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Pressure dependence of the viscosity of silicate melts

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Abstract—Most viscosity measurements on anhydrous melt compositions of geological interest have shown an isothermal decrease in viscosity with increasing pressure. These compositions (*e.g.*, $NaAlSi_3O_8$, $NaAlSi_2O_6$ and $Na_2Si_3O_7$), however, have highly polymerized melt structures at one atmosphere. The number of non-bridging oxygens to tetrahedrally coordinated cations (Si^{4+}, Al^{3+}, Fe^{3+}, Ti^{4+}, or P^{5+}) in these melts is less than 1 (NBO/T < 1).

In order to test possible relations between pressure dependence of viscosity and polymerization of the melt, three compositions ($CaMgSi_2O_6$, $Na_2Si_2O_5$ and Na_2SiO_3) all of which are relatively depolymerized at one atmosphere (NBO/T ≥ 1), have been investigated. An isothermal increase in viscosity of these melts to 20 kbar pressure indicates a fundamental difference in the behavior of highly polymerized versus depolymerized melts. Furthermore, as a function of pressure, density increases in highly polymerized melts are greater than increases observed for depolymerized melts.

The positive pressure dependence of the viscosity of melts with NBO/T ≥ 1 is in accord with the response of other inorganic liquids to the effects of pressure. Conversely, it is melts with NBO/T < 1 that appear to behave anomalously. Raman spectroscopic and X–ray data suggest that the decrease in viscosity is due to subtle changes in the anionic framework of melts. No spectroscopic evidence has been found for pressure–induced coordination changes in aluminum to 40 kbar.

Obsidian, andesite and most basalt melts have NBO/T < 1 and their viscosities are observed to decrease with increasing pressure under isothermal conditions. Basanites, picrites, komatiites and related silica–deficient, aluminum–poor melts with NBO/T > 1 will probably show an increase in their viscosities as a function of pressure. Several geological applications are briefly discussed in the light of this contrasting viscous behavior.

INTRODUCTION

THE VISCOSITY of silicate melts is an important parameter in problems related to the generation, evolution and emplacement of igneous rocks (*e.g.*, BARTLETT, 1969). Apart from the obvious effects of lava viscosity on land forms, it governs melt aggregation and segregation at source, the ascent of magmas to the surface, and xenolith transport. Viscosity also exerts important controls on transport processes, and through these processes affects nucleation and crystal growth, crystal settling and flotation of solids.

Although viscosities of many melt compositions are reasonably well known at 1 atmosphere (*e.g.*, BOTTINGA and WEILL, 1972; URBAIN *et al.*, 1982; SCARFE, 1986), knowledge of the effect of pressure on melt viscosity is more limited. KUSHIRO (1976, 1977, 1978, 1980) showed that the viscosities of several anhydrous silicate and aluminosilicate melts decrease when measured isothermally at pressures up to 20 kbar (Figure 1). KUSHIRO *et al.* (1976), FUJII and KUSHIRO (1977a, b) and SCARFE (1981) have also shown that qualititatively similar behavior is exhibited by anhydrous rock melts of andesitic and basaltic composition (Figure 1). In the case of rock melts, sufficient data are available to indicate a viscosity decrease both isothermally and along the liquidus with pressure. Although the decrease in viscosity along the anhydrous liquidus may be due to structural changes in the melt, brought about by increasing temperature, the decrease in viscosity measured under isothermal conditions must be attributed to pressure–induced structural changes in the melt.

All the melts depicted in Figure 1 have highly polymerized structures at 1 bar (RIEBLING, 1966; TAYLOR and BROWN, 1979; MYSEN *et al.*, 1980a, 1982). If the number of non–bridging oxygens in these melts is used as a measure of the degree of polymerization (*e.g.*, BOTTINGA and WEILL, 1972; SCARFE, 1973; SCARFE *et al.*, 1979; MYSEN *et al.*, 1982; MYSEN, 1986), the number of non–bridging oxygens to tetrahedrally coordinated cations (NBO/T) is less than one. In order to test the compositional extent of the negative pressure dependence of viscosity, three compositions ($Na_2O \cdot 2SiO_2$, $Na_2O \cdot SiO_2$ and $CaMgSi_2O_6$) that are relatively depolymerized melts at 1 atmosphere (MYSEN *et al.*, 1980a), with NBO/T ≥ 1, were selected for study.

