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VISCOSITY OF A PANTELLERITE MELT AT ONE ATMOSPHERE

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ABSTRACT

Laboratory measurements of the viscosity of a pantellerite melt from Fantale, Ethiopia, were made with a concentric-cylinder viscometer at 1300-1450°C at one atmosphere. All experiments were conducted in air. Viscosities (~ 10^4 poise) were independent of shear rate, demonstrating Newtonian viscous flow. The temperature dependence of the viscosity can be described by the Arrhenius relationship, $\eta=\eta_o \exp(E\eta/RT)$, from which the activation energy for viscous flow ($E\eta$) was calculated as 85±15 kcal $mole^{-1}$. There was good agreement between measured viscosities and viscositites calculated using the Bottinga-Weill-Shaw method. Between 1300-1450°C the pantellerite melt had a lower viscosity than obsidian, but a considerably higher viscosity than basalt. These differences can be explained on the basis of melt chemistry and its influence on melt structure. Extrapolation of the results to the eruptive temperature of the Fantale flows provides an upper limit for their viscosity.

SOMMAIRE

Des mesures en laboratoire de la viscosité d'un fondu pantelléritique de Fantale, Ethiopie, ont été faites avec un viscosimètre à cylindres concentriques, à des températures de 1300-1450°C à un atmosphère. Toutes les expériences ont été réalisées à l'air libre. Les viscosités (~10^4 poises) étaient indépendantes du taux de cisaillement, démontrant un écoulement newtonien. La fonction température-viscosité peut être décrite par la relation d'Arrhenius, $\eta=\eta_o \exp(E\eta/RT)$; à partir de laquelle on a calculé une énergie d'activation de l'écoulement visqueux ($E\eta$) de 85±15 kcal/mole. Les viscosités mesurées s'accordent bien avec celles calculées par la méthode de Bottinga-Weill-Shaw. Entre 1300 et 1450°C le liquide pantelléritique a une viscosité plus faible que celle d'une obsidienne, mais nettement plus élevée que celle d'un basalte. Ces différences peuvent s'expliquer par le chimisme du fondu et son influence sur la structure de celui-ci. L'extrapolation de ces résultats à la température d'éruption des coulées de Fantale fournit une limite supérieure à leur viscosité.

INTRODUCTION

The viscosity of magma is an important parameter in problems concerning the generation and emplacement of magmatic rocks (e.g. Shaw 1965; Ramberg 1967). Melt viscosities are also indicators of melt structure (e.g. Bockris & Lowe 1954; Mackenzie 1960; Lacy 1967; Bottinga & Weill 1972; Shaw 1972; Scarfe 1973).

Although the viscosity of anhydrous obsidian melt is reasonably well-known (Volarovic & Korcemkin 1937; Carron 1969; Murase & McBirney 1973), the viscosity of pantellerite melt has not been investigated in the laboratory. Field and laboratory evidence suggests that these peralkaline silicic melts extrude at relatively high temperatures, may have low viscosities, and are often associated with a halogen-bearing volatile phase (e.g. Gibson 1972; Schmincke 1974; Macdonald *et al.* 1974).

This paper describes the laboratory determination of the viscosity of an anhydrous pantellerite melt at temperatures between 1300-1450°C at one atmosphere. Since the study was carried out above the liquidus temperature of basalt (~1200°C), a comparison can be made between the viscosities of obsidian, pantellerite, and basalt melts. From such comparisons it is possible to make deductions concerning the polymerized structure of these melts.

EXPERIMENTAL METHOD

The starting material was a pantellerite specimen from the Quaternary volcano, Fantale, Ethiopia (Table 1). The glassy rock, which is similar to Y.335 (Gibson 1972), contains a few phenocrysts of anorthoclase and quartz and traces of aenigmatite, ferrohedenbergite, and alkali amphibole. The rock has a large molecular excess of alkalis over alumina (agpaitic index = 1.53) and acmite and sodium metasilicate appear in the norm.

