

# Toward a general viscosity equation for natural anhydrous and hydrous silicate melts

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## Abstract

A new and empirical viscosity equation for anhydrous and hydrous natural silicate melts has been developed using the following formulation:

$$\log \eta = A + \frac{B}{T} + \exp\left(C + \frac{D}{T}\right),$$

where  $\eta$  is the viscosity,  $T$  is the temperature in K, and  $A$ ,  $B$ ,  $C$ , and  $D$  are linear functions of mole fractions of oxide components except for  $\text{H}_2\text{O}$ . The formulation is applied successfully to fit the temperature and compositional dependence of viscosity for some binary systems. Furthermore, our model with eight parameters fits the compositional and temperature dependence of the viscosity data of anhydrous natural silicate melts better than 10-parameter model in literature. The main purpose of this work is to fit the entire high- and low-temperature viscosity database (1451 data points) of all “natural” silicate melts using this empirical formulation. The general viscosity equation has 37 parameters and is as follows:

$$\begin{aligned} \log \eta = & [-6.83X_{\text{SiO}_2} - 170.79X_{\text{TiO}_2} - 14.71X_{\text{Al}_2\text{O}_{3\text{ex}}} - 18.01X_{\text{MgO}} - 19.76X_{\text{CaO}} + 34.31X_{(\text{Na,K})_2\text{O}_{\text{ex}}} \\ & - 140.38Z + 159.26X_{\text{H}_2\text{O}} - 8.43X_{(\text{Na,K})\text{AlO}_2}] + [18.14X_{\text{SiO}_2} + 248.93X_{\text{TiO}_2} + 32.61X_{\text{Al}_2\text{O}_{3\text{ex}}} \\ & + 25.96X_{\text{MgO}} + 22.64X_{\text{CaO}} - 68.29X_{(\text{Na,K})_2\text{O}_{\text{ex}}} + 38.84Z - 48.55X_{\text{H}_2\text{O}} + 16.12X_{(\text{Na,K})\text{AlO}_2}]1000/T \\ & + \exp\{[21.73X_{\text{Al}_2\text{O}_{3\text{ex}}} - 61.98X_{(\text{Fe, Mn})\text{O}} - 105.53X_{\text{MgO}} - 69.92X_{\text{CaO}} - 85.67X_{(\text{Na,K})_2\text{O}_{\text{ex}}} \\ & + 332.01Z - 432.22X_{\text{H}_2\text{O}} - 3.16X_{(\text{Na,K})\text{AlO}_2}] + [2.16X_{\text{SiO}_2} - 143.05X_{\text{TiO}_2} - 22.10X_{\text{Al}_2\text{O}_{3\text{ex}}} + 38.56X_{(\text{Fe, Mn})\text{O}} \\ & + 110.83X_{\text{MgO}} + 67.12X_{\text{CaO}} + 58.01X_{(\text{Na,K})_2\text{O}_{\text{ex}}} + 384.77X_{\text{P}_2\text{O}_5} - 404.97Z + 513.75X_{\text{H}_2\text{O}}]1000/T\}, \end{aligned}$$

where  $\eta$  is the viscosity in Pa s,  $T$  is the temperature in K,  $X_i$  means mole fraction of oxide component  $i$ , and  $Z = (X_{\text{H}_2\text{O}})^{1/[1+(185.797/T)]}$ .  $\text{Al}_2\text{O}_{3\text{ex}}$  or  $(\text{Na,K})_2\text{O}_{\text{ex}}$  mean excess oxides after forming  $(\text{Na,K})\text{AlO}_2$ . The  $2\sigma$  deviation of the fit is 0.61  $\log \eta$  units. This general model is recommended for viscosity calculations in modeling magma chamber processes and volcanic eruptions.

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## 1. Introduction

Knowledge of the viscosity of silicate melts is critical to the understanding of igneous processes, such as melt segregation

and migration in source regions, magma recharge, magma mixing, differentiation by crystal fractionation, convection in magma chambers, dynamics and style of eruptions, and magma fragmentation. Numerous measurements have been made on the viscosity of various silicate melts, from felsic (e.g., rhyolitic melt, [Neuville et al., 1993](#)) to ultramafic composition (e.g., peridotite liquid, [Dingwell et al., 2004](#)), from anhydrous (e.g., [Neuville](#)

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et al., 1993) to hydrous ones (e.g., Whittington et al., 2000), and from high temperature to low temperature. A number of authors have made efforts to model the viscosity data for the purpose of interpolation and extrapolation. Bottinga and Weill (1972) and Shaw (1972) were pioneers in developing viscosity models for natural silicate melts. Because of the extreme difficulty in calibrating a better viscosity model, these models were the only ones available for over 20 years (Lange, 1994). Recently, more advanced models and relationships have been developed for specific melt compositions such as rhyolitic melts (e.g., Hess and Dingwell, 1996; Zhang et al., 2003). For melt compositions from rhyolite to peridotite, Persikov (1998) developed a viscosity model for anhydrous and hydrous silicate melts at high temperatures (for viscosity below  $10^5$  Pa s), and Giordano and Dingwell (2003a) developed new models for anhydrous silicate melts applicable to a larger temperature range, 700–1600 °C.

In spite of recent advances in viscosity models, there is still a need for a general model that would apply to all natural silicate melts, all accessible temperature ranges, and especially including the effect of H<sub>2</sub>O content. The model of Giordano and Dingwell (2003a) is noteworthy in this connection. In the modeled temperature range (700–1600 °C) for anhydrous melts, it has a  $2\sigma$  uncertainty of 0.78 in  $\log\eta$ . However, the model is limited to anhydrous melts, and cannot be applied to estimate viscosity at lower temperatures. For example, the model predicts  $\log\eta$  of 16.9 for a phonolite at 614.7 °C, while the experimentally determined  $\log\eta$  is 11.63 (Giordano et al., 2000). Viscosity at <700 °C is critical for understanding magma fragmentation and welding in tuffs. The purpose of this work is to develop a practical viscosity model for natural silicate melts that is applicable to both anhydrous and hydrous natural melts and to the entire temperature range in which experimental data are available.

## 2. Temperature dependence of viscosity

The temperature dependence of viscosity of silicate melts has been extensively studied from a theoretical point of view or through empirical fitting of viscosity data. For a narrow temperature range, usually for viscosities between 0.1 and  $10^4$  Pa s, the dependence of viscosity on temperature is well described by the Arrhenius equation (e.g., Bottinga and Weill, 1972; Shaw, 1972). When the temperature range is large enough, most silicate melts exhibit a non-Arrhenian relationship between viscosity and temperature (e.g., Neuville et al., 1993; Hess and Dingwell, 1996; Whittington et al., 2000). It is possible that the isostructural viscosity variation is Arrhenian (Scherer, 1984), but viscosity variation due to temperature-induced structure change is the origin of the non-Arrhenian behavior. Many equations have been proposed to explain or fit the temperature dependence of viscosity (e.g., Brush, 1962).

One thermodynamic description of the temperature dependence of viscosity of silicate melts is the Adam–Gibbs equation (e.g., Adam and Gibbs, 1965; Richet, 1984):

$$\eta = A_e \exp[B_e/(TS_{\text{conf}})], \quad (1)$$

where  $\eta$  is the viscosity,  $A_e$  is the pre-exponential factor independent of temperature,  $B_e$  is an energy term,  $T$  is the temperature in K, and  $S_{\text{conf}}$  is the configurational entropy of the melt. For compositions corresponding to a pure stable crystalline phase (such as diopside), the configurational entropy as a function of temperature can be determined from appropriate heat capacity measurements of liquids, and crystals and glasses down to 0 K (Richet et al., 1986). However, for a multicomponent melt system in which oxide concentrations are variable, the configurational entropy as a function of temperature and composition cannot be evaluated independently. The above equation becomes a fitting equation with many parameters, which loses its theoretical appeal. Hence this model is not used often to fit viscosity–temperature relationship of silicate melts.

The most often used empirical description for the temperature dependence of viscosity is the VFT (Vogel–Fulcher–Tammann) equation (e.g., Fulcher, 1925; Tammann and Hesse, 1926):

$$\log \eta = A + \frac{B}{T - T_0}, \quad (2)$$

where  $A$ ,  $B$ , and  $T_0$  are fitting parameters. Another model related to the fragility of the melt has also been used (e.g., Avramov, 1998; Zhang et al., 2003).

$$\log \eta = A + \left(\frac{B}{T}\right)^\alpha, \quad (3)$$

where  $\alpha$  is the fragility parameter and depends on heat capacity. Moreover, for a restricted compositional range  $\alpha$  is found to depend linearly on chemical composition, as illustrated by data in sodium or lead silicates (Avramov, 1998).

Both Eqs. (2) and (3) are three-parameter equations with no explicit consideration of melt composition, which is the least number of parameters to fit the non-Arrhenian behavior. We tried to extend Eqs. (2) and (3) to multicomponent melts by allowing the three parameters to vary with composition, but did not find a working scheme to fit the viscosity data ( $2\sigma$  uncertainty in  $\log\eta$  is too large,  $>0.9$  log unit). With many trials, the following empirical relation was found to be extendable to multicomponent melts:

$$\log \eta = A + \frac{B}{T} + \exp\left(C + \frac{D}{T}\right), \quad (4)$$

where  $A$ ,  $B$ ,  $C$ , and  $D$  are fitting parameters and are allowed to vary linearly with mole fraction of oxide components in melts. This equation would imply that the activation energy for viscous relaxation depends on temperature exponentially:  $E_a = d(\ln\eta)/d(1/T) = 2.303[B + D \exp(C + D/T)]$ , consistent with the activation energy of viscous flow derived from Eq. (1)

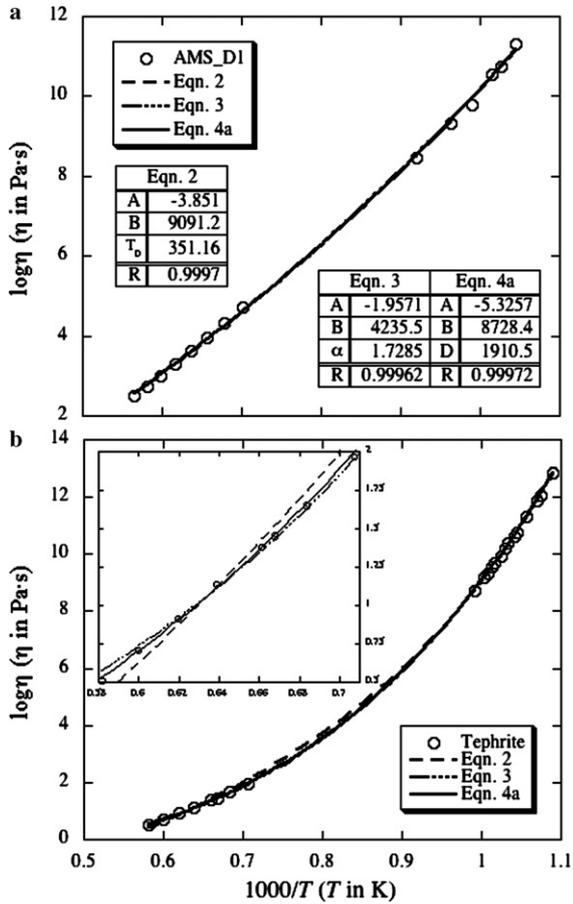


Fig. 1. Comparisons of fitting results using Eqs. (2)–(4a) for viscosity data of (a) AMS\_D1 trachyte (Romano et al., 2003) and (b) tephrite (Whittington et al., 2000).

in Richet et al. (1986). It is not clear whether there is theoretical basis for Eq. (4), but it works empirically to fit viscosity data of multicomponent silicate melts.