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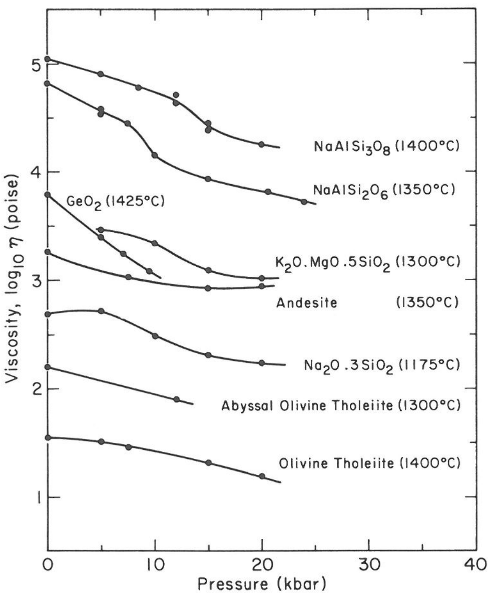

FIG. 1. Viscosity as a function of pressure for melts that have a highly polymerized structure at 1 bar. All measurements were made isothermally at the temperatures shown. Data sources are given in Table 3.

Sodium disilicate and metasilicate were selected because of their chemical simplicity, relatively low melting temperatures, and because data are available on the properties of their melts at 1 bar. Diopside was chosen because it is a major component of melts of geological interest.

This paper describes the determination of the viscosity of these melts at one bar and at high pressures and discusses the pressure dependence of viscosity in the light of previous work on synthetic and natural systems.

EXPERIMENTAL METHOD

Starting materials

Glasses and crystalline starting materials were prepared from mixtures of reagent grade Na_2CO_3, $CaCO_3$, MgO and SiO_2 at 1 bar. Fusions were performed for 1–2 hours in platinum crucibles at approximately 100°C above the respective melting points or liquidi of the compounds. Portions of the glasses were crystallized in 6–15 hours at approximately 100°C below the melting points.

For 1-bar viscosity measurements on diopside and sodium disilicate composition, 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 (see below). Crystalline starting materials were used for all high pressure experiments. Glasses were not used for high pressure experiments because they may soften and deform at temperatures below the melting point.

One-atmosphere viscometry

Viscosities were measured with a concentric-cylinder viscometer (DINGWALL and MOORE, 1954) with a cylinder design after DIETZEL and BRUCKNER (1955). Under run conditions the volume of the glass slug (approximately 8 cm^3) 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. Further details of the apparatus and method of operation can be found in SCARFE (1977). Viscosities were calculated from the equation for Newtonian liquids:

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

where M is the torque, Ω is the angular velocity of the outer cylinder, r and R are the respective radii of the inner and outer cylinders, and $(h + k)$ is the effective length of the inner cylinder (SCARFE, 1977).

The apparatus was calibrated under run conditions with a standard soda–lime–silica glass (U.S. National Bureau of Standards glass 710). Rotation speeds could be varied from 4 to 36 seconds per revolution. Viscosities were accurate to ±5% and temperatures to ±5°C. All experiments were conducted in air.

High-pressure viscometry

High pressure viscosities were measured by falling–sphere viscometry (SHAW, 1963; KUSHIRO, 1976) in a solid–media, high-pressure apparatus (BOYD and ENGLAND, 1960). The 0.75″-diameter furnace assembly incorporated a graphite heater with a 3-degree tapered inner wall, which reduces the temperature gradient along the sample to 10°C (KUSHIRO, 1976, 1978). Sealed platinum capsules, 5 mm in diameter and 10 mm long, were used to contain the samples in all experiments. The piston–out technique was used with a −4% correction to the pressure for friction. Pressures have an uncertainty of ±0.5 kbar, and temperatures, measured with Pt-Pt90Rh10 thermocouples, have an uncertainty of ±10°C. After the pressure was applied, the temperature was raised to approximately 100°C below the melting point for 5 min. to equilibrate the system thermally. The temperature was then rapidly raised to the desired experimental value within a few seconds with a programmable controller.

