RHEOLOGICAL PROPERTIES OF MOLTEN KILAUEA IKI BASALT CONTAINING SUSPENDED CRYSTALS

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INTRODUCTION

In order to understand the flow behavior of molten silicates containing suspended crystals, we need to know the rheological behavior of the system as a function of volume fraction of the suspended crystalline phases at appropriate temperatures, oxygen fugacities and bulk compositions. This approach can be applied to magma transport during volcanic eruptions, large scale convective and mixing processes in magmatic systems, and fouling of internal boiler surfaces by coal ash slags in plants burning pulverized coal.

EXPERIMENTAL METHODS

We are currently determining the dynamic viscosity and crystallization sequence for a basalt from Kilauea Iki, Hawaii at 100 kPa total pressure. The oxygen fugacity is controlled by mixing CO and CO_2. The mixing proportions are chosen to yield oxygen fugacities corresponding to the high temperature extrapolation of quartz-fayalite-magnetite buffer (i.e. QFM, see Huebner (1)). Viscosities are being measured in an iron-saturated, Pt-30% Rh, rotating-cup viscometer of the Couette type from 1250° to 1150°C. The temperature interval for the crystallization sequence ranges from 1270° to 1130°C; the oxygen fugacity is maintained by flowing CO/CO_2 mixtures and is monitored by a ZrO_2 sensor cell. Low temperature limits on the investigated crystallization sequence are dictated by the sluggish kinetics encountered in this system.

RESULTS

The major element bulk composition of the starting material used in our experiments is given in Table 1:

TABLE 1. Analyses of Starting Material

Oxide	Kilauea Iki	Shaw *et. al*(2)
SiO_2	46.29	50.14
Al_2O_3	10.44	13.37
MgO	17.90	8.20
FeO*	11.34	10.13
Fe_2O_3	-	1.21
CaO	8.49	10.80
Na_2O	1.84	2.32
P_2O_5	0.22	0.27
K_2O	0.40	0.53
TiO_2	1.89	2.63
MnO	0.19	0.17
TOTAL	99.90	99.77

*All iron as FeO

The crystallization experiments were carried out employing a specimen of Kilauea Iki whole rock powder. The experimental results obtained at the QFM buffer are listed in Table 2. Olivine and chrome spinel are the only crystalline phases which occur between 1240°and 1179°C; clinopyroxene and plagioclase feldspar crystallize at approximately 1170°C.

Approximately 30 weight per cent crystallization occurs between 1250° and 1180°C. The liquid line of descent is characterized by a slight SiO_2, Al_2O_3 and alkali enrichment and an FeO and MgO depletion.

The volume percentage of melt as a function of temperature is shown in Figure 1. The break in slope at approximately 1170°C, corresponds to the appearance of clinopyroxene and plagioclase feldspar (see Table 2).

TABLE 2. Results of Selected Kilauea Iki Liquidus Experiments

Exp't No.	Time (Hrs)	Temp (°C)	Experiment Products	Vol % Melt[a]	Wt % Melt[b]
14	93.0	1240	olivine, chrome spinel, glass	71.8	78.1
9	189.5	1230	olivine, chrome spinel, glass	80.2[c]	76.1
8	24.0	1219	olivine, chrome spinel, glass	77.3	74.8
10	290.0	1209	olivine, chrome spinel, glass	76.2	74.2
12	289.0	1189	olivine, chrome spinel, glass	63.8	72.5
13	364.0	1179	olivine, chrome spinel, glass	71.8	71.5
16	380.0	1170	olivine, chrome spinel, clinopyroxene, plagioclase, glass	69.6	68.5
19	400.0	1160	olivine, chrome spinel, clinopyroxene, plagioclase, glass	54.7	53.5
20	400.0	1149	olivine, chrome spinel, clinopyroxene, plagioclase, glass	40.7	49.8

a) Volume percent of melt was determined by a 1000 point mode on metallograph.
b) Weight percent of melt was determined by constrained least squares analysis of phase compositions.
c) Volume percent glass was determined by 850 point mode on metallograph.

This volume percentage of melt, V_m, is given by Equations 1 and 2:

$$V_m\ (Ol+Chsp) = 0.157\ T(°C) - 114.0, \text{ where } T(°C) \geq 1170, \quad 1)$$

$$V_m\ (Ol+Chsp+Cpx+Plag) = 1.36\ T\ (°C) - 1522.7, \text{ where } T\ (°C) \leq 1170. \quad 2)$$

Extrapolation of Equation 1 to V_m = 100 corresponds to T = 1360°C for the liquidus. Extrapolation of Equation 2 to V_m = 0 yields T = 1119°C for the disappearance of liquid, the solidus temperature.

The measured apparent viscosities of the Kilauea Iki molten basalt between 1250° and 1150°C varied from 30 to 2000 Pa•s. Sigmoidal torque versus rotation speed curves were obtained at all investigated temperatures. The curves are linear at low rotation speeds, less than 0.4 revolutions/second, with a positive slope. This corresponds to Newtonian behavior. However, at higher rotation speeds, the curves are concave toward the rotation speed axis, indicating pseudoplastic behavior. This pseudoplastic behavior becomes more pronounced at low temperature as the volume per cent of suspended crystals increases. We have analyzed the results in terms of an extended the power law indicated by Equation 3:

$$\log \tau_{yx} = A_1 + A_2\left(\log \left(\frac{du}{dx}\right)\right) + A_3\left(\log \left(\frac{du}{dx}\right)\right)^2 \quad 3)$$

where τ_{yx} is the stress, and $(\frac{du}{dx})$ the strain rate. The apparent viscosity, μ, is given by Equation 4:

$$\mu = \tau_{yx} \Big/ \left(\frac{du}{dx}\right) \quad 4)$$

Figure 2 is a plot of Equation 3 portraying experimental results obtained at the 1236°C isotherm. Figure 3 is a log-log plot of apparent viscosity as a function of shear rate at the same temperature. The apparent viscosity decreases with increasing shear rate, which is common for pseudoplastic liquids. The log of the viscosity at unit shear rate, log μ_0, is calculated from Equation 3 as $\log \mu_0 = A_1$.

