

**A COMPARISON OF CALCULATED AND MEASURED RHEOLOGICAL PROPERTIES OF CRYSTALLISING LAVAS IN THE FIELD AND IN THE LABORATORY.** Harry Pinkerton & Gill Norton, Environmental Science Division, Lancaster University, Lancaster LA1 4YQ, U.K.

**Summary:** Models of most magmatic processes, including realistic models of planetary lava flows require accurate data on the rheological properties of magma. Previous studies suggest that field and laboratory rheological properties of hawaiian lavas can be calculated from their physico-chemical properties using a non-Newtonian rheology model. The present study uses new measurements of the rheological properties of crystallising lavas to show that this is also true for lavas from Mount Etna. Rheological measurements on quenched Etna basalts were made in a specially designed furnace using a Haake Rotovisco viscometer attached to a spindle which has been designed to eliminate slippage at the melt-spindle interface. Using this spindle, we have made measurements at lower temperatures than other workers in this field. From these measurements, Mount Etna lavas are Newtonian at temperatures above 1120 °C and they are thixotropic pseudoplastic fluids with a yield strength at lower temperatures. The close agreement between calculated and measured rheology over the temperature range 1084 - 1125 °C support the use of the non-Newtonian rheology model in future modelling of planetary lava flows.

**Introduction:** At temperatures above 1150 °C, Hawaiian lavas are Newtonian, and at lower temperatures they approximate to Bingham materials (1). Since most basaltic lavas are erupted at, or below, this temperature, and since we are not aware of any rheological measurements on basaltic melts at temperatures below 1120 °C, one of our objectives was to acquire accurate rheological data in the temperature range at which basaltic lavas are erupted (1084-1125 °C). We also wished to determine whether there were significant differences between field and laboratory rheological measurements on Mount Etna, since Shaw and colleagues (1,2) found little difference between field and laboratory measurements on hawaiian lavas.

The rheological system used in this study is a concentric cylinder viscometer within a high temperature furnace which is similar to that developed independently by Spera et al. (3). Rheological measurements are performed using a Haake Rotovisco viscometer. Special spindles have been developed for sub-liquidus rheological measurements. These ensure that the spindles do not break during measurements, and they minimise the problems caused by slippage between the melt and spindle at high crystal concentrations. The viscometer was calibrated using standard soda-lime-silica float glass. Measured viscosities were within 5% of the supplied values at all measured temperatures, and thermocouple calibration confirm that temperature errors are  $\pm 2$  °C.

**Laboratory rheological measurements on a Mount Etna lava:** Results presented here are based on two sets of measurements on lava collected during the 1983 eruption of Mount Etna (4). The lava was air-quenched from an eruptive temperature of 1095 °C. Controlled degassing in the laboratory was achieved by heating the powdered Etna basalt in the furnace at a temperature of 1145 °C. The lavas retained small crystal nuclei after heating in an Oxygen-free Nitrogen atmosphere at this temperature for 6 hours. During slow cooling from this temperature, the presence of these nuclei ensured rapid crystal growth rates. Consequently, our starting samples were similar in crystallinity to lavas which had cooled slowly in the field. Temperatures were raised at a rate of 10 °C /min to 1084 °C and a rheological measurement was made at this temperature and at temperature intervals of 5 °C up to 1125 °C. Thermal equilibrium within samples was attained at all temperatures by keeping the temperature constant at the required temperature for 60 minutes before making any measurement. We also made rheological measurements as the temperature was lowered to 1190 °C. Quenched samples confirm that the melts which were subjected to a heating cycle had a higher crystal content at any given temperature than those which had been cooled to this temperature.

**Rheological results:** Data from the laboratory rheological experiments are recorded as instrument torque vs. spindle rotation rate plots. Using the analytical procedure described by Spera et al. (3), the raw data are transformed to shear stress-shear strain rate relationships. The measurements, which have been analysed for strain rates in the range 0.3 to 5 s<sup>-1</sup>, suggest that the 1983 Etna lava is Newtonian above 1120 °C. When the strain rate was very slowly reduced to zero, the lavas at temperatures below 1120 °C had yield strengths which varied systematically with temperature. The maximum yield strength recorded in the laboratory was 78 Pa at a temperature of 1087 °C. While the lavas are therefore Herschel-Bulkley models, their yield strengths are so low that they can be approximated as power law fluids ( $r^2 > 0.95$ ) at temperatures below 1120 °C. The exponent in the power law equation decreases systematically from 1.00 above 1120 °C to 0.46 at 1084 °C.

