equation 3) at 980 and 1010 °C, respectively. Viscosity estimates of Unzen (UNZ, open diamond) and Colima (COL, open circle) lavas plotted on y axis were determined with Einstein-Roscoe equation (see Table 1). BEZ—Bezymianny; KRA—Anak Krakatau.

strain rate (γ) can therefore be associated to the applied stress (σ) through a power law equation (Ostwald, 1925):

$$\sigma = k\gamma^n, \quad (1)$$

where k and n are the Ostwald and non-Newtonian constants, respectively (Fig. 3). The non-Newtonian parameter remains nearly constant for all samples, permitting the following simplification:

$$\sigma = k\gamma^{0.51}. \quad (2)$$

The accordance of the suspensions to a singular non-Newtonian constant is further reflected in the obtained viscosity data.

The results of all performed experiments reveal a linear relationship between the logarithms of viscosity and strain rate (Table 3; Fig. 4). It is interesting that, regardless of the volcano, and therefore the geochemistry, the crystal content, or the presence of 0%–25% bubbles, all calculated viscosities equally decrease by 1.5 orders of magnitude by accelerating the strain rate from 10^{-6} to ~10^{-3} s^{-1}, the point at which the strain rate began to speed up and the viscosity dropped under a given applied pressure. In contrast, single-phase melts at a similar viscosity are Newtonian up to ~10^{-3} s^{-1}; i.e., their viscosity does not exhibit a dependence on the strain rate up to this limit where viscous heating lowers the viscosity (Hess et al., 2007). The viscosity/strain rate linear relationship and the deviation from this main trend can thus be decoupled, easing our task to pinpoint different mechanical influences. We suggest that the presence of crystals causes the common linear trend described, whereas the deviation from this trend is an effect of microcracking and viscous heating, which serves to increase the temperature of the interstitial melt and therefore further decrease the viscosity.

GENERAL NON-NEWTONIAN RHEOLOGICAL LAW

The ubiquitous decrease in viscosity with increasing strain rate allows us to refine our physico-chemical picture of eruptive flows. The range of apparent viscosities exhibited by the suspensions is narrower than that of the interstitial melt viscosities obtained in previous work for pure melt phases within our temperature range (Table 1; Fig. 4; Giordano et al., 2006; Hess and Dingwell, 1996). This suggests that for high-crystal-content lavas (50%–80%), the rheological regime is primarily dictated by the crystal phase while the importance of the interstitial melt viscosity is lessened. That observation implies, in turn, that with >50% particles, suspension rheology equations such as the Einstein-Roscoe equation are irrelevant for the description of these lavas.

The effect of strain rate is universal in this investigation, regardless of crystallinity or chemistry (see a and b parameters in Table 3). The strain-rate dependence of viscosity was obtained by averaging the slopes (a) and intersections (b) of the linear regressions at 940 °C. We then followed the Hess and Dingwell (1996) method and used the various b values of Unzen and Colima to parameterize the temperature dependence according to the well-known non-Arrhenian behavior of silicate melts. Thus, a general expression capable of describing the non-Newtonian rheology of these lavas between ~850 and 1010 °C is provided by:

$$\log \eta_b = -0.993 + 8974/T - 0.543 \cdot \log \gamma, \quad (3)$$

where η_b is the apparent viscosity (Pa·s), T is temperature (°C), and γ is the strain rate (s^{-1}). This is not a theoretical equation, but rather was entirely derived empirically and is only applicable

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/35/9/843/3534709/i0091-7613-35-9-843.pdf
by University of Oslo user

when the vesicle content is below 25% and at moderate strain rates between 10^{-3} and 10^{-6} s^{-1}. Yet this master equation described the entirety of our suspension viscosities within ±0.2 log unit. We anticipate it will be highly effective in delivering insights into the modeling of magma ascent and volcanic eruption.

The shear thinning exhibited by suspension lavas favors plug flow inside conduits (Ramos, 1999). At an active volcano such magma ascent dynamics are identified by the detection of periodic seismic swarms at a limited depth range along the conduit margin (Iverson et al., 2006; Neuberg et al., 2006; Tuffen et al., 2003), and surficially expressed by dome growth or the extrusion of a spine. Plug disruption is known to produce catastrophic explosive eruption (Gonnermann and Manga, 2003; Papale, 1999), but numerical models need better rheological constraints. However, the master equation and data presented herein strongly support recent modeling of stick-slip motion during the 2004–2005 dome growth phase at Mount St. Helens (Iverson et al., 2006), and therefore will help merge the fields of volcanology, seismology, and numerical modeling in upcoming times of volcanic crisis.