Although the above four-parameter equation can also fit viscosity data of a single composition, not all four parameters are necessary, and a three-parameter equation, either Eqs. (2) or (3) would be more advisable. Nevertheless, letting  $C = 0$  reduces Eq. (4) to a three-parameter equation, which may fit viscosity data of a single composition:

$$\log \eta = A + \frac{B}{T} + \exp\left(\frac{D}{T}\right). \quad (4a)$$

Fig. 1 compares fits of viscosity data using Eqs. (2)–(4a) on anhydrous trachyte melt (AMS\_D1, Romano et al., 2003) and tephrite melt (Whittington et al., 2000). As shown in Fig. 1, these three equations all fit viscosity data well for a given anhydrous melt.

The primary purpose of proposing Eq. (4) is to fit viscosity data of multicomponent silicate melts by making the four parameters linearly dependent on composition. Below, we first discuss the compositional dependence of viscosity in binary melts, then move on to fit viscosity of anhydrous natural silicate melts, and finally fit the entire viscosity database on “natural” anhydrous and hydrous silicate melts.

### 3. Viscosity of binary melts

At low temperatures the viscosity of melts in simple binary systems often shows minima at intermediate compositions. This minimum diminishes with increasing temperature, and eventually disappears at high enough temperature (Neuville and Richet, 1991). The minimum of viscosity data in a binary system can be explained by a combination of the Adam–Gibbs model and mixing law of configurational entropy of two end-members (Neuville and Richet, 1991). However, in this strategy, many fitting parameters are needed to account for the viscosity dependence on composition and temperature. For example, Neuville and Richet (1991) used a 15-parameter equation to fit the viscosity data of  $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ – $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$  binary system. Moreover, asymmetry of viscosity as a function of composition, such as in the  $\text{Na}_2\text{Si}_3\text{O}_7$ – $\text{K}_2\text{Si}_3\text{O}_7$  binary system, can make it even more difficult for the Adam–Gibbs model to fit the viscosity data in the binary system (Richet, 1984).

On the other hand, assuming that each of the four parameters is a linear function of composition, Eq. (4) becomes an eight-parameter equation to fit the temperature and compositional dependence of viscosity of a binary system:

$$\log \eta = (a_1X_1 + a_2X_2) + \frac{(b_1X_1 + b_2X_2)}{T} + \exp\left(\left(c_1X_1 + c_2X_2\right) + \frac{(d_1X_1 + d_2X_2)}{T}\right), \quad (5)$$

where  $a$ ,  $b$ ,  $c$ , and  $d$  with subscript 1 and 2 are fitting parameters,  $X$  is mole fraction of two end-members in the system. Compared to the 15-parameter equation of Neuville and Richet (1991), the number of fitting parameters is almost halved although the physical meaning of each parameter is less clear in Eq. (5).

Fits using Eq. (5) and all fits below are carried out using the commercially available program MatLab or Stata, which employs nonlinear least square regression to minimize  $\chi^2 = \sum (\log \eta_{\text{calc},i} - \log \eta_{\text{obs},i})^2$ . The fitting errors on all parameters are obtained by the program Stata. When the standard error of a parameter is larger than the absolute value of the parameter, the parameter is removed and a new fit with one less fitting parameter is carried out.

Fig. 2 shows fits of viscosity data of four binary systems:  $\text{MgSiO}_3$ – $\text{CaSiO}_3$  pyroxenes (Urbain et al., 1982; Scarfe and Cronin, 1986; Neuville and Richet, 1991),  $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ – $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$  (pyrope–grossular) garnets (Neuville and Richet, 1991),  $\text{NaAlSi}_3\text{O}_8$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$  (albite–anorthite) plagioclases (Kozu and Kani, 1944; Urbain et al., 1982; Hummel and Arndt, 1985), and  $\text{NS}_3$ – $\text{KS}_3$  ( $\text{Na}_2\text{Si}_3\text{O}_7$ – $\text{K}_2\text{Si}_3\text{O}_7$ ) (Taylor and Dear, 1937; Lillie, 1939; Taylor and Doran, 1941; Poole, 1948; Shartsis et al., 1952; Bockris et al., 1955; Mackenzie, 1957; Taylor and Rindone, 1970; Ammar et al., 1977). The viscosities of partially crystallized samples during measurement are not used in the fitting. The fitting parameters are shown in Table 1. The  $2\sigma$  deviations in terms of  $\log \eta$  for pyroxene, garnet, plagioclase

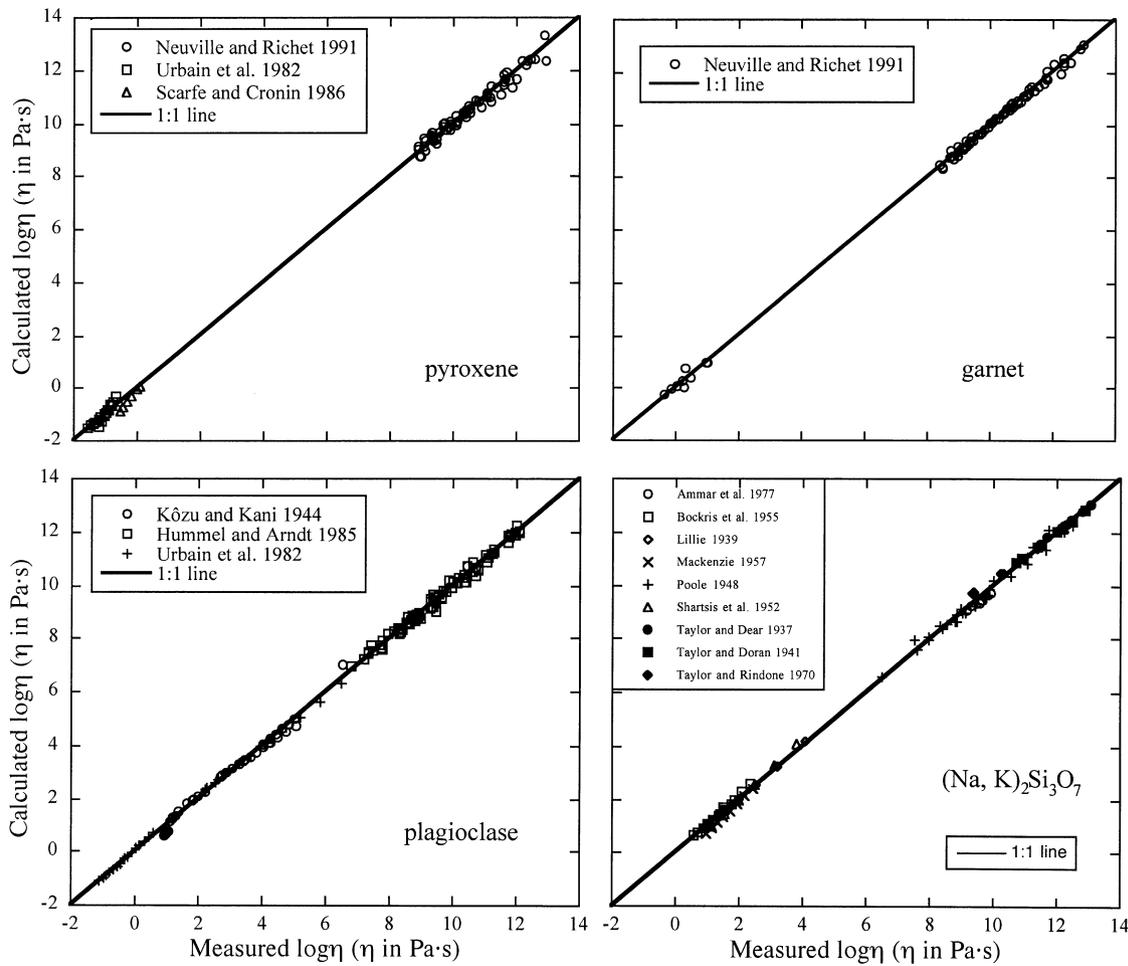


Fig. 2. Comparisons of experimental viscosity data with calculated values using Eq. (5) with fitting parameters in Table 1. The data sources are as follows:  $\text{CaSiO}_3$ – $\text{MgSiO}_3$  pyroxenes (Urbain et al., 1982; Scarfe and Cronin, 1986; Neuville and Richet, 1991);  $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ – $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$  garnets (Neuville and Richet, 1991);  $\text{CaAl}_2\text{Si}_2\text{O}_8$ – $\text{NaAlSi}_3\text{O}_8$  plagioclases (Kôzu and Kani, 1944; Urbain et al., 1982; Hummel and Arndt, 1985);  $\text{NS}_3$ – $\text{KS}_3$  ( $\text{Na}_2\text{Si}_3\text{O}_7$ – $\text{K}_2\text{Si}_3\text{O}_7$ ) (Taylor and Dear, 1937; Lillie, 1939; Taylor and Doran, 1941; Poole, 1948; Shartsis et al., 1952; Bockris et al., 1955; Mackenzie, 1957; Taylor and Rindone, 1970; Ammar et al., 1977).

and  $\text{NS}_3$ – $\text{KS}_3$  systems are 0.39, 0.25, 0.29 and 0.30, respectively. There is a minimum viscosity at intermediate compositions in all four binary systems at low temperatures, such as pyroxene and garnet at 1050 K (Fig. 3A), plagioclase at 1123 K (Fig. 3B) and  $\text{NS}_3$ – $\text{KS}_3$  at 715 K (Fig. 3C).