Log μ_0 is plotted as a function of reciprocal temperature in an Arrhenius diagram given in Figure 4. The log viscosity curves illustrated there show a sharp break in slope with decreasing temperature. Data above and below this break have been fitted by limiting straight lines from which apparent activation energies can be calculated. The apparent activation energy in the temperature interval 1250° - 1170°C is 65 ± 30 kcal mol^{-1}. For temperatures below 1170°C where appreciable crystallization occurs (see Table 2 and Figure 1) and the system exhibits strongly pseudoplastic behavior, the apparent activation energy is 341 ± 42 kcal mol^{-1}. Also shown in Figure 4 are the results of Shaw (3) obtained on a Hawaiian basalt similar to our Kilauea Iki specimen (see Table 1). The general trend of the two sets of data is similar, but the break in the slope of Shaw's data occurs at a lower temperature than it does in ours, presumably because of the change from Newtonian to pseudoplastic behavior in his system. In both studies, the break in the slope of the viscosity curves occurs at 20 to 30 volume percent of suspended crystals. The non-Newtonian behavior of these molten silicate suspensions appears to arise from the increasing volume of suspended crystals in the melt. This suggests that in modeling fluid flow in silicate liquids, power law behavior should be considered when the suspended crystal volume exceeds 20 percent.

REFERENCES

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(3) Shaw, H. R. (1969) Jour. Petrology, Vol. 10, p. 510-535.

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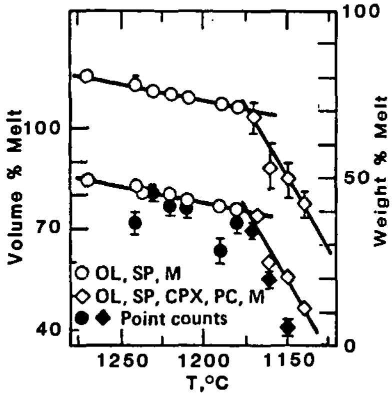

Fig. 1. Volume percent and weight percent melt as a function of temperature for Kilauea Iki basalt. The upper curve gives weight percent melt, indicated by the right ordinate. Open symbols on the lower curve give volume percent melt remaining (left ordinate), calculated from weight percent data and densities of phases. Solid symbols are from modal analyses.

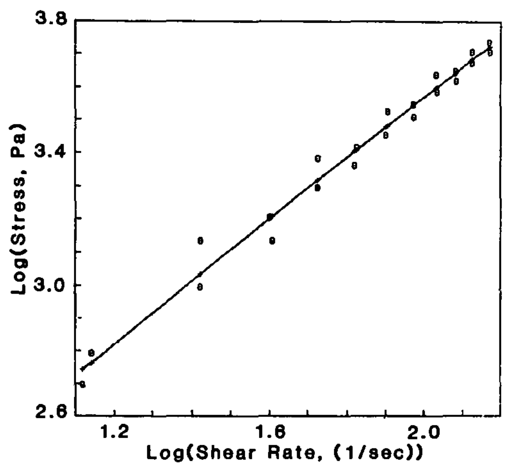

Fig. 2. Log (Stress) as a function of log (Shear Rate) for Kilauea Iki basalt melt at 1236°C.

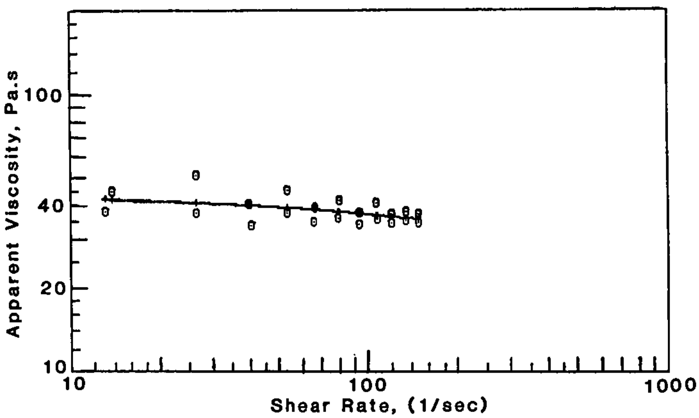

Fig. 3. Apparent viscosity of Kilauea Iki basalt melt as a function of shear rate at 1236°C.

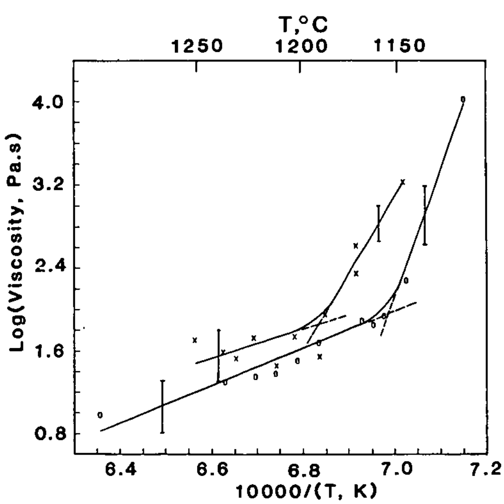

Fig. 4. Log (Apparent Viscosity) as a function of a reciprocal temperature. Present study, X; Shaw (1969), θ.