A variety of spheres of different density (chrome diopside, forsterite, ZrO_2, BN and Au–Pd alloy) with diameters generally <1.0 mm were used. Mineral and refractory spheres were made with the sphere-making device designed by Bond (1951). Alloy spheres were made by melting Au–Pd wire.

Under each set of temperature–pressure conditions a minimum of two experiments of different duration were made to determine the sinking or floating velocity of spheres of two different densities. After the charge was quenched (250°C/sec) and sectioned, the melt viscosity was calculated from the velocity and density of the spheres, with Stokes' equation combined with the Faxen correction for wall effects (Shaw, 1963):

$$\eta = \frac{2gr^2\Delta\rho}{9v(1+3.3r/h_c)}\left[1 - 2.104\left(\frac{r}{r_c}\right) + 2.09\left(\frac{r}{r_c}\right)^3 - 0.95\left(\frac{r}{r_c}\right)^5\right], \quad (2)$$

where η is the viscosity, g is the gravitational constant, r is the radius of the sphere, r_c is the radius of the container, h_c is the height of the container, $\Delta\rho$ is the density contrast between the sphere and the melt, and v is the sphere velocity. Melt densities were used exclusively in the calculation of melt viscosities. Viscosities have a maximum estimated uncertainty of ±15%.

Because two spheres of different density were used in each experiment (*e.g.*, BN with $\rho = 2.29$ g/cm^3, which floats, and chrome diopside with $\rho = 3.33$ g/cm^3, which sinks), two Stokes' equations with two unknown parameters (η and ρ) provide the simultaneous determination of melt viscosity and density (Fujii and Kushiro, 1977a). Sphere densities were corrected for compressibility and thermal expansion at the conditions of each experiment. The density of glass quenched from the melts at high pressures was measured on a torsion microbalance (Berman, 1939).

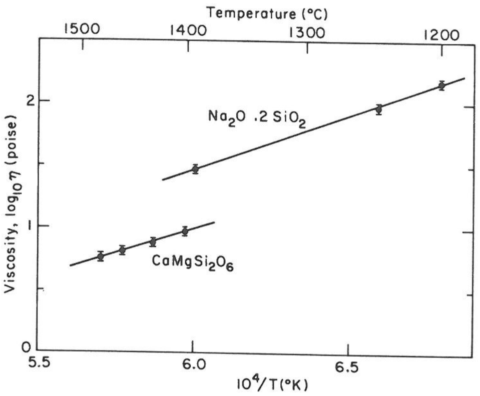

Fig. 2. Viscosity versus reciprocal temperature for melts of diopside and sodium disilicate composition at 1 bar.

Table 1. Viscosity of melts at one bar

Composition	Temperature (°C)	Viscosity (poise)
$Na_2O \cdot 2SiO_2$	1200	147
	1245	92
	1395	30
$CaMgSi_2O_6$	1401	9.3
	1432	7.4
	1461	6.5
	1480	5.6

Viscosities determined for three rotational speeds at each temperature. Measurements made under both cooling and heating paths. Uncertainties in viscosity and temperature are ±5% and ±5°C, respectively.

RESULTS

Viscosity measurements at 1 bar on melts of sodium disilicate and diopside composition are shown in Table 1 and Figure 2. At constant temperature there is a linear relationship between the rotation speed and the angular displacement of the inner cylinder. This relationship is equivalent to a plot of shear stress versus shear rate, which for Newtonian liquids is a straight line through the origin.