Glass free from bubbles and crystals was fused from rock powder in air at 1600°C for two hours (Table 1). Fusion was carried out in alumina crucibles and the liquid was poured into a steel mold, the internal dimensions of which were identical to the internal dimensions of the outer cylinder of the viscometer (Fig. 1). Under run conditions the volume of the glass

TABLE 1. Chemical Analyses of Rocks and Glass

	a	b	c	d	e	f
SiO_2	72.76	72.12	72.50	71.37	72.50	73.40
TiO_2	0.05	0.34	0.39	0.04	0.10	0.20
Al_2O_3	1.36	9.25	9.27	14.72	13.50	14.24
Fe_2O_3	0.19	3.28	3.31	1.08	0.50	0.24
FeO	-	4.07	4.03	1.38	1.85	1.76
MnO	-	0.26	0.26	0.06	0.10	0.06
MgO	3.81	0.04	0.08	0.35	1.30	0.18
CaO	8.11	0.32	0.37	1.36	0.90	1.35
Na_2O	12.86	5.70	5.39	3.74	4.55	5.15
K_2O	0.67	4.45	4.43	5.69	4.15	4.10
H_2O	-	0.22	-	0.33	0.70	0.50
P_2O_5	-	0.01	0.02	-	tr	0.03
	99.83	100.06	100.05	100.12	100.15	101.17

XRF analyses of b and c by J. G. Holland (wet chemical analyses of FeO and H_2O by A. Stelmach)

a. Soda-lime-silicate glass (Proc. Soc. Glass Technol., 1956. 40, 58-104).

b. Pantellerite: Fantale (Gibson 1972, similar to Y335).

c. Glass: pantellerite rock powder (∿50 g) fused for 2 hours at 1600°C in air. Some oxidation took place during the viscosity experiment which was ∿ 3 hours in duration.

d. Obsidian: Oki (Volarovic & Korcemkin 1937, composition 37) gives a viscosity of 10^6 poise at 1400°C. The other obsidians, Erevan and Arita, give lower and higher viscosities respectively.

e. Obsidian: Volcano (Carron 1969, composition E).

f. Obsidian: Newberry Caldera (Murase & McBirney 1973).

slug (~8 cc) filled the cavity between the inner and outer platinum cylinders of the viscometer. The silicate liquid was sandwiched between the outer rotating cylinder and the inner stationary cylinder which was suspended from a torsion wire. The torque transmitted to the inner cylinder by the silicate liquid was measured as an angular displacement and recorded by a light-spot deflection on a linear scale (Fig. 1). Further details of the apparatus and method of operation are in Dingwall & Moore (1954), Dietzel & Brückner (1955), and van Wazer *et al.* (1963). Viscosities were calculated from the equation for Newtonian liquids

$$\eta = \frac{M}{4\pi\Omega\,(h+k)} \quad \frac{1}{r^2} - \frac{1}{R^2} \qquad (1)$$

where M is the torque, Ω is the angular velocity of the outer cylinder, r is the radius of the inner cylinder, R is the radius of the outer cylinder, and $(h+k)$ is the effective length of the inner cylinder.

The apparatus was calibrated under run conditions using a standard soda-lime silicate glass (Table 1). Rotational speeds could be varied from 4-36 seconds per revolution. Viscosities were accurate to ±5% and temperatures to ±5°C. Since the oxidation state of the melt was thought to have only a marginal effect on viscosity (Shaw 1969; Murase & McBirney 1970; Scarfe 1973), all experiments were conducted in air. Loss of iron from the melt was minimized by using 'iron-saturated' platinum cylinders.

RESULTS AND DISCUSSION

At constant temperature there is a linear relationship between the rotation speed of the outer cylinder and the angular displacement of the inner cylinder (Fig. 2). This is equivalent to a plot of shear rate against shear stress, which for Newtonian liquids is a straight line through the origin. This conclusion is in keeping with the observation that most silicate melts of geological interest show Newtonian viscous behavior at temperatures above their liquidi (e.g. Shaw 1963, 1969; Carron 1969; Murase & McBirney 1973; Scarfe 1973).