The compositional location of viscosity minimum varies with temperature. This can be seen from the viscosity data of plagioclase (albite–anorthite) binary system (Hummel and Arndt, 1985). As shown in Fig. 3B, the viscosity minimum of albite–anorthite system is located at around 40 mol% of anorthite in the composition range at 1123 K, but the minimum is at a greater anorthite content at higher temperatures. This variation has been explained by Richet (1984) to be due to the mixing of configurational entropies of anorthite and albite melts, which increase at considerably different rates with increasing temperature. The magnitude of the viscosity minimum diminishes with increasing temperature, as inferred by Neuville and Richet (1991). As shown in Fig. 3C, the viscosity minimum in  $\text{NS}_3$ – $\text{KS}_3$  system is less pronounced at 1673 K than the one at 715 K.

#### 4. Viscosity models for natural anhydrous and hydrous silicate melts

The main purpose of this work is to present a working model to calculate the viscosity of all natural anhydrous and hydrous silicate melts covering the entire experimental temperature range. The equation used to fit the viscosity data is Eq. (4), with each of  $A$ ,  $B$ ,  $C$ , and  $D$  as a linear function of the compositional parameters. For example, for an  $N$ -component system, the parameter  $A$  may be written as:

$$A = \sum_{i=1}^N a_i X_i, \quad (6a)$$

or

$$A = a_0 + \sum_{i=1}^{N-1} a_i X_i, \quad (6b)$$

where  $a_0$  and  $a_i$  are fitting parameters, with  $i$  being the  $i$ th oxide in the anhydrous melts. This formulation requires many fitting parameters. In order to avoid the impression

Table 1  
Fitting parameters of Eq. (5) in the binary systems of pyroxene, garnet, plagioclase and NS<sub>3</sub>-KS<sub>3</sub>

Parameter	Pyroxene	Garnet	Plagioclase	NS <sub>3</sub> -KS <sub>3</sub>
$a_1$	-3.1287 (0.4255)	2.3593 (1.1691)	-4.5179 (1.0170)	-3.2839 (0.5488)
$a_2$	-9.4323 (0.4710)	-4.3178 (0.1053)	-6.3903 (0.6947)	-6.1410 (0.7446)
$b_1$		-21260.4 (1635.9)	5940.2 (3446.3)	4770.6 (2081.4)
$b_2$	17903.8 (952.7)		16551.2 (1944.6)	11821.8 (1348.6)
$c_1$	-1.2322 (0.3808)	0.8438 (0.1057)	-2.0844 (0.9118)	-1.1788 (0.9117)
$c_2$	-5.9221 (0.9186)		-3.1234 (1.5216)	-5.1302 (3.2636)
$d_1$	4071.6 (371.3)	2704.9 (115.7)	5061.4 (831.2)	2464.7 (478.4)
$d_2$	7465.5 (863.6)	2878.9 (8.8)	4690.9 (1299.1)	4295.5 (2.0116)

Note. Numbers in parentheses are two times the standard errors ( $2\sigma$ ) of the fitting respective parameters. For pyroxene, 1 = CaSiO<sub>3</sub>, 2 = MgSiO<sub>3</sub>; for garnet, 1 = Ca<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub> (grossular), 2 = Mg<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub> (pyrope); for plagioclase, 1 = CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub> (anorthite), 2 = NaAlSi<sub>3</sub>O<sub>8</sub> (albite); for NS<sub>3</sub>-KS<sub>3</sub>, 1 = Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub>, 2 = K<sub>2</sub>Si<sub>3</sub>O<sub>7</sub>.

that the model works only because of many parameters, we first present an effort to use formulation of Eq. (4) to fit a smaller data set that has been modeled recently by [Giordano and Dingwell \(2003a\)](#) and show that our model can fit the same data using a smaller number of parameters than that of [Giordano and Dingwell \(2003a\)](#).

#### 4.1. A simple model for natural anhydrous melts

For multicomponent silicate melts, the dependence of viscosity on melt composition is complicated. In the quest of seeking simpler equations with a smaller number of fitting parameters, various parameters such as NBO/T (e.g., [Giordano and Dingwell, 2003a](#)) and SM ( $SM = \sum (Na_2O + K_2O + CaO + MgO + MnO + FeO_{tot}/2)$ ) ([Giordano and Dingwell, 2003a](#)) have been used in modeling melt viscosity. We explored various parameters to simplify the compositional dependence. After a number of trials, we found that using the sum of network formers, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and P<sub>2</sub>O<sub>5</sub>, as one single parameter works well in the context of Eq. 6b. Hence we define:

$$SAP = X_{SiO_2} + X_{Al_2O_3} + X_{P_2O_5}, \quad (7)$$

where  $X_i$  is the mole fraction of oxide  $i$  in the melt. Based on the above considerations, we use the following equation to relate viscosity, temperature, and melt composition:

$$\log \eta = (a_0 + a_1X) + \frac{(b_0 + b_1X)}{T} + \exp \left( (c_0 + c_1X) + \frac{(d_0 + d_1X)}{T} \right), \quad (8)$$

where  $X = SAP$ ;  $a$ ,  $b$ ,  $c$ , and  $d$  with subscript 0 or 1 are fitting parameters.

[Giordano and Dingwell \(2003a\)](#) presented two models for the viscosity of anhydrous silicate melts. The data set contained 314 viscosity data points. Their preferred model using the parameter SM contained 10 fitting parameters. Although their database contained viscosity data below 700 °C, they only modeled the data in the temperature range of 700–1600 °C. With 10 parameters, the  $2\sigma$  deviation of their preferred model is 0.78  $\log \eta$  units at 700–1600 °C.

The purpose of using Eq. (8) to fit viscosity data is to compare with previous fits. Hence we decided to fit the same viscosity database of the anhydrous natural silicate melts as used by [Giordano and Dingwell \(2003a\)](#). All the viscosity data used by them plus the data at temperatures below 700 °C are used to carry out the nonlinear fit and the new model is as follows:

$$\log \eta = (-21.3517 + 12.7366X) + \frac{29300.3 - 9757.4X}{T} + \exp \left( (29.9791 - 32.4047X) + \frac{-58868.8 + 65081.8X}{T} \right). \quad (9)$$

The standard errors for the fitting parameters are shown in [Table 2](#). Applying the above equation to viscosity data at 700–1600 °C, the  $2\sigma$  deviation is 0.63  $\log \eta$  units ([Fig. 4A](#)). That is, with a smaller number of fitting parameters (8 versus 10), the formulation of Eq. (4) is able to fit anhydrous melt viscosity data to a slightly better precision at this temperature range than the model of [Giordano and Dingwell \(2003a\)](#).

Another measure of a successful model is applicability to a wide range of conditions. For example, [Hess and Dingwell \(1996\)](#) compared their viscosity model for hydrous rhyolite at both high and low temperatures to the model of [Shaw \(1972\)](#) although his model was for all anhydrous and hydrous silicate melts but at high temperatures only, and showed that their model is superior to that of [Shaw \(1972\)](#) at low temperatures. Our eight-parameter model is able to fit low-temperature viscosity data (i.e., data at  $\leq 700$  °C, [Fig. 4B](#)). For the whole temperature range, Eq. (9) reproduces the experimental data with a  $2\sigma$  standard uncertainty of 0.77 ([Fig. 4](#)). The model of [Giordano and Dingwell \(2003a\)](#), on the other hand, did not include data at  $\leq 700$  °C in the fit and hence did not predict the data well. Although [Giordano and Dingwell's](#) model is not designed for application below 700 °C, the applicability of our eight-parameter model to the full temperature range of viscosity data demonstrates its superiority. Viscosity data at  $\leq 700$  °C are of importance in processes such as magma fragmentation and welding in tuffs.

In summary, with a smaller number of fitting parameters, our new model does a better job than the most recent viscosity models ([Giordano and Dingwell, 2003a](#)). This verifies that Eq. (4) provides a practical way to describe the compositional and temperature dependences of the viscosity of natural silicate melts, and the success of the model below is not purely because of the many parameters involved.