A linear relationship exists between the logarithm of the viscosity and reciprocal temperature. The temperature dependence of the viscosity can be described by an Arrhenius relationship of the form:

$$\eta = \eta_0 \exp(E_\eta/RT), \quad (3)$$

where η_0 is a constant, E_η is the activation energy for viscous flow, R is the gas constant, and T is the absolute temperature. Activation energies for $Na_2O \cdot 2SiO_2$ and $CaMgSi_2O_6$ were calculated as 41 ± 3 and 37 ± 3 kcal/mol, respectively. Results on sodium disilicate are in agreement with Shartsis *et al.* (1952) and Bockris *et al.* (1955). Measurements on diopside are in accord with the data published by Kirkpatrick (1974) and Scarfe *et al.* (1983) and are close to values calculated with the Bottinga and Weill (1972) viscosity model.

Experiments were not performed at 1 bar on a melt of sodium metasilicate composition. This melt volatilizes readily at high temperatures and significant changes in bulk composition are observed in

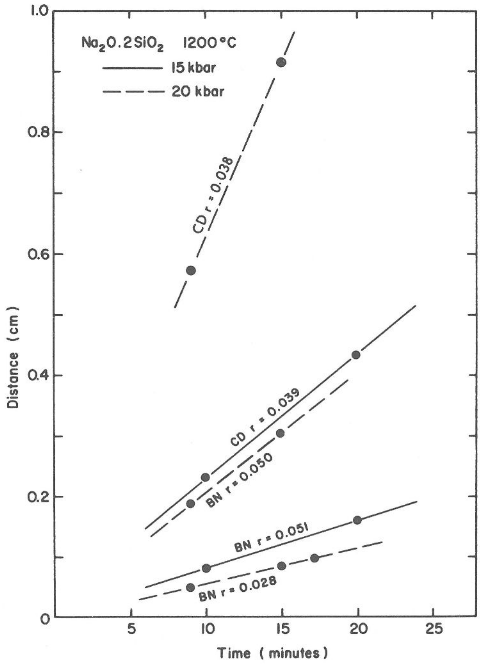

FIG. 3. Example of time–distance plots for spheres of boron nitride (ρ = 2.29 g/cm^3) and chrome diopside (ρ = 3.33 g/cm^3) in a melt of sodium disilicate composition.

short time durations. Viscosity and density data for this composition were taken from SHARTSIS *et al.* (1952) and BOCKRIS *et al.* (1955).

Measurements as a function of pressure were made isothermally at temperatures above the liquidus. In order to determine constant velocities of sinking or flotation of spheres, time–distance curves were constructed (Figure 3). All time–distance curves were straight lines, passing close to the origin or intersecting the time axis. In the latter case, a few seconds elapse before melting is complete and the spheres commence sinking or floating (KUSHIRO, 1976; KUSHIRO *et al.*, 1976). Optically there was no evidence for reaction between spheres and melt in the short time duration of these experiments.

Viscosities initially increase with increasing pressure (Table 2 and Figure 4). Above 15 kbar, however, the viscosity of a melt of $Na_2O \cdot SiO_2$ composition decreased. Between 1 bar and 15 kbar, diopside and sodium disilicate melts show viscosity increases of about a factor of 4, whereas sodium metasilicate increases by a factor of 7.5. The decrease in the viscosity of sodium disilicate melt above 15 kbar cannot be attributed to water access to the charge. Care was taken to ensure complete dehydration of all starting materials, and all charges were heated to red heat with a torch prior to final welding of the capsules.

Table 2. Viscosity and density of melts at 1 bar and at high pressure

Composition	Pressure (kbar)	Viscosity (poise)	Density (g/cm^3)
$Na_2O \cdot 2SiO_2$	0.001	151	2.39
(1200°C)	10.0	257	2.44
	15.0	620	2.53
	20.0	274	2.54
	25.0	90	2.69
$Na_2O \cdot SiO_2$	0.001	2.0	2.25
(1300°C)	10.0	15	2.29
	20.0	15	2.40
$CaMgSi_2O_6$	0.001	3.0	2.77
(1640°C)	12.5	6.4	2.96
	15.0	11.2	3.00

Each value of viscosity and density represents 2–6 experiments using several types of sphere with different diameters. One atmosphere viscosities obtained by extrapolation on log η versus $1/T$ Arrhenius plots. One atmosphere densities from SHARTSIS *et al.* (1952), or by extrapolation. Densities of diopside composition glasses produced at 1725°C are recorded in Figure 5. Uncertainties in viscosity, temperature and pressure are ±15%, ±10°C and ±0.5 kbar, respectively.