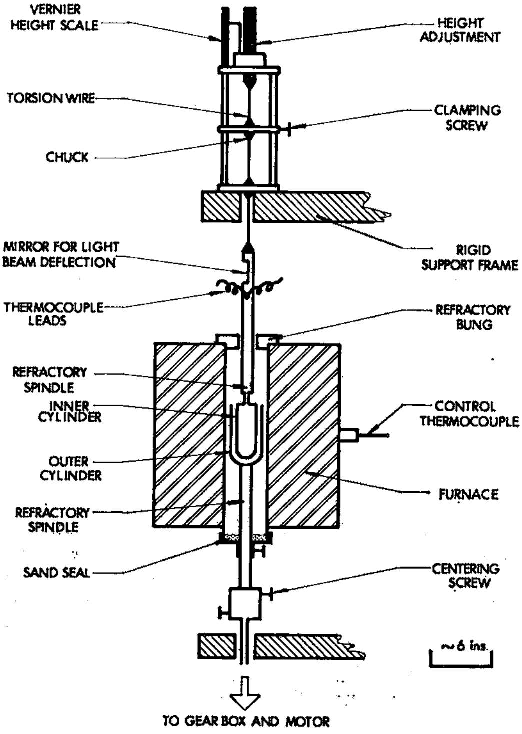

FIG. 1. Cross-section of concentric-cylinder viscometer. Cylinder design after Dietzel & Brückner (1955); general design after Dingwall & Moore (1954).

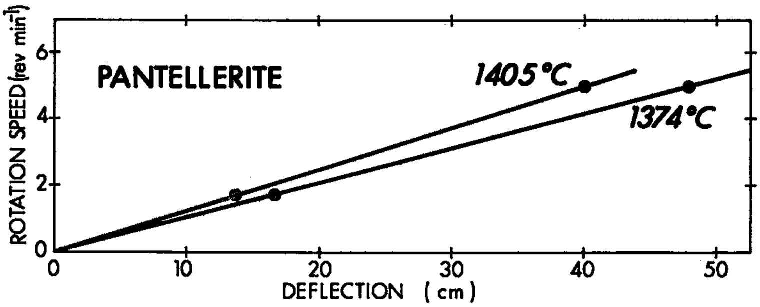

FIG. 2. Relationship between rotation speed and light-spot deflection at two temperatures.

A linear relationship exists between the logarithm of the viscosity and reciprocal temperature in the range 1300-1450°C (Table 2 & Fig. 3). The temperature-dependence of the viscosity can be described by an Arrhenius relationship of the form $\eta=\eta_o \exp(E\eta/RT)$, where η_o is a constant and $E\eta$ is the activation energy for viscous flow. The activation energy for viscous flow was calculated to be 85±15 kcal mole^{-1}. This value is in fair agreement with 68±15 kcal mole^{-1} obtained from viscosities calculated using the Shaw modification (1972) of the Bottinga-Weill (1972) method of predicting viscosities. Calculated and observed viscosities agree to within ~0.2 logarithm units (Table 2).

At any given temperature, the pantellerite has a lower viscosity than obsidian (Fig. 4); however, activation energies are similar. The obsidians from Volcano (Carron 1969) and the Newberry Caldera (Murase & McBirney 1973) have activation energies of 71±3 kcal mole^{-1} and ~90 kcal mole^{-1} respectively. There is no simple explanation for the discrepancy in the obsidian results. Since the bulk compositions are similar (Table 1), the discrepancies must be the result of the use of different experimental methods. Volarovic & Korcemkin (1937) and Carron (1969) used concentric-cylinder viscometry,