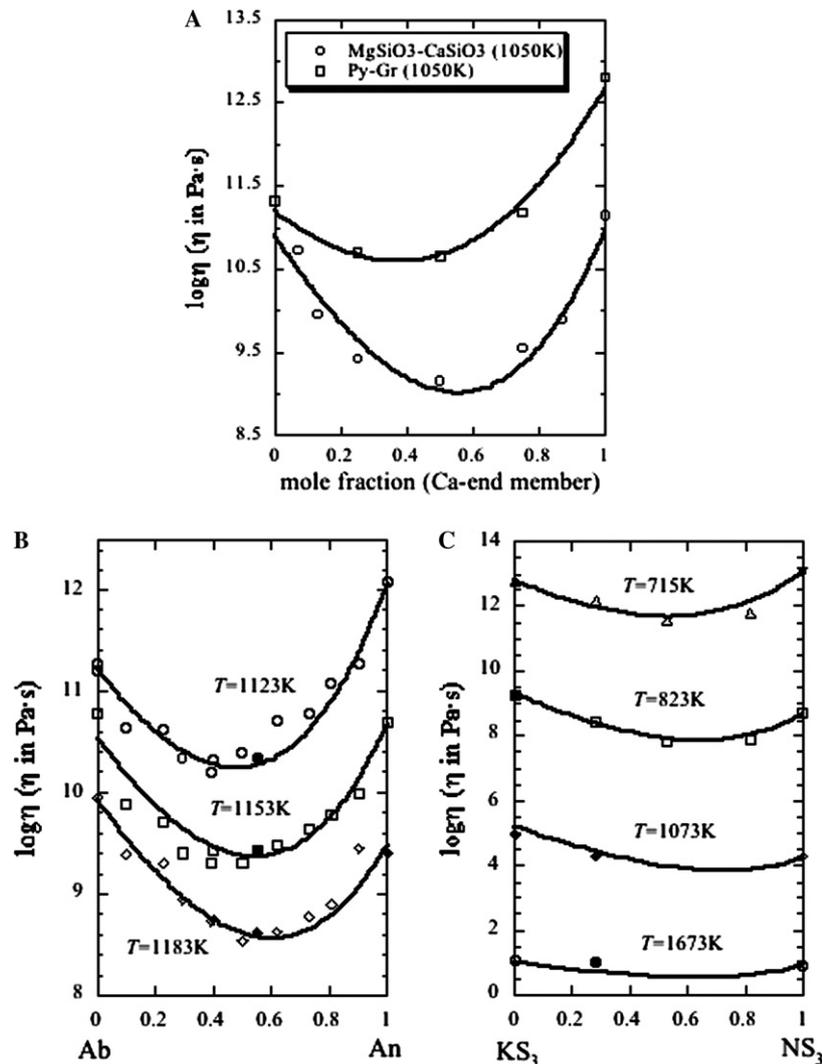


Fig. 3. Viscosity as a function of composition in four binary systems: (A) pyroxene and garnet, (B) plagioclase and (C)  $\text{NS}_3\text{--KS}_3$  ( $\text{Na}_2\text{Si}_3\text{O}_7\text{--K}_2\text{Si}_3\text{O}_7$ ). The solid curves are calculated from Eq. (5) with fitting parameters in Table 1. The sources of viscosity data are as follows: (A) interpolated from [Neville and Richet \(1991\)](#) using Arrhenius relationship of viscosity and temperature (narrow temperature range) with the same compositions. (B) open symbols, [Hummel and Arndt, 1985](#); solid symbols, interpolated data from [Hummel and Arndt \(1985\)](#) using Arrhenius relationship of viscosity and temperature (narrow temperature range). (C) Data are from [Taylor and Dear \(1937\)](#), [Lillie \(1939\)](#), [Taylor and Doran \(1941\)](#), [Poole \(1948\)](#), [Bockris et al. \(1955\)](#), [Mackenzie \(1957\)](#), and [Ammar et al. \(1977\)](#); interpolated data from [Taylor and Doran \(1941\)](#), [Poole \(1948\)](#), [Shartsis et al. \(1952\)](#), [Bockris et al. \(1955\)](#), and [Ammar et al. \(1977\)](#); and [Poole \(1948\)](#) and [Mackenzie \(1957\)](#) using VFT equation for the same compositions.

Table 2  
Fitting parameters for Eq. (8)

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
0	−21.3517 (2.1976)	29300.3 (2159.0)	29.9791 (14.7288)	−58868.8 (27112.4)
1	12.7366 (3.8896)	−9757.4 (3708.8)	−32.4047 (16.8378)	65081.8 (30272.4)

Note. Numbers in parentheses are  $2\sigma$  errors of fitting coefficients, respectively.

#### 4.2. Viscosity data

The primary motivation of this work is to develop a practical viscosity model for natural anhydrous and hydrous silicate melts. Viscosity data for the development of our viscosity model come from literature. We limit the

compositional range to “natural” silicate melts (including Fe-free haplogranitic, haploandesitic, haplobasanitic, haplotephritic, haplophonolitic and haplotrachytic melts). The compositions range from peridotite to rhyolite, from peralkaline to peraluminous silicate melts, and from anhydrous to hydrous melts. Simple synthetic melts, such as  $\text{Li}_2\text{O--SiO}_2$ ,  $\text{Na}_2\text{O--SiO}_2$ ,  $\text{K}_2\text{O--SiO}_2$ ,  $\text{CaSiO}_3\text{--MgSiO}_3$ , feldspar systems, are not included, but synthetic melts intended to approximate natural silicate melts are included. Simple synthetic melts are excluded from our model because we are not there yet in developing a completely general compositional model for the viscosity of all silicate melts. For example, including simple melts such as  $\text{Na}_2\text{O--SiO}_2$  would expand the compositional space to pure  $\text{Na}_2\text{O}$  melt, which may require parameters *A*, *B*, *C*, and *D* in Eq. (4) to vary as

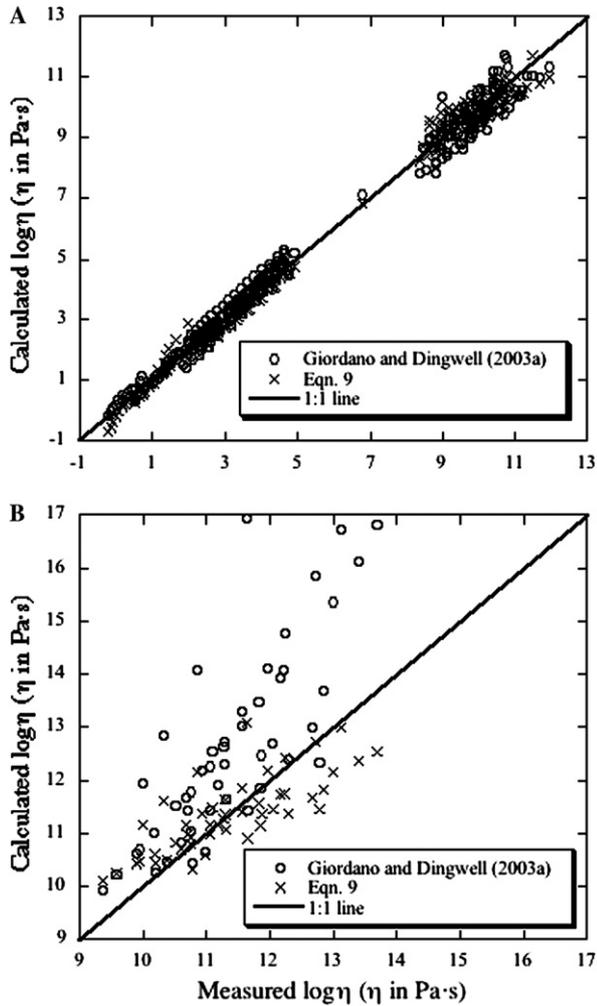


Fig. 4. Comparison of experimental viscosity data with calculated values (A) in the temperature range from 700 to 1600 °C (which is the temperature range that Giordano and Dingwell (2003a) recommended for their model); and (B) below 700 °C.

a nonlinear function of oxide mole fractions. This limitation was also encountered in literature when other silicate liquid properties are modeled: (1) the density model of liquids is developed only for natural silicate liquids, excluding simple synthetic melts (Lange, 1997; Lange and Carmichael, 1987), (2) the thermodynamic model of silicate melts is also developed only for natural silicate liquids, excluding simple synthetic melts (Ghiorso et al., 1983, 2002).

The compositions of “natural” silicate melts for which viscosity data are available are listed in Table 3 on an anhydrous basis. The references are also given in Table 3. There are 1451 viscosity measurements. Natural melt compositions covered in the database are presented in Fig. 5 on an anhydrous basis. The compositions covered by the data include: anhydrous peridotite to rhyolite, anhydrous peralkaline to peraluminous melts, hydrous basalt to rhyolite, hydrous peralkaline to peraluminous melts. The FeO-free melts include haplogranitic melts (H1–26), haploandesite (A2 and A4), haplobasanite (Bn3), haplotephrite (Te2), haplophonolite (Ph4) and haplotrachyte (Tr6) as shown

in Table 3. Some samples with the same or similar sample names (such as two HPG8, and one HPG08) but different chemical compositions are treated as different samples with different chemical compositions (that is, we did not treat all compositions to be the same and average the chemical analyses). The viscosity ranges from 0.1 to  $10^{15}$  Pa s. The temperature ranges from 573 to 1978 K. The H<sub>2</sub>O concentration is  $\leq 12.3$  wt% for rhyolitic melt, and below 5 wt% for other melts.

Viscosity data from partially crystallized melt (such as andesite ME113e, Richet et al., 1996) are not used. Viscosity data of phonolite melt with 0.88 wt% water in Whittington et al. (2001) are shown by these authors to be outliers, and are hence not included. The viscosities of Sample A (LGB rhyolite) in Neuville et al. (1993) are not used because these authors suspected the quality of the viscosity data. Data on rhyolite shown to be outliers by Zhang et al. (2003) are not included. The data of Friedman et al. (1963) are not used due to their large uncertainty. Some viscosity data of identical composition, experimental temperature and viscosity value were reported in two or more publications and it is not clear to us whether or not they mean the same measurements. Such data are counted only once in the database and in our regression, such as viscosity data of EIF basanite (Gottsmann et al., 2002; Giordano and Dingwell, 2003a). All the viscosity data used in the following fit are listed in a data file in the electronic annex of this journal.

Most viscosity data in the database are at 1 bar, and some are at pressures up to 5 kbar. The pressure effect is ignored as it has been shown that the effect is negligible for pressures up to 5 kbar (Persikov, 1998; Zhang et al., 2003).

#### 4.3. The preferred model

The eight-parameter model (Eq. (9)) grouped the effects of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and P<sub>2</sub>O<sub>5</sub> on viscosity. The model, although appealing because of its simplicity, still does not reproduce experimental viscosity data well. Furthermore, it does not apply to hydrous melts. In order to produce a model that can be used to calculate viscosity to better precision, more compositional parameters are necessary. In our preferred model in this section, the goal is to fit the entire viscosity database on “natural” silicate melts as accurately as possible. Although using the least number of parameters to fit is also a goal, it is subordinate to the goal of fitting the viscosity data as accurately as possible.