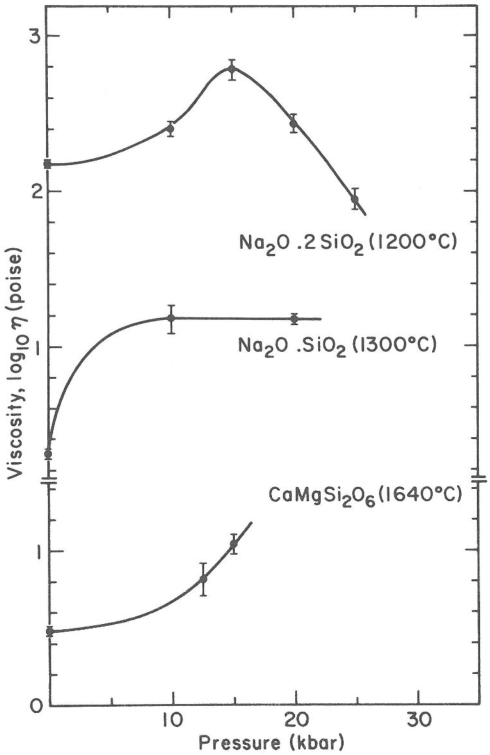

FIG. 4. Viscosity as a function of pressure for melts that have a relatively depolymerized structure at 1 bar. All measurements were made isothermally at the temperatures shown.

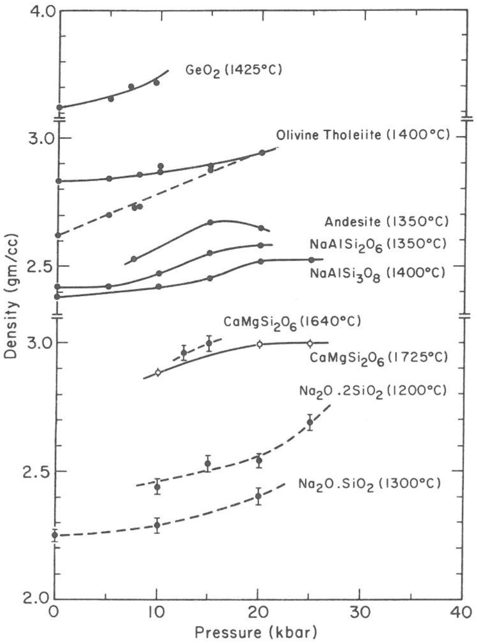

FIG. 5. Density as a function of pressure for melts and glasses quenched from the melts. All measurements were made isothermally at the temperatures shown. Data sources are given in Table 3. Glasses are shown as solid lines; melts as broken lines.

In the same pressure range, the density of melts and glasses increases (Table 2 and Figure 5). Up to 15 kbar, glasses formed from melts exhibit smaller density changes than the melts themselves (Table 3). Melt densities between 1 bar and 20 kbar for sodium disilicate, sodium metasilicate and diopside increase by 6.3, 6.7 and 8.3%, respectively. Above 15 kbar, where the viscosity of sodium disilicate begins to decrease, the density of the melt shows a greater rate of increase than between 1 bar and 15 kbar. The compressibility of the melt, therefore, increases more rapidly at pressures greater than 15 kbar.

DISCUSSION

The positive pressure dependence of the viscosity of sodium disilicate, sodium metasilicate and diopside melts contrasts with the negative pressure dependence of the viscosity of albite, jadeite and sodium trisilicate melts (Figure 1). As discussed by MYSEN *et al.* (1980a), the structure of melts of sodium disilicate, sodium metasilicate and diopside composition are relatively depolymerized at 1 bar; whereas, melts of albite, jadeite and sodium trisilicate have highly polymerized, three-dimensional, anionic networks at 1 atmosphere.