TABLE 2. Viscosity of Pantellerite Melt

temperature (°C)	1405	1374	1345	1325	E (kcal mole^{-1})
$\log_{10}\eta$obs (poise)	4.08	4.16	4.44	4.54	85 ± 15
$\log_{10}\eta$calc (poise)	3.87	4.04	4.20	4.31	68 ± 15

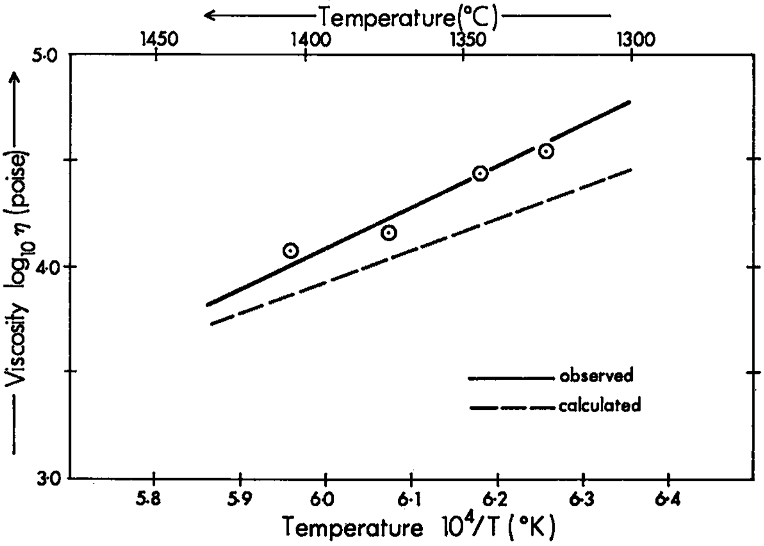

FIG. 3. Viscosity versus reciprocal temperature for a melt of pantellerite composition. Data from Table 2.

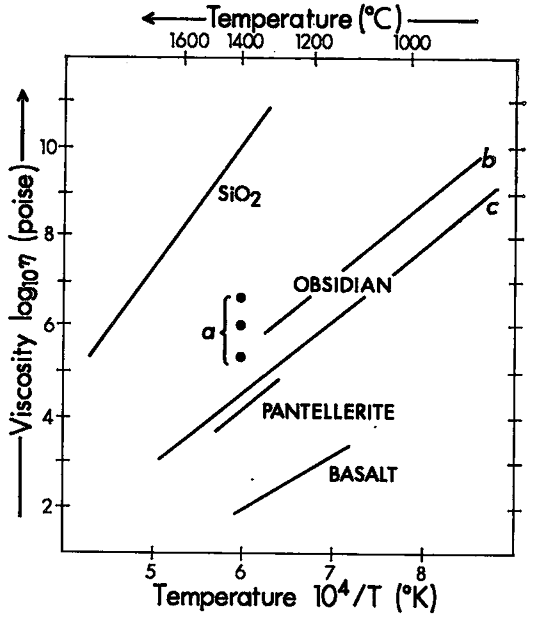

FIG. 4. Viscosity versus reciprocal temperature for melts of composition of pantellerite (this study) and obsidian (a, Volarovic & Korcemkin 1937; b, Murase & McBirney 1973; c, Caron 1969) compared with silica (Hofmaier & Urbain 1968) and basalt (Scarfe 1973).

whereas Murase & McBirney (1973) used a beam-bending method. At low temperatures Carron (1969) used a deformation method.

The lower viscosity of pantellerite may be explained by its melt chemistry (Table 1). Evidence from simplified systems shows that aluminum ions usually have the role of network-formers and have four-fold coordination in the melt (Kozakevitch 1961; Riebling 1966). Alkalis and most of the iron, on the other hand, function as network-modifiers having six-fold or higher coordination in the melt (Mackenzie 1960). Some ferric iron may be in four-fold coordination and will act as a network-former (Kurkjian & Sigety 1968; Waff 1977). Nevertheless, reduction in aluminum and an increase in alkalis and iron (Table 1) depolymerize the melt, decreasing the viscosity of the pantellerite relative to the obsidian.