In the preferred model, parameters *A*, *B*, *C*, and *D* in Eq. (4) are assumed to be linear functions of oxide mole fractions because the assumption is simple and because it considers different effects of the different oxide components to the viscosity. Fe in the natural silicate melts has two oxidation states: ferric and ferrous. The two behave differently in the structure of the silicate melts. Although the oxidation state of Fe has been found to affect melt viscosity significantly, especially at low temperatures (Dingwell and

Table 3  
Melt composition on anhydrous basis (on wt% basis)

Composition	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Total	ID	Ref
Basanite (EIF)	41.15	2.74	12.10	10.11	0.00	11.24	15.66	2.76	3.04	1.02	99.82	Bn1	19
Basanite (EIF)	41.22	2.74	12.12	10.03	0.00	11.26	15.69	2.76	3.05	1.02	99.89	Bn2	17
Basanite (NIQ)	43.57	2.97	10.18	0.00	0.00	9.17	26.07	7.59	0.96	0.00	100.51	Bn3	1
Peridotite	45.83	0.18	4.87	8.63	0.00	31.63	6.37	0.32	0.00	0.00	97.83	Pr	27
Basalt (ETN)	47.03	1.61	16.28	10.88	0.20	5.17	10.47	3.75	1.94	0.59	97.92	Bl1	25
Basalt (ETN)	47.81	1.94	17.91	10.90	0.19	4.75	9.96	3.94	2.11	0.48	99.99	Bl2	17
Basalt	48.21	1.25	15.50	10.64	0.00	9.08	11.92	2.40	0.08	0.14	99.22	Bl3	21
Tephrite (Ves_G_tot)	49.20	0.83	16.40	7.20	0.13	5.10	10.20	2.70	6.50	0.72	98.98	Te1	19
Basalt (MTV9)	49.61	4.27	11.01	14.73	0.00	4.46	10.04	2.81	0.47	2.51	99.91	Bl5	28
Basalt (Kilauea 1921)	50.01	2.60	12.56	10.79	0.24	9.39	10.88	2.33	0.48	0.00	99.37	Bl7	29
Tephrite	50.56	2.35	14.03	0.00	0.00	8.79	15.00	7.04	3.01	0.00	100.78	Te2	1
Basalt (MTV4)	50.66	3.95	11.35	13.90	0.00	3.94	9.60	2.98	0.51	2.40	99.29	Bl6	28
Basalt (MTV6)	50.84	4.26	11.38	15.05	0.00	4.42	10.18	3.01	0.55	0.04	99.73	Bl8	28
Basalt (MTV2)	50.87	4.05	11.36	14.20	0.00	4.23	9.62	3.06	0.52	0.09	98.00	Bl9	28
Phonolite (Ves_W_tot)	51.20	0.67	18.60	6.10	0.13	2.50	7.30	3.75	7.90	0.40	98.55	Ph1	19
Phonolite (V_1631_G)	53.14	0.59	19.84	4.72	0.13	1.77	6.75	4.77	8.28	0.00	99.99	Ph2	23
Phonolite (V_1631_W)	53.52	0.60	19.84	4.80	0.14	1.76	6.76	4.66	7.91	0.00	99.99	Ph3	23
Basalt	53.54	1.05	17.29	7.82	0.00	5.46	8.32	3.59	1.64	0.20	98.91	Bl4	21
Andesite	58.56	0.64	18.98	7.45	0.00	3.48	6.17	3.24	0.92	0.00	99.44	A1	21
Andesite	58.69	0.01	21.57	0.02	0.02	5.38	9.49	3.30	1.57	0.00	100.05	A2	26
Phonolite	58.82	0.79	19.42	0.00	0.00	1.87	2.35	9.31	7.44	0.00	100.00	Ph4	2
Andesite (Crater Lake)	59.46	0.73	17.90	5.18	0.10	3.71	6.45	4.23	1.47	0.00	99.26	A5	29
Phonolite (ATN)	59.70	0.46	18.52	3.60	0.17	0.65	2.80	3.89	8.45	0.15	98.39	Ph5	19
Phonolite (Td_ph)	60.46	0.56	18.81	3.31	0.20	0.36	0.67	9.76	5.45	0.06	99.64	Ph6	22
Trachyte (IGC)	60.74	0.27	19.22	3.37	0.18	0.28	2.11	5.28	6.32	0.06	97.83	Tr1	20
Trachyte (AMS_D1)	60.86	0.39	18.27	3.88	0.12	0.90	2.96	4.12	8.50	0.00	100.00	Tr2	23
Andesite	61.17	0.84	17.29	5.39	0.00	3.35	5.83	3.85	1.39	0.00	99.11	A3	11
Trachyte (AMS_B1)	61.26	0.38	18.38	3.50	0.14	0.74	2.97	4.58	8.04	0.00	99.99	Tr3	23
Andesite (Crater Lake)	62.15	0.76	16.80	4.96	0.25	3.26	5.08	5.02	1.72	0.00	100.00	A6	32
Andesite	62.40	0.55	20.01	0.03	0.02	3.22	9.08	3.52	0.93	0.12	99.88	A4	8
Trachyte (MNV)	63.88	0.31	17.10	2.90	0.13	0.24	1.82	5.67	6.82	0.05	98.92	Tr4	20
Trachyte (PVC)	63.99	0.45	16.96	2.55	0.14	0.32	0.83	6.33	6.37	0.09	98.03	Tr5	19
Trachyte	64.45	0.50	16.71	0.00	0.00	2.92	5.36	6.70	3.37	0.00	100.01	Tr6	2
Dacite	65.28	0.59	17.05	4.02	0.08	1.82	4.70	4.34	1.29	0.13	99.30	D1	30
Dacite (UNZ)	66.00	0.36	15.23	4.08	0.10	2.21	5.01	3.84	2.16	0.14	99.13	D2	24
Granite (263-2)	66.77	0.39	20.15	4.31	0.01	0.72	3.64	1.37	2.17	0.00	99.53	R1	16
Trachyte (570-2)	66.95	0.87	21.24	2.57	0.06	0.01	1.63	1.83	4.55	0.00	99.71	Tr7	16
Plagioliparite (851-2)	67.16	0.01	21.65	2.81	0.01	0.73	2.65	2.85	1.82	0.00	99.69	R2	16
Trachyte (570-3)	68.71	0.90	19.28	2.59	0.06	0.00	1.65	1.87	4.66	0.00	99.72	Tr8	16
Trachyte (570-1)	70.16	0.92	17.18	2.74	0.06	0.00	1.70	2.07	4.88	0.00	99.71	Tr9	16
Plagioliparite (851-1)	71.22	0.24	16.80	2.91	0.06	0.80	2.62	3.09	1.94	0.00	99.68	R3	16
Granite (130)	71.42	0.01	16.10	4.58	0.01	1.57	0.94	1.94	2.92	0.00	99.49	R4	16
Granite (Barlak)	73.12	0.19	13.56	3.19	0.00	0.18	1.68	3.86	4.20	0.00	99.98	R33	31
Rhyolite	73.23	0.19	13.60	2.78	0.00	0.17	1.69	3.78	4.11	0.13	99.68	R5	21
Trachyte (570-4)	73.35	0.90	14.83	2.38	0.07	0.00	1.64	1.87	4.70	0.00	99.74	Tr10	16
HPG05	73.49	0.00	13.26	0.00	0.00	0.00	0.00	2.40	8.98	0.00	98.13	H21	38
HPG8An10	73.60	0.00	15.60	0.00	0.00	0.00	2.10	4.40	3.80	0.00	99.50	H4	33
Rhyolite	73.79	0.05	15.11	0.42	0.05	0.07	0.97	4.71	4.02	0.01	99.20	R6	9
Rhyolite (GB4)	73.89	0.06	15.77	0.75	0.00	0.14	0.58	4.62	4.19	0.00	100.00	R34	34
HPG8Na5	74.10	0.00	11.70	0.00	0.00	0.00	0.00	9.00	4.40	0.00	99.20	H5	4, 35
HPG8Ca5 (Ca5)	74.10	0.00	12.20	0.00	0.00	0.00	5.20	4.40	4.00	0.00	99.90	H6	36
HPG8K5	74.60	0.00	11.80	0.00	0.00	0.00	0.00	4.40	9.20	0.00	100.00	H7	4
Rhyolite (M981023)	74.70	0.08	13.28	1.65	0.00	0.00	0.77	4.30	5.22	0.00	100.00	R7	18
HPG04	74.90	0.00	13.52	0.00	0.00	0.00	0.00	3.64	7.22	0.00	99.28	H22	38
Rhyolite (P3RR)	75.37	0.07	12.84	1.57	0.07	0.04	0.72	4.19	5.13	0.00	100.00	R8	17
HPG8Al5 (Al05)	75.40	0.00	16.10	0.00	0.00	0.00	0.00	4.70	4.30	0.00	100.50	H8	37
HPG03	75.52	0.00	13.90	0.00	0.00	0.00	0.00	4.77	5.53	0.00	99.72	H23	38
HPG8Mg5 (Mg5)	75.60	0.00	12.00	0.00	0.00	4.90	0.00	4.50	4.00	0.00	101.00	H9	36
Rhyolite	76.03	0.06	11.48	1.05	0.06	0.36	3.21	2.42	4.60	0.00	99.27	R9	13
HPG02	76.08	0.00	13.89	0.00	0.00	0.00	0.00	5.96	3.84	0.00	99.77	H24	38
AOQ	76.12	0.00	13.53	0.00	0.00	0.00	0.00	4.65	5.68	0.00	99.98	H1	6
Rhyolite	76.38	0.06	11.59	1.03	0.05	0.36	3.25	2.44	4.66	0.00	99.82	R10	13
HPG01	76.52	0.00	14.05	0.00	0.00	0.00	0.00	7.14	2.19	0.00	99.90	H25	38

Table 3 (continued)