**Discussion of the rheological properties of Etna lavas:** Post-rheological geochemical analyses of the sample quenched at 1097.5 °C show that the composition is not significantly different from that of the original

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lava. In addition, the composition of the top of the sample is virtually identical to the composition of the bottom; this confirms that volatile-loss and crystal settling are not important on the time scale of these experiments. Viscous heating and crystal settling rates have been calculated, and they were negligible for the time scales and shear strain rates used in these experiments. In addition, calculations, supported by thin section analysis, confirms that migration of crystals and bubbles away from the spindle due to radial motion of the lava on shearing did not occur. Our measurements also indicate that, as previously found on Hawaii (1,2), the lavas are thixotropic at all temperatures measured. During the time interval between rheological measurements, the static yield strength increased; the magnitude of the regained yield strength is dependent on the time at rest. An additional complication arose because stirring induces crystallisation, especially at high degrees of supercooling; this leads to rheopectic behaviour, a dramatic increase in viscosity, and the development of a yield strength.

Because crystal growth rates are considerably slower than rates at which crystals melt, the crystal content on melting a lava at a given heating rate will generally be greater than in a sample which has been cooled to the same temperature at the same relatively rapid rate. This explains why the apparent viscosities of crystallising Etna lavas were larger in samples that have been heated than in those which have cooled (Fig 1). It also explains why the laboratory measurements on heating are close to those obtained in the field where the lavas have cooled slowly prior to eruption in a volatile-rich environment (Fig 1).

**Comparison of measured and calculated rheological properties:** The viscosities measured in this study are significantly higher than values calculated using the method of Shaw (5). This difference is due to changing chemistry of the melt during crystallisation, together with the hydrodynamic interaction effects caused by bubbles and crystals in the experimental sample. The factors controlling the development of a non-Newtonian rheology in crystallising melts have been reviewed recently (6,7), and it is accepted that basic melts can be approximated as Newtonian fluids at crystal concentrations below 25 vol%. At higher concentrations, lavas behave as pseudoplastic materials with a yield strength, and their shear stress-strain rate relationships can be calculated from the crystal sizes, shapes and size distributions.

In Fig 1, we show the calculated apparent viscosity of a supercooled Etna lava (lower dotted line); that of the residual melt during crystallisation (higher dotted line); and the calculated trends for 20% and 40% crystal content (upper dotted lines). Modelled crystal contents are similar to those of quenched samples heated to 1116 °C and 1098 °C respectively. The close agreement between theoretical and measured values of apparent viscosity in the field and in the laboratory (Fig 1) support the usefulness of the model which has been developed to calculate the rheological properties of lavas at sub-liquidus temperatures (6,7). This is the first stage in the development of finite element models which will predict the dimensions and advance rates of lavas from Mount Etna. Once these model is refined and tested, they can be used to refine existing models (e.g. 8,9) of planetary lava flows.

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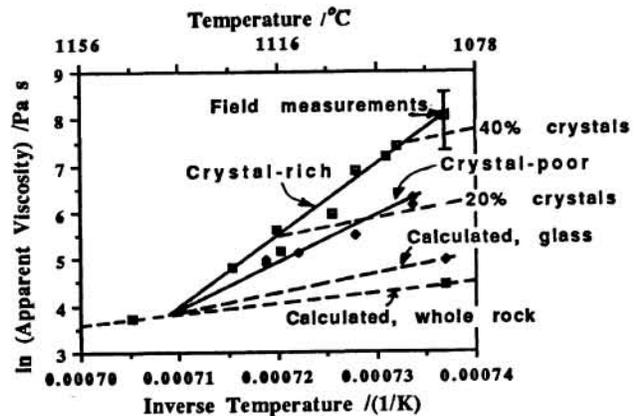


Figure 1 Apparent viscosity, at unit strain rate, of lavas from Mount Etna. Calculated trends are shown as dotted lines, and measured trends for the crystal-rich and crystal-poor lavas are shown as solid regression lines through measured data points.