In summary, the observed microtextures and viscosity data obtained present a new view on the rheology of lava containing 50%–80% crystals. Within this limit, the suspension obeys a simple linear regression that predicts its rheology up to strain rates of 10^{-3} s^{-1}. Above this strain rate, rheological models need to consider microcracking and heating generated by viscous dissipation. The simple non-Newtonian equation of strain-rate dependent rheology proposed here should enable its easy incorporation in current volcanic eruption models. We believe that the result will enhance understandings of volcanic flows.

ACKNOWLEDGMENTS

We thank J.K. Russell and F.J. Ryerson for constructive reviews. Financial support was provided to Cordonnier by the German Research Foundation (DFG)–Intercontinental Scientific Drilling Program, and to Lavallee by the Bavarian Elite Network and the Desjardins Foundation. This research was partially funded by Istituto Nazionale di Geofisica e Vulcanologia grant UR# V3_2/17. This is publication no. GEOTECH–270 of the R&D-Programme GEOTECHNOLOGIEN funded by the German Ministry of Education and Research (BMBF) and DFG, Grant 03G0584A.

REFERENCES CITED

Alidibirov, M., and Dingwell, D.B., 1996, Magma fragmentation by rapid decompression: Nature, v. 380, p. 146–148, doi: 10.1038/380146a0.

Alidibirov, M., Dingwell, D.B., Stevenson, R.J., Hess, K.U., Webb, S.L., and Zinke, J., 1997, Physical properties of the 1980 Mount St. Helens cryptodome magma: Bulletin of Volcanology, v. 59, p. 103–111, doi: 10.1007/s004450050178.

Barnes, H.A., 1999, The yield stress—A review or "πανταρει"—Everything flows?: Journal of Non-Newtonian Fluid Mechanics, v. 81, p. 133–178.

Bruckner, R., and Deubener, J., 1997, Description and interpretation of the two phase flow behaviour of melts with suspended crystals: Journal of Non-Crystalline Solids, v. 209, p. 283–291, doi: 10.1016/S0022–3093(96)00571–6.

Dingwell, D.B., 1996, Volcanic dilemma: Flow or blow?: Science, v. 273, p. 1054–1055, doi: 10.1126/science.273.5278.1054.

Einstein, A., 1911, A new determination of the molecular dimensions: Annalen Der Physik, v. 34, p. 591–592 (Translation of the 1906 German version, v. 19, p. 289).

Gent, A.N., 1960, Theory of the parallel plate viscometer: British Journal of Applied Physics, v. 11, p. 85–87, doi: 10.1088/0508–3443/11/2/310.

Giordano, D., Mangiacapra, A., Potuzak, M., Russell, J.K., Romano, C., Dingwell, D.B., and Di Muro, A., 2006, An expanded non-Arrhenian model for silicate melt viscosity: A treatment for metaluminous, peraluminous and peralkaline liquids: Chemical Geology, v. 229, p. 42–56, doi: 10.1016/j.chemgeo.2006.01.007.

Gonnermann, H.M., and Manga, M., 2003, Explosive volcanism may not be an inevitable consequence of magma fragmentation: Nature, v. 426, p. 432–435, doi: 10.1038/nature02138.

Hess, K.U., and Dingwell, D.B., 1996, Viscosities of hydrous leucogranitic melts: A non-Arrhenian model: American Mineralogist, v. 81, p. 1297–1300.

Hess, K.U., Cordonnier, B., Lavallée, Y., and Dingwell, D.B., 2007, High-load, high-temperature deformation apparatus for synthetic and natural silicate melts: Review of Scientific Instruments (in press).

Hui, H.J., and Zhang, Y.X., 2007, Toward a general viscosity equation for natural anhydrous and hydrous silicate melts: Geochimica et Cosmochimica Acta, v. 71, p. 403–416.

Iverson, R.M., Dzurisin, D., Gardner, C.A., Gerlach, T.M., LaHusen, R.G., Lisowski, M., Major, J.J., Malone, S.D., Messerich, J.A.C.M.S., Pallister, J.S., Qamar, A.I., Schilling, S.P., and Vallance, J.W., 2006, Dynamics of seismogenic volcanic extrusion at Mount St. Helens in 2004–05: Nature, v. 444, p. 439–443.