Composition	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Total	ID	Ref
Rhyolite	76.57	0.06	11.65	1.04	0.07	0.36	3.23	2.46	4.62	0.00	100.06	R11	13
Rhyolite (MCR)	76.59	0.08	12.67	1.00	0.00	0.03	0.52	3.98	4.88	0.00	99.75	R12	14
Rhyolite	76.60	0.10	12.70	1.17	0.00	0.02	0.31	4.10	4.60	0.00	99.60	R13	15
HPG09	76.88	0.00	11.45	0.00	0.00	0.00	0.00	3.60	5.60	0.00	97.53	H10	38
Rhyolite (LGB)	76.92	0.10	12.92	0.89	0.05	0.11	0.86	3.89	4.25	0.03	100.02	R14	10
Rhyolite (RH)	76.99	0.03	13.02	0.71	0.10	0.04	0.48	4.31	4.31	0.00	99.99	R15	10
Rhyolite	77.00	0.06	11.77	1.00	0.06	0.36	3.29	2.48	4.68	0.00	100.70	R16	13
Rhyolite (RH-r)	77.01	0.03	13.14	0.71	0.10	0.04	0.51	4.28	4.18	0.00	100.00	R17	10
Rhyolite	77.07	0.06	11.67	0.99	0.07	0.35	3.28	2.42	4.62	0.00	100.53	R18	13
Rhyolite (SH-r)	77.08	0.09	12.44	1.30	0.02	0.02	0.36	4.49	4.20	0.00	100.00	R19	10
Rhyolite (EDFmr)	77.15	0.09	12.82	0.56	0.07	0.07	0.52	4.11	4.61	0.01	100.01	R20	12
Rhyolite (SH)	77.17	0.08	12.40	1.30	0.02	0.01	0.35	4.50	4.20	0.00	100.03	R21	10
Rhyolite (EDF)	77.18	0.09	12.91	0.61	0.07	0.07	0.51	4.05	4.52	0.01	100.02	R22	12
HPG8Al2 (Al02)	77.20	0.00	13.90	0.00	0.00	0.00	0.00	4.50	4.30	0.00	99.90	H11	37
Rhyolite	77.27	0.03	11.75	1.05	0.05	0.36	3.31	2.43	4.73	0.00	100.98	R23	13
Rhyolite	77.38	0.05	11.70	1.03	0.05	0.36	3.24	2.44	4.80	0.00	101.05	R24	13
Rhyolite	77.46	0.05	11.64	1.04	0.07	0.35	3.23	2.45	4.70	0.00	100.99	R25	13
Rhyolite (BL6)	77.48	0.17	12.20	1.30	0.05	0.17	1.14	3.90	3.60	0.00	100.01	R26	10
Rhyolite (BL6-r)	77.53	0.17	12.17	1.30	0.05	0.17	1.13	3.89	3.60	0.00	100.01	R27	10
Rhyolite (LGB-r)	77.88	0.07	12.73	0.76	0.04	0.06	0.50	3.93	4.03	0.01	100.01	R28	10
Rhyolite (BL3)	77.88	0.16	12.03	1.19	0.05	0.05	1.06	3.64	3.88	0.01	99.95	R29	12
HPG8	77.90	0.00	11.89	0.00	0.00	0.00	0.00	4.53	4.17	0.00	98.49	H2	5
Rhyolite	77.90	0.07	12.05	0.76	0.00	0.05	0.52	4.01	4.06	0.00	99.42	R30	11
Rhyolite (EDF-1)	78.00	0.09	12.15	0.54	0.07	0.06	0.50	4.08	4.48	0.02	99.99	R31	10
Rhyolite (EDF-2)	78.00	0.09	12.15	0.54	0.07	0.07	0.50	4.08	4.48	0.00	99.98	R32	10
HPG11	78.14	0.00	11.64	0.00	0.00	0.00	0.00	1.26	9.11	0.00	100.15	H12	38
HPG10	78.21	0.00	11.69	0.00	0.00	0.00	0.00	2.41	7.43	0.00	99.74	H13	38
HPG07	78.28	0.00	11.92	0.00	0.00	0.00	0.00	5.91	2.23	0.00	98.34	H14	38
HPG8	78.60	0.00	12.50	0.00	0.00	0.00	0.00	4.60	4.20	0.00	99.90	H3	3, 4, 7
HPG08	78.60	0.00	11.99	0.00	0.00	0.00	0.00	4.57	4.20	0.00	99.36	H15	38
HPG06	78.98	0.00	12.11	0.00	0.00	0.00	0.00	7.04	0.62	0.00	98.75	H26	38
HPG16	81.03	0.00	9.91	0.00	0.00	0.00	0.00	1.24	7.39	0.00	99.57	H16	38
HPG15	81.74	0.00	10.03	0.00	0.00	0.00	0.00	2.47	5.66	0.00	99.90	H17	38
HPG14	82.22	0.00	10.17	0.00	0.00	0.00	0.00	3.66	3.89	0.00	99.94	H18	38
HPG12	82.31	0.00	10.16	0.00	0.00	0.00	0.00	5.89	0.70	0.00	99.06	H19	38
HPG13	82.94	0.00	10.30	0.00	0.00	0.00	0.00	4.68	2.41	0.00	100.33	H20	38

The melt compositions are listed according to SiO<sub>2</sub> content. References: 1, Whittington et al. (2000); 2, Whittington et al. (2001); 3, Dorfman et al. (1996); 4, Hess et al. (1995); 5, Dingwell et al. (1992); 6, Schulze et al. (1996); 7, Dingwell et al. (1996); 8, Richet et al. (1996); 9, Burnham (1964); 10, Stevenson et al. (1998); 11, Neuville et al. (1993); 12, Stevenson et al. (1996); 13, Goto et al. (2005); 14, Zhang et al. (2003); 15, Shaw (1963); 16, Goto et al. (1997); 17, Gottsmann et al. (2002); 18, Stein and Spera (1993, 2002); 19, Giordano and Dingwell (2003a); 20, Giordano et al. (2004); 21, Persikov (1991); 22, Giordano et al. (2000); 23, Romano et al. (2003); 24, Giordano et al. (2005); 25, Giordano and Dingwell (2003b); 26, Liebske et al. (2003); 27, Dingwell et al. (2004); 28, Toplis et al. (1994); 29, Kushiro et al. (1976); 30, Alidibirov et al. (1997); 31, Persikov et al. (1986); 32, Dunn and Scarfe (1986); 33, Dingwell et al. (2000); 34, Scaillet et al. (1996); 35, Dingwell et al. (1998a); 36, Hess et al. (1996); 37, Dingwell et al. (1998b); 38, Hess et al. (2001).

Virgo, 1987; Liebske et al., 2003), often there is not enough information to calculate the ferric to ferrous ratio of the experimental melts at low temperatures. Hence all iron is considered as FeO.

Previous studies (e.g., Riebling, 1966; Bruckner, 1983) show that aluminum-saturated melts [Na/Al (molar) = 1] have higher viscosities than either aluminum-oversaturated (peraluminous) or aluminum-undersaturated (alkaline to peralkaline) melts. Hence, NaAlO<sub>2</sub> and KAlO<sub>2</sub> would be reasonable end-members in this multicomponent system. Al<sub>2</sub>O<sub>3</sub> in the melt is considered to combine with alkalis to form (Na,K)AlO<sub>2</sub>. After forming (Na,K)AlO<sub>2</sub>, either excess alkalis or excess aluminum are left as a component in the melts.

For hydrous melts, H<sub>2</sub>O content plays a major role and the effect is not linear. Viscosity decreases rapidly with the

first small amount of total dissolved water, and then not so rapidly at higher H<sub>2</sub>O contents (Lange, 1994; Dingwell et al., 1996). Water is present in the silicate melts as at least two species: molecular H<sub>2</sub>O and hydroxyl group (Stolper, 1982). The exact role of OH and molecular H<sub>2</sub>O on affecting melt viscosity is not known. Following Zhang et al. (2003), we use H<sub>2</sub>O content raised to some power as an additional parameter. After many trials, the following parameter seems useful in fitting viscosity data of hydrous melts:

$$Z = (X_{\text{H}_2\text{O}})^{\frac{1}{1+(e_1/T)}}, \quad (10)$$

where  $e_1$  is a constant,  $T$  is the temperature in K, and  $X_{\text{H}_2\text{O}}$  is the oxide mole fraction of total dissolved H<sub>2</sub>O. Combining Eqs. (4), (6a), and (10) we use the following model to fit all the viscosity data in the database:

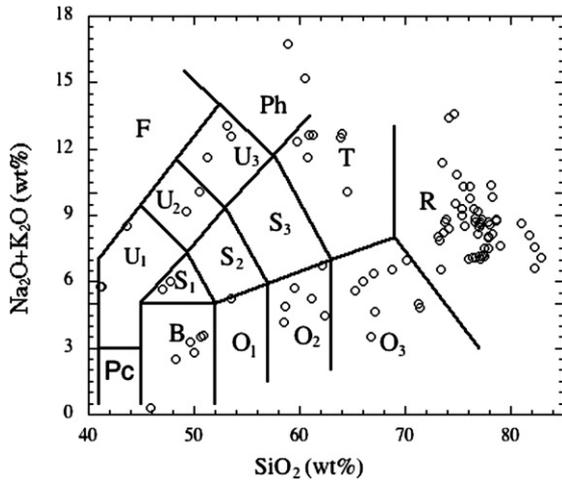


Fig. 5. Total alkalis versus  $\text{SiO}_2$  diagram (Le Bas et al., 1986) showing the compositions of samples modeled in our work. Pc, picrobasalt; B, basalt;  $\text{O}_1$ , basaltic andesite;  $\text{O}_2$ , andesite;  $\text{O}_3$ , dacite; R, rhyolite;  $\text{S}_1$ , trachybasalt;  $\text{S}_2$ , basaltic trachyandesite;  $\text{S}_3$ , trachyandesite; T, trachyte or trachydacite;  $\text{U}_1$ , basanite or tephrite;  $\text{U}_2$ , phonotephrite;  $\text{U}_3$ , tephriphonolite; Ph, phonolite; F, foidite.

$$\log \eta = \left( \sum_i a_i X_i \right) + \frac{(\sum_i b_i X_i)}{T} + \exp \left( \left( \sum_i c_i X_i \right) + \frac{(\sum_i d_i X_i)}{T} \right), \quad (11)$$

where  $X_i$  is the mole fraction of  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_{3\text{ex}}$ ,  $\text{FeO}_T$ ,  $\text{MnO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $(\text{Na,K})_2\text{O}_{\text{ex}}$ ,  $\text{P}_2\text{O}_5$ ,  $\text{H}_2\text{O}$ ,  $(\text{Na,K})\text{AlO}_2$ , plus another term related to  $\text{H}_2\text{O}$ ,  $(X_{\text{H}_2\text{O}})^{1/[1+(e_1/T)]}$ , because

Table 4  
Fitting parameters for Eq. (11)

	$a$	$b \times 10^3$	$c$	$d \times 10^3$
$\text{SiO}_2$	-6.83 (0.47)	18.14 (0.47)		2.16 (0.16)
$\text{TiO}_2$	-170.79 (20.98)	248.93 (33.12)		-143.05 (26.57)
$\text{Al}_2\text{O}_{3\text{ex}}$	-14.71 (4.32)	32.61 (4.70)	21.73 (10.75)	-22.10 (11.27)
(Fe, Mn)O			-61.98 (25.91)	38.56 (26.81)
MgO	-18.01 (2.78)	25.96 (4.16)	-105.53 (19.50)	110.83 (19.95)
CaO	-19.76 (3.27)	22.64 (3.65)	-69.92 (11.23)	67.12 (11.26)
$(\text{Na,K})_2\text{O}_{\text{ex}}$	34.31 (9.60)	-68.29 (7.96)	-85.67 (50.49)	58.01 (46.09)
$\text{P}_2\text{O}_5$				384.77 (118.21)
Z	-140.38 (78.46)	38.84 (27.10)	332.01 (189.53)	-404.97 (237.47)
$\text{H}_2\text{O}$	159.26 (79.94)	-48.55 (29.76)	-432.22 (207.27)	513.75 (260.04)
$(\text{Na,K})\text{AlO}_2$	-8.43 (1.70)	16.12 (1.68)	-3.16 (0.83)	
$e_1$	185.797 (91.556)			