KUSHIRO (1976, 1978) and VELDE and KUSHIRO (1978) explained the negative $(d\eta/dP)_T$ for albite and jadeite melts by pressure-induced coordination changes in aluminum. Earlier, WAFF (1975) had predicted on theoretical grounds that aluminum would change from four to six coordination at pressures below 35 kbar. From both infrared absorption spectroscopy and the wavelength shift of both Al

Table 3. Viscosity and density changes between 1 bar and 20 kbar

Composition	Ref.	NBO/T	Viscosity % change	Density % change		Temperature (°C)
				Glass	Melt	
$CaMgSi_2O_6$	(1)	2	+273 (15)	3.8 (10–20)	8.3 (15)	1640
$Na_2O \cdot SiO_2$	(1)	2	+650		6.7	1300
$Na_2O \cdot 2SiO_2$	(1)	1	+311 (15)		6.3	1200
$K_2O \cdot MgO \cdot 5SiO_2$	(2)	0.80	−64 (5–20)			1300
$Na_2O \cdot 3SiO_2$	(3)	0.67	−65			1175
$NaCaAlSi_2O_7$	(4)	0.67	−29 (15)		12 (15)	1450
$NaAlSi_2O_6$	(3)	0	−90	6.8		1350
$NaAlSi_3O_8$	(5)	0	−84	5.7		1400
Ol. nephel.	(4)	1.17	−17		10	1450
Alk. ol. bas.	(4)	0.83	−57 (15)		10 (15)	1400
Ol. tholeiite	(6)	0.76	−57	3.9	12.2	1400
Abyssal thol.	(7)	0.66	−51 (12)		7.1 (12)	1300
Andesite	(8)	0.27	−51	4.7 (7.5–20)		1350
Obsidian	(9)	0.10	−80			1400

Data sources: (1) present study, (2) KUSHIRO (1977), (3) KUSHIRO (1976), (4) SCARFE (1981), (5) KUSHIRO (1978), (6) FUJII and KUSHIRO (1977a), (7) FUJII and KUSHIRO (1977b), (8) KUSHIRO *et al.* (1976), (9) SCARFE (unpubl.). For additional data not included in the Table see SHARMA *et al.* (1979b), KUSHIRO (1981, 1983, 1984 and 1986), SHARPE *et al.* (1983), BREARLEY *et al.* (1986) and DUNN and SCARFE (1986). Measurements made isothermally at the temperatures shown. Pressure in parentheses indicates that measurements were performed to that pressure or over that pressure range. Plus sign indicates increase; minus sign a decrease; all density changes are positive. NBO/T is the theoretical ratio of nonbridging oxygens to tetrahedrally coordinated cations in the melt (see text).

K_α and Al K_β, VELDE and KUSHIRO (1978) concluded that aluminum in the melt gradually changes from four-fold to six-fold coordination as the pressure increases from 1 atmosphere to 30 kbar.

SHARMA *et al.* (1979a), however, criticized several aspects of Velde and Kushiro's interpretation. They pointed out the lack of evidence for the presence in the infrared spectra of non-bridging oxygens that would be expected if aluminum transforms from four-fold to six-fold coordination, and the ambiguities introduced by overlap in Al K_β shifts for Al^{3+} in four and six coordination. Furthermore, studies of quenched melts of albite and jadeite composition by Raman spectroscopy (SHARMA *et al.*, 1979a; MYSEN *et al.*, 1980a,b, 1982, 1985; SEIFERT *et al.*, 1982; FLEET *et al.*, 1984) and by X-ray radial distribution function work (HOCHELLA and BROWN, 1985) show that there are only minor changes in the spectra between 1 bar and 40 kbar. These changes are a result of ordering of Al and Si in the three-dimensional network (SHARMA *et al.*, 1979a) and a decrease of several degrees in the T-O-T angles (SEIFERT *et al.*, 1982; MYSEN *et al.*, 1983).