At 1300°C there are two orders of magnitude difference (10^2-10^4 poise) between the viscosities of pantellerite and basalt melts (Fig. 4). Melts of basalt composition have a higher proportion of network-modifier cations and a less polymerized polyanionic melt framework (Hess 1971). Thus, the difference in viscosity between pantellerite and basalt melt is one of degree of polymerization. A further measure of the polymerization is the magnitude of the activation energies for viscous flow at 1300-1450°C. The values for obsidian and pantellerite may be compared with 56 ± 5 kcal mole^{-1} for basalt (Scarfe 1973) and 123 ± 1.8 kcal mole^{-1} for silica (Hofmaier & Urbain 1968). The measurements on silica were made above 1600°C.

When these results are extrapolated to the eruptive temperature of pantellerite magmas they provide an approximate upper limit on the viscosity of the weakly phyric Fantale flows. The flows were probably extruded close to their liquidus temperatures, which may have been as high as 1000°C, with oxygen fugacities close to the fayalite-magnetite-quartz buffer (Nicholls & Carmichael 1969). A melt containing a few percent crystals will have a higher viscosity than a melt without crystals. Using Einstein-Roscoe equations, Shaw (1965) calculated factors of 1.3 and 1.8 for 10% and 20% crystals respectively. However, experiments on basaltic compositions (Shaw 1969; Murase & McBirney 1973; Scarfe 1973) have shown larger factors. Nevertheless, the increase in viscosity is unlikely to be much greater than one order of magnitude for the Fantale melt containing ~15% crystals. Thus an upper limit on the viscosity of the Fantale pantellerite is ~10^8 poise.

Volatiles dissolved in the melt may reduce viscosities considerably below those obtained in this paper. Volatiles are thought to play an important role in the origin and evolution of pantellerites (Macdonald *et al.* 1974) and a halogen-bearing volatile phase has been discussed by Gibson (1972, 1974) in connection with the Fantale pantellerites. Shaw (1963) has demonstrated the effective way in which water depolymerizes and decreases the viscosity of obsidian melts. Although the effect of Cl and F on the viscosity of melts of geological interest is not well-understood, evidence from slag and glass systems (Eitel 1965; Bills 1963; Hirayama & Camp 1969) suggests that fluorine will be an important melt depolymerizer whereas chlorine may be rather less effective. It is possible, therefore, that upon eruption the Fantale pantellerite had a viscosity considerably lower than 10^8 poise.

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REFERENCES

BILLS, P. (1963): Viscosities in silicate slag systems. *J. Iron Steel Inst.* **201**, 133-140.

BOCKRIS, J. O. M. & LOWE, D. C. (1954): Viscosity and structure of molten silicates. *Proc. Roy. Soc. Lond.* A266, 423-435.

BOTTINGA, Y. & WEILL, D. F. (1972): The viscosity of magmatic silicate liquids: a model for calculation. *Amer. J. Sci.* 272, 438-475.

CARRON, J. P. (1969):Recherches sur la viscosité et les phénomènes de transport des ions alcalins dans les obsidiennes granitiques. *Ecole Normale Supérieure Paris, Travaux Lab. Géol.* No. 3, 112.

DIETZEL, A. & BRÜCKNER, R. (1955): Aufbau eines Absolutviskosimeters für hohe Temperaturen und Messung der Zähigkeit geschmolzener Borsäure für Eichzwecke. *Glastechn. Ber.* 28, 455-467.

DINGWALL, A. G. F. & MOORE, H. (1954): The effects of various oxides on the viscosity of glasses of the soda-lime-silica type. *J. Soc. Glass Tech.* 37, 316-372.

EITEL, W. (1965): *Silicate Science* 2. Academic Press, New York.

GIBSON, I. L. (1972): The chemistry and petrogenesis of a suite of pantellerites from the Ethiopian rift. *J. Petrology* 13, 31-44.