Note. Numbers in parentheses are  $2\sigma$  errors of fitting coefficients, respectively.

a simple linear term with  $\text{H}_2\text{O}$  is not enough to account for the dependence of viscosity on  $\text{H}_2\text{O}$  content. The values of  $a_i$ ,  $b_i$ ,  $c_i$ ,  $d_i$ , and  $e_1$  with standard errors obtained from the fit are listed in Table 4. In the process of fitting, some parameters turned out to be unnecessary and some could be combined. These simplifications were made to reduce the number of parameters. The final fit contains 37 fitting parameters. As shown in Table 4, all the fitting parameters are statistically significant. This model can reproduce all the viscosity data (in the electronic annex) with a  $2\sigma$  deviation of  $0.61 \log \eta$  units in the available temperature and compositional range of natural silicate melts. Fig. 6 shows comparison between measured viscosity values of all the melts in the database, including hydrous and anhydrous natural melts, and those calculated from Eq. (11). Because this is our preferred model, the full equation is written down as follows:

$$\begin{aligned} \log \eta = & [-6.83X_{\text{SiO}_2} - 170.79X_{\text{TiO}_2} - 14.71X_{\text{Al}_2\text{O}_{3\text{ex}}} \\ & - 18.01X_{\text{MgO}} - 19.76X_{\text{CaO}} + 34.31X_{(\text{Na,K})_2\text{O}_{\text{ex}}} \\ & - 140.38Z + 159.26X_{\text{H}_2\text{O}} - 8.43X_{(\text{Na,K})\text{AlO}_2}] \\ & + [18.14X_{\text{SiO}_2} + 248.93X_{\text{TiO}_2} + 32.61X_{\text{Al}_2\text{O}_{3\text{ex}}} \\ & + 25.96X_{\text{MgO}} + 22.64X_{\text{CaO}} - 68.29X_{(\text{Na,K})_2\text{O}_{\text{ex}}} \\ & + 38.84Z - 48.55X_{\text{H}_2\text{O}} \\ & + 16.12X_{(\text{Na,K})\text{AlO}_2}]1000/T \\ & + \exp\{[21.73X_{\text{Al}_2\text{O}_{3\text{ex}}} - 61.98X_{(\text{Fe, Mn})\text{O}} \\ & - 105.53X_{\text{MgO}} - 69.92X_{\text{CaO}} - 85.67X_{(\text{Na,K})_2\text{O}_{\text{ex}}} \\ & + 332.01Z - 432.22X_{\text{H}_2\text{O}} - 3.16X_{(\text{Na,K})\text{AlO}_2}] \\ & + [2.16X_{\text{SiO}_2} - 143.05X_{\text{TiO}_2} - 22.10X_{\text{Al}_2\text{O}_{3\text{ex}}} \\ & + 38.56X_{(\text{Fe, Mn})\text{O}} + 110.83X_{\text{MgO}} + 67.12X_{\text{CaO}} \\ & + 58.01X_{(\text{Na,K})_2\text{O}_{\text{ex}}} + 384.77X_{\text{P}_2\text{O}_5} - 404.97Z \\ & + 513.75X_{\text{H}_2\text{O}}]1000/T\}, \quad (12) \end{aligned}$$

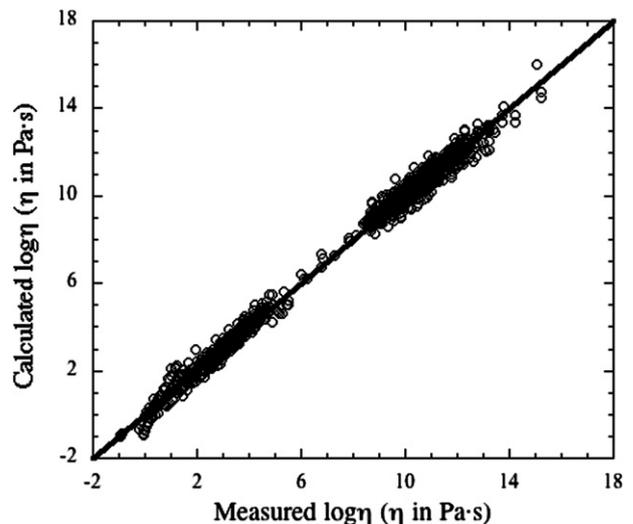


Fig. 6. Comparison of experimental viscosity values with calculated values using Eq. (12).

Table 5  
Examples of calculation using Eq. (12)

Composition	wt%	Composition	Mole fraction	$T$ (K)	Calculated $\log \eta$ (Pas)
SiO <sub>2</sub>	53.52	SiO <sub>2</sub>	0.5336	753.75	9.47
TiO <sub>2</sub>	0.60	TiO <sub>2</sub>	0.0045	748.75	9.60
Al <sub>2</sub> O <sub>3</sub>	19.84	Al <sub>2</sub> O <sub>3ex</sub>	0.0212	727.75	10.15
FeO <sub>r</sub>	4.80	(Fe, Mn)O	0.0412	717.65	10.42
MnO	0.14	MgO	0.0262	704.35	10.80
MgO	1.76	CaO	0.0722		
CaO	6.76	(Na,K) <sub>2</sub> O <sub>ex</sub>	0.0000		
Na <sub>2</sub> O	4.66	P <sub>2</sub> O <sub>5</sub>	0.0000		
K <sub>2</sub> O	7.91	H <sub>2</sub> O	0.1104		
P <sub>2</sub> O <sub>5</sub>	0.00	(Na,K)AlO <sub>2</sub>	0.1907		
H <sub>2</sub> O	3.32				

Note. The melt is hydrous phonolite from Romano et al. (2003).

where  $Z = (X_{\text{H}_2\text{O}})^{1/[1+(185.797/T)]}$ , and all mole fractions (including H<sub>2</sub>O) add up to 1. Examples of calculation are given in Table 5.

Fig. 6 compares calculated viscosity with experimental viscosity for all data in the database and shows that there is no systematic misfit. We examined the behavior of Eq. (12) by varying temperature and various oxide concentrations. The calculated viscosity varies smoothly and monotonically with these parameters with no up and down fluctuations. Furthermore, in order to investigate whether some melts are systematically misfit or are not fit as well as other melts, we list  $\Delta \pm 2\sigma$  for each melt composition in Table 6, where  $\Delta$  is the average difference between the experimental  $\log \eta$  and calculated  $\log \eta$ , and  $\sigma$  is the standard deviation. The value of  $\Delta$  characterizes systematic misfit and  $2\sigma$  is a measure of data scatter. As shown in Table 6, all rock groups of melts have small  $\Delta$  values; but  $\Delta$  values for subgroups vary from 0 up to 0.30 and most subgroups still have small  $\Delta$  values. There is no correlation between the  $\Delta$  values and compositions of the melts. On  $2\sigma$  values, there are some variations, but no group is obviously misfit. There is no correlation between the reproducibility and the degree of polymerization.

Two sets of viscosity data on hydrous leucogranite (Whittington et al., 2004) and anhydrous HPG8An10 (Dingwell et al., 2000) are not included in the fit, but are chosen to test whether our preferred model can predict data not included in the fit. Because water content in the “anhydrous” melt of Whittington et al. (2004) is not determined, the viscosity data of anhydrous melt are not used due to large effect of a small amount of water on viscosity (Lange, 1994; Zhang et al., 2003). As shown in Fig. 7, this new model has the capability to predict the viscosity at low temperature with a  $2\sigma$  deviation of 0.61.

There are many viscosity models for specific compositions, and many of them have better accuracy than our 37-parameter general model. For example, the viscosity model for hydrous and anhydrous rhyolitic melt by Zhang et al. (2003) has a  $2\sigma$  uncertainty of 0.36  $\log \eta$  units; specific models for five individual anhydrous and hydrous melt

Table 6  
The  $2\sigma$  deviations and data points of sub-groups in the viscosity database

Composition	$\Delta \pm 2\sigma$	Number of data points
<i>Basanite (Bn1-3)</i>	$-0.10 \pm 0.55$	66
Anhydrous	$-0.21 \pm 0.56$	33
Hydrous	$0.01 \pm 0.45$	33
<i>Tephrite (Tel-2)</i>	$0.13 \pm 0.75$	71
Anhydrous	$0.23 \pm 0.73$	38
Hydrous	$0.01 \pm 0.72$	33
<i>Phonolite</i>	$-0.05 \pm 0.63$	164
Ph1-3		
Anhydrous	$-0.04 \pm 0.54$	40
Hydrous	$0.30 \pm 0.38$	25
Ph4-6		
Anhydrous	$-0.15 \pm 0.57$	59
Hydrous	$-0.13 \pm 0.63$	40
<i>Trachyte</i>	$0.04 \pm 0.53$	253
Tr1-3		
Anhydrous	$-0.04 \pm 0.71$	43
Hydrous	$-0.01 \pm 0.39$	56
Tr4-6		
Anhydrous	$0.11 \pm 0.52$	68
Hydrous	$0.13 \pm 0.43$	55
Tr7-10		
Anhydrous	$-0.12 \pm 0.41$	31
<i>Andesite</i>	$-0.01 \pm 0.43$	166
A1-2, A5		
Anhydrous	$-0.05 \pm 0.40$	27
Hydrous	$-0.02 \pm 0.37$	42
A3-4, A6		
Anhydrous	$-0.03 \pm 0.40$	52
Hydrous	$0.06 \pm 0.52$	45
<i>Rhyolite</i>	$-0.00 \pm 0.54$	352
R1-4		
Anhydrous	$0.05 \pm 0.45$	25
R5-8, R33-34		
Anhydrous	$0.02 \pm 0.13$	7
Hydrous	$0.13 \pm 0.51$	40
R9-32		
Anhydrous	$0.04 \pm 0.43$	83
Hydrous	$-0.06 \pm 0.58$	197
<i>Dacite (D1-2)</i>	$0.14 \pm 0.47$	41
Anhydrous	$0.20 \pm 0.37$	32
Hydrous	$-0.09 \pm 0.53$	9
<i>Basalt</i>	$0.01 \pm 0.92$	75
Bl1-3, Bl5		
Anhydrous	$-0.11 \pm 1.05$	20
Hydrous	$0.07 \pm 0.51$	21
Bl4, Bl6-9		
Anhydrous	$0.06 \pm 1.09$	28
Hydrous	$0.03 \pm 0.74$	6
<i>Periodite (Pr)</i>	$-0.07 \pm 0.55$	8
Anhydrous	$-0.07 \pm 0.55$	8
<i>Haplogranitic melt (H1-26)</i>	$0.03 \pm 0.72$	255
Anhydrous	$-0.01 \pm 0.78$	161
Hydrous	$0.09 \pm 0.61$	94
<i>Leucogranite<sup>a</sup></i>		
Hydrous	$-0.15 \pm 0.51$	14
<i>HPG8An10<sup>a</sup></i>		
Anhydrous	$-0.02 \pm 0.22$	8

<sup>a</sup> The melt used to test the model.