Three other important pieces of evidence can be cited against an explanation for viscosity decreases based upon pressure-induced aluminum coordination changes. The first is that other compositions not containing aluminum, show viscosity decreases similar to those of albite and jadeite with pressure. Sodium trisilicate (KUSHIRO, 1976) $K_2O \cdot MgO \cdot 5SiO_2$ (KUSHIRO, 1977) and GeO_2 (SHARMA *et al.*, 1979b) all show negative $(d\eta/dP)_T$. The second is that the Raman spectra of glasses of GeO_2 composition between 1 bar and 18 kbar (SHARMA *et al.*, 1979b) and $Na_2O \cdot 3SiO_2$ composition between 1 bar and 20 kbar (MYSEN *et al.*, 1980a,b) show only minor changes. These changes are due to subtle modifications in the network structure of the melts and do not result from pressure-induced coordination changes in silicon or germanium. In fact, molecular dynamics calculations on the pressure effect on liquid SiO_2 (WOODCOCK *et al.*, 1976) suggest that six-fold coordinated silicon is not present in the melt, at least to 200 kbar. Similar calculations for aluminosilicate melts suggest that >100 kbar are required to induce Al-coordination changes (ANGELL *et al.*, 1982, 1983). Recent ^{27}Al solid-state NMR spectroscopy on albite glass quenched from approximately 2000°C indicates that ≥80 kbar may be required to induce an Al-coordination transformation (OHTANI *et al.*, 1985). Finally, according to KUSHIRO (1981), for fully polymerized melts along the join SiO_2–$CaAl_2O_4$, the absolute value of $(d\eta/dP)_T$ decreases with increasing Al/(Al + Si). Anorthite ($CaAl_2Si_2O_8$) and more aluminous compositions beyond Al/(Al + Si) > 0.5 show insignificant or slightly positive pressure dependence of melt viscosity. It is concluded, therefore, that pressure-induced coordination changes are not responsible for the decrease in viscosity of highly polymerized three-dimensional, network liquids as a function of pressure. Rather, it is suggested that the weakening of bridging T-O-T bonds resulting from the decrease of the T-O-T angles may explain the negative pressure dependence of highly polymerized silicate melts.

In contrast to the highly polymerized network liquids discussed above, most inorganic and polymer liquids exhibit increasing viscosities with pressure (BRIDGMAN, 1931; O'REILLY, 1964; SAKKA and MACKENZIE, 1969). Such behavior is predicted by the free-volume theory of silicate melts (COHEN and TURNBULL, 1959) as applied to the pressure-dependence of liquid viscosities (MATHESON, 1966). Under compression, free volume will be removed from the structure, giving rise to increases in viscosity and density. The pressure dependence of the viscosity of melts of sodium disilicate, sodium metasilicate and diopside composition presented in this paper follows the expected trend, all show positive $(d\eta/dP)_T$.

In the case of disilicate melts such as $Na_2O \cdot 2SiO_2$ (NBO/T = 1), the decrease in viscosity above 15 kbar may be explained by a collapse and weakening of the structure. Support for this interpretation comes from the small density increase between 1 bar and 15 kbar and the larger density change thereafter (see below). In this context, BREARLEY *et al.* (1986), in an investigation of the pressure dependence of melt viscosities on the diopside-albite join (NBO/T = 2-0), found that the intermediate composition $Di_{75}Ab_{25}$ (NBO/T = 1.2) passed through a minimum viscosity at approximately 12 kbar and 1600°C. Such behavior may be compared with the change of the viscosity of water with pressure at low temperatures (*e.g.*, BRIDGMAN, 1931; ANGELL *et al.*, 1983).

The densities of both types of melts increase with pressure, although the compressibility of highly polymerized melts is greater than the compressibility of relatively depolymerized melts (Tables 2 and 3). In both cases, compression induces some compaction and ordering of the melt structure. In the case of depolymerized melts, free volume is removed under pressure and both the density and viscosity increase; whereas, in highly polymerized melts, the free volume theory is violated, because density increases with pressure, but viscosity decreases.