——— (1974): A review of the geology, petrology and geochemistry of the volcano Fantale. *Bull. Volcanol.* 38, 793-802.

HESS, P. C. (1971): Polymer model of silicate melts. *Geochim. Cosmochim. Acta* 35, 289-306.

HIRAYAMA, C. & CAMP, F. E. (1969): The effect of fluorine and chlorine substitution on the viscosity and fining of soda-lime and potassium-barium silicate glass. *Glass Tech.* 10, 123-127.

HOFMAIER, G. & URBAIN, G. (1968): The viscosity of pure silica. *In* Science of Ceramics 4 (G. H. Stewart, ed.), 25-32. British Ceramic Soc., London.

KOZAKEVITCH, P. (1961): Viscosity of lime-alumina-silica melts between 1600 and 2100°C. *In* Phvsical Chemistry of Process Metallurgy, Part 1 (G. R. H. Pierre, ed.). *Met. Soc. A.I.M.E. Conf.* 7, 97-116.

KURKJIAN, C. R. & SIGETY, E. A. (1968): Coordination of Fe^{3+} in glass. *Phys. Chem. Glasses* 9, 73-83.

LACY, E. D. (1967): The Newtonian flow of simple silicate melts at high temperatures. *Phys. Chem. Glasses* 8, 238-246.

MACDONALD, R., BAILEY, D. K. & BARBERI, F. (1974): Recommendations for further studies on the peralkaline oversaturated volcanic rocks. *Bull. Volc.* 38, 828-836.

MACKENZIE, J. D. (1960): Structure of some inorganic glasses from high temperature studies. *In* Modern Aspects of the Vitreous State 1 (J. D. Mackenzie, ed.), 188-218. Butterworths, London.

MURASE, T. & MCBIRNEY, A. R. (1970): Viscosity of lunar lavas. *Science* 167, 1491-1493.

——— & ——— (1973): Properties of some common igneous rocks and their melts at high temperatures. *Bull. Geol. Soc. Amer.* 84, 3563-3592.

NICHOLLS, J. & CARMICHAEL, I. S. E. (1969): Peralkaline acid liquids: a petrological study. *Contr. Mineral. Petrology* 20, 268-294.

RAMBERG, H. (1967): *Gravity Deformation and the Earth's Crust.* Academic Press, London.

RIEBLING, E. F. (1966): Structure of sodium aluminosilicate melts containing at least 50 mole % SiO_2 at 1500°C. *J. Chem. Phys.* 44, 2857-2865.

SCARFE, C. M. (1973): Viscosity of basic magmas at varying pressure. *Nature Phys. Sci.* 241, 101-102.

SCHMINCKE, H. U. (1974): Volcanological aspects of peralkaline silicic welded ash-flow tuffs. *Bull. Volc.* 38, 594-636.

SHAW, H. R. (1963): Obsidian-H_2O viscosities at 1000 and 2000 bars in the temperature range 700°-900°C. *J. Geophys. Res.* 68, 6337-6343.

——— (1965): Comments on viscosity, crystal settling and convection in granitic magmas. *Amer. J. Sci.* 263, 120-152.

——— (1969): Rheology of basalt in the melting range. *J. Petrology* 10, 510-535.

——— (1972): Viscosities of magmatic silicate liquids: an empirical method of prediction. *Amer. J. Sci.* 272, 870-893.

VAN WAZER, J. R., LYONS, J. W., KIM, K. Y. & COLWELL, R. E. (1963): *Viscosity and Flow Measurement.* Interscience, New York.

VOLAROVIC, M. P. & KORCEMKIN, L. I. (1937): Der zusammenhang zwischen der Viskosität geschmolzener Gesteine und dem Aziditätskoeffizienten nach F. J. Loewinson-Lessing. *C.R. (Dokl.) Acad. Sci. USSR* 17, 417-422.

WAFF, H. S. (1977): The structural role of ferric iron in silicate melts. *Can. Mineral.* 15, 198-199.

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