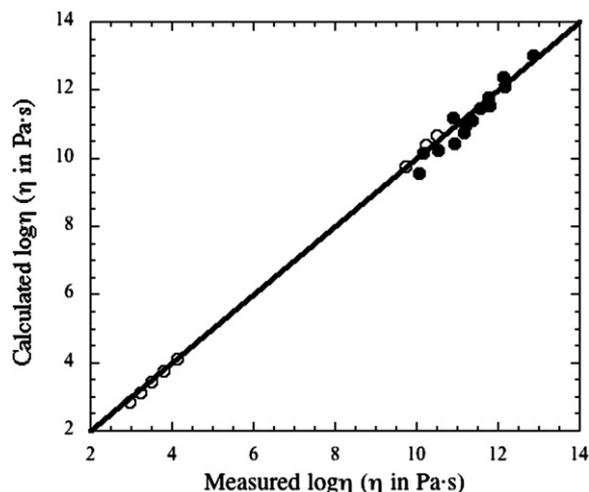


Fig. 7. The predictions of Eq. (12). Data sources: filled symbols, Whittington et al. (2004); open symbols, Dingwell et al. (2000).

compositions by Giordano et al. (2005) have very low  $2\sigma$  uncertainties. Therefore, although we recommend the use of our grand model, we realize that some specific models have better accuracy and should be used when appropriate.

One unattractive feature of our preferred model is the large number of parameters used. This means the fitting parameters themselves are not well resolved. However, it does not affect the accuracy of the calculation of viscosities as long as no extrapolation is attempted. That is, the model should not be extrapolated to binary systems, nor to viscosities above  $10^{15}$  Pa s, nor to temperature below 573 K, nor to  $\text{H}_2\text{O}$  content above 5 wt% for melts other than rhyolite. (For rhyolite, the highest  $\text{H}_2\text{O}$  content in the viscosity database is 12.3 wt%.) As mentioned earlier, Eq. (12) predicts smooth and monotonic variations of  $\log \eta$  with mole fraction of oxides or temperature. Although it is desirable to develop a model with a smaller number of fitting parameters, the drawback of many fitting parameters should not prevent the use of Eq. (12) in calculating viscosity of natural silicate melts in a wide range of applications such as volcanic eruption dynamics, as well as other magmatic processes. For example, the viscosity model of Bottinga and Weill (1972) has 285 fitting parameters for anhydrous melts at high temperatures and it was widely applied. Eq. (12) is easy to include in a software program or in a spreadsheet program. We recommend its use to calculate viscosities of all natural silicate melts. Other applications of the viscosity model include: (1) estimation of glass transition temperature of any natural silicate melt given cooling rate (Dingwell and Webb, 1990; Dingwell et al., 2004; Giordano et al., 2005), and (2) estimation of cooling rate of any natural hydrous silicate glass based on apparent equilibrium temperature from  $\text{H}_2\text{O}$  speciation (Dingwell and Webb, 1990; Zhang, 1994; Zhang et al., 2000, 2003).

Even though this viscosity model can reproduce the entire viscosity database to a better accuracy and for a greater range of compositions than previous models, the uncertainty in reproducing the viscosity data is still larger than the

experimental data uncertainty, which is usually  $0.1 \log \eta$  units or less. Hence there is still much room for improvement. In our opinion, the most important improvement might come from the development of a better functional equation to describe viscosity dependence on temperature, pressure and composition. For example, our models adopted a different functional form of viscosity. A second improvement might derive from consideration of the effect of ferric and ferrous iron, which requires knowledge of experimental conditions under which the glasses were prepared for the low-temperature viscosity measurements. A third improvement might arise from improved quantification of the effect of  $\text{H}_2\text{O}$  on viscosity, both in terms of accurate determination of  $\text{H}_2\text{O}$  for reported viscosity data and in terms of the functional form used to handle the dependence of viscosity on  $\text{H}_2\text{O}$  content. Specifically, we suggest that in the future every viscosity data should be accompanied by  $\text{H}_2\text{O}$  content and other concentrations; simply describing a melt as dry anorthite is not good enough. A fourth improvement might originate from the incorporation of the effect of  $\text{CO}_2$  and other volatile components in the melt. So far, the effect of  $\text{CO}_2$  on the viscosity of silicate melts has only been carried out in several synthetic melts (Lange, 1994; Bourgue and Richet, 2001). A fifth improvement might stem from the incorporation of the pressure effect (Persikov, 1998). New experimental viscosity data are needed especially at high pressures, at low temperatures, for melts with well-characterized ferric/ferrous ratios, and for melts with various and well-characterized volatile ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) concentrations.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.gca.2006.09.003](https://doi.org/10.1016/j.gca.2006.09.003).

## References

- Adam, G., Gibbs, J.H., 1965. On the temperature dependence of cooperative relaxation properties in glass-forming liquids. *J. Chem. Phys.* **43**, 139–146.

- Alidibirov, M., Dingwell, D.B., Stevenson, R.J., Hess, K.-U., Webb, S.L., Zinke, J., 1997. Physical properties of the 1980 Mount St. Helens cryptodome magma. *Bull. Volcanol.* **59**, 103–111.
- Ammar, M.M., El-Badry, Kh., Gharib, S., 1977. Viscous properties of some alkali silicate glasses in the annealing range. *Egypt. J. Phys.* **8**, 1–8.
- Avramov, I., 1998. Viscosity of glassforming melts. *Glastech. Ber. C* **71**, 198–203.
- Bockris, J.O'M., Mackenzie, J.D., Kitchener, J.A., 1955. Viscous flow in silica and binary liquid silicates. *Trans. Faraday Soc.* **51**, 1734–1748.
- Bottinga, Y., Weill, D.F., 1972. The viscosity of magmatic silicate liquids: a model for calculation. *Am. J. Sci.* **272**, 438–475.
- Bourgue, E., Richet, P., 2001. The effects of dissolved CO<sub>2</sub> on the density and viscosity of silicate melts: a preliminary study. *Earth Planet. Sci. Lett.* **193**, 57–68.
- Bruckner, R., 1983. Structure and properties of silicate melts. *Bull. Minéral.* **106**, 9–22.
- Brush, S.G., 1962. Theories of liquid viscosity. *Chem. Rev.* **62**, 513–548.
- Burnham, C.W., 1964. Viscosity of a H<sub>2</sub>O rich pegmatite melt at high pressure (abstract). *Geol. Soc. Am. Special Paper* **76**, 26.
- Dingwell, D.B., Virgo, D., 1987. The effect of oxidation state on the viscosity of melts in the system Na<sub>2</sub>O–FeO–Fe<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>. *Geochim. Cosmochim. Acta* **51**, 195–205.
- Dingwell, D.B., Webb, S.L., 1990. Relaxation in silicate melts. *Eur. J. Mineral.* **2**, 427–449.
- Dingwell, D.B., Courtial, P., Giordano, D., Nichols, A.R.L., 2004. Viscosity of peridotite liquid. *Earth Planet. Sci. Lett.* **226**, 127–138.
- Dingwell, D.B., Hess, K.-U., Romano, C., 1998a. Extremely fluid behavior of hydrous peralkaline rhyolites. *Earth Planet. Sci. Lett.* **158**, 31–38.
- Dingwell, D.B., Hess, K.-U., Romano, C., 1998b. Viscosity data for hydrous peraluminous granitic melts: comparison with a metaluminous model. *Am. Mineral.* **83**, 236–239.
- Dingwell, D.B., Hess, K.-U., Romano, C., 2000. Viscosities of granitic (sensu lato) melts: influence of the anorthite component. *Am. Mineral.* **85**, 1342–1348.
- Dingwell, D.B., Knoche, R., Webb, S.L., 1992. The effect of B<sub>2</sub>O<sub>3</sub> on the viscosity of haplogranitic liquids. *Am. Mineral.* **77**, 457–461.
- Dingwell, D.B., Romano, C., Hess, K.-U., 1996. The effect of water on the viscosity of a haplogranitic melt under P–T–X conditions relevant volcanism. *Contrib. Mineral. Petrol.* **124**, 19–28.
- Dorfman, A., Hess, K.-U., Dingwell, D., 1996. Centrifuge-assisted falling-sphere viscometry. *Eur. J. Mineral.* **8**, 507–514.
- Dunn, T., Scarfe, C.M., 1986. Variation of the chemical diffusivity of oxygen and viscosity of an andesite melt with pressure at constant temperature. *Chem. Geol.* **54**, 203–215.
- Friedman, I., Long, W., Smith, R.L., 1963. Viscosity and water content of rhyolitic glass. *J. Geophys. Res.* **68**, 6523–6535.
- Fulcher, G.S., 1925. Analysis of recent measurements of the viscosity of glasses. *J. Am. Ceram. Soc.* **8**, 339–355.
- Ghiorso, M.S., Carmichael, I.S.E., Rivers, M.L., Sack, R.O., 1983. The Gibbs free energy of mixing of natural silicate liquids; an expanded regular solution approximation for the calculation of magmatic intensive variables. *Contrib. Mineral. Petrol.* **84**, 107–145.
- Ghiorso, M.S., Hirschmann, M.M., Reiners, P.W., Kress III, V.C., 2002. The pMELTS: A revision of MELTS for improved calculation of phase relations and major element partitioning related to partial melting of the mantle to 3 GPa. *Geochem. Geophys. Geosyst.* **3**. doi:10.1029/2001GC000217.
- Giordano, D., Dingwell