Kennedy, B., Spieler, O., Scheu, B., Kueppers, U., Taddeucci, J., and Dingwell, D.B., 2005, Conduit implosion during Vulcanian eruptions: Geology, v. 33, p. 581–584, doi: 10.1130/G21488.1.

Lejeune, A.M., and Richet, P., 1995, Rheology of crystal-bearing silicate melts—An experimental-study at high viscosities: Journal of Geophysical Research—Solid Earth, v. 100, p. 4215–4229, doi: 10.1029/94JB02985.

McBirney, A.R., and Murase, T., 1984, Rheological properties of magmas: Annual Review of Earth and Planetary Sciences, v. 12, p. 337–357, doi: 10.1146/annurev.ea.12.050184.002005.

Melnik, O., and Sparks, R.S.J., 1999, Nonlinear dynamics of lava dome extrusion: Nature, v. 402, p. 37–41, doi: 10.1038/46950.

Murase, T., McBirney, A.R., and Melson, W.G., 1985, Viscosity of the Dome of Mount St-Helens: Journal of Volcanology and Geothermal Research, v. 24, p. 193–204, doi: 10.1016/0377–0273(85)90033–2.

Neuberg, J., Tuffen, H., Collier, L., Green, D., Powell, T.W., and Dingwell, D., 2006, The trigger mechanism of low-frequency earthquakes on Montserrat: Journal of Volcanology and Geothermal Research, v. 153, p. 37–50, doi: 10.1016/j.jvolgeores.2005.08.008.

Ostwald, W., 1925, Concerning the function rate of the viscosity of dispersion systems: IV: Kolloid-Zeitschrift, v. 36, p. 248–250, doi: 10.1007/BF01422893.

Papale, P., 1999, Strain-induced magma fragmentation in explosive eruptions: Nature, v. 397, p. 425–428, doi: 10.1038/17109.

Petford, N., 2003, Rheology of granitic magmas during ascent and emplacement: Annual Review of Earth and Planetary Sciences, v. 31, p. 399–427, doi: 10.1146/annurev.earth.31.100901.141352.

Pinkerton, H., and Norton, G., 1995, Rheological properties of basaltic lavas at sub-liquidus temperatures—Laboratory and field-measurements on lavas from Mount Etna: Journal of Volcanology and Geothermal Research, v. 68, p. 307–323, doi: 10.1016/0377–0273(95)00018–7.

Ramos, J.I., 1999, Two-dimensional simulations of magma ascent in volcanic conduits: International Journal for Numerical Methods in Fluids, v. 29, p. 765–789, doi: 10.1002/(SICI)1097–0363(19990415)29:7<765:AID-FLD816>3.0.CO;2-B.

Roscoe, R., 1952, The viscosity of suspensions of rigid spheres: British Journal of Applied Physics, v. 3, p. 267–269, doi: 10.1088/0508–3443/3/8/306.

Ryerson, F.J., Weed, H.C., and Piwinskii, A.J., 1988, Rheology of subliquidus magmas. 1. Picritic compositions: Journal of Geophysical Research—Solid Earth and Planets, v. 93, p. 3421–3436.

Spieler, O., Kennedy, B., Kueppers, U., Dingwell, D.B., Scheu, B., and Taddeucci, J., 2004, The fragmentation threshold of pyroclastic rocks: Earth and Planetary Science Letters, v. 226, p. 139–148, doi: 10.1016/j.epsl.2004.07.016.

Stevenson, R.J., Dingwell, D.B., Webb, S.L., and Sharp, T.G., 1996, Viscosity of microlite-bearing rhyolitic obsidians: An experimental study: Bulletin of Volcanology, v. 58, p. 298–309, doi: 10.1007/s004450050141.

Tuffen, H., Dingwell, D.B., and Pinkerton, H., 2003, Repeated fracture and healing of silicic magma generate flow banding and earthquakes?: Geology, v. 31, p. 1089–1092.

Vigneresse, J.L., and Tikoff, B., 1999, Strain partitioning during partial melting and crystallizing felsic magmas: Tectonophysics, v. 312, p. 117–132, doi: 10.1016/S0040–1951(99)00167–5.

Manuscript received 3 January 2007
Revised manuscript received 30 April 2007
Manuscript accepted 3 May 2007

Printed in USA

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/35/9/843/3534709/i0091-7613-35-9-843.pdf
by University of Oslo user