Finally, it should be noted that for liquids where the units involved in viscous flow and diffusion are the same, the diffusivity and viscosity are inversely related (COHEN and TURNBILL, 1954); hence, a decrease in viscosity would be accompanied by an increase in diffusion rate. Recently, SHIMIZU and KUSHIRO (1984) found an inverse relationship between the diffusion of oxygen (O^{2-}) anions and viscosity as a function of pressure in jadeite and diopside melt and DUNN and SCARFE (1986) found a similar relationship for andesite melt. These observations raise the question whether viscous flow may be rate limited by the diffusion of oxygen in silicate melts at high pressure.

GEOLOGICAL APPLICATIONS

The ratio of non-bridging oxygens to tetrahedrally coordinated cations (NBO/T) is a measure of the degree of polymerization of a silicate melt and it can be calculated from the chemical analysis. According to MYSEN *et al.* (1982), for multicomponent melts of geological interest, the major cations in tetrahedral coordination are Al^{3+} and Si^{4+}. However, provided that there is sufficient ($Na^+ + K^+ + Ca^{2+} + Mg^{2+}$) to charge balance both Al^{3+} and Fe^{3+}, ferric iron may be considered a network former (VIRGO and MYSEN, 1985) together with Ti^{4+} and P^{5+}. All other cations will be network modifiers in six-fold or higher coordination in the melt. The results of calculations of NBO/T for all compositions studied to date are given in Table 3.

It has already been noted that anhydrous rock melts of andesite and basalt composition exhibit decreases in viscosity with pressure similar to those described above for melts such as albite, jadeite and sodium trisilicate (Table 3). For example, olivine tholeiite and andesite melts show decreases in viscosity of approximately 50%, whereas decreases for albite and jadeite melts are about 90%. Both basalt and andesite melts have $NBO/T < 1$. The only rock composition with $NBO/T > 1$ that has been studied so far, is a melt of olivine nephelinite composition with an $NBO/T = 1.17$. This composition exhibits virtually no change in viscosity as a function of pressure under isothermal conditions (SCARFE, 1981). Thus, it seems that the correlation between the NBO/T of a melt and the pressure dependence of its viscosity, observed for melts of simple chemistry, may also hold for multicomponent rock melts (the only exception being two compositions measured by SHARPE *et al.*, 1983). Obsidian, andesite and most basalt melts have $NBO/T < 1$, and their viscosities are observed to decrease with increasing pressure under isothermal conditions. On the other hand, picrites, komatiites and related silica-deficient, aluminum-poor melts with $NBO/T > 1$, will probably show an increase in their viscosities as a function of pressure.

Because there are few aspects of igneous petrology that are not in some way related to the viscosity of silicate melts, the contrasting behavior of highly polymerized versus relatively depolymerized silicate melts, finds wide application. Apart from the effects of viscosity on the emplacement of volcanic and intrusive rocks (*e.g.*, HARRIS *et al.*, 1970), it plays an important part in many deep-seated magmatic processes. It is a factor in melt aggregation and segregation at source, the ascent of magmas toward the surface, and in xenolith transport. Viscosity also exerts a control on transport processes such as convection in magmas.

The decrease in viscosity with pressure of rhyolite, andesite and basalt melts, both along their liquidi and at constant temperature, indicates that most anhydrous magmas become more fluid with depth. Melts of picrite and komatiite composition, however, may become more viscous with depth, a factor which may place constraints on the ease with which these latter melts separate from the source, and their subsequent ascent to the surface. Crystal settling and crystal fractionation will be more effective at high pressures in melts with $NBO/T < 1$.

Finally, it is worth emphasizing that the preceding discussion has been limited to volatile-free melts and magmas that contain only a few percent crystals and are Newtonian in behavior. Magmas containing more than 10–20% crystals will show non-Newtonian viscous behavior (SHAW, 1969; SCARFE, 1973; MURASE and MCBIRNEY, 1973) and the considerations discussed in this paper will not be applicable. The way in which water reduces the viscosity of most melts of geological interest has been known for some time (*e.g.*, SHAW, 1963; SCARFE, 1973; DINGWELL, 1987; DINGWELL and MYSEN, 1985); however, the effect of CO_2 on viscosity has yet to be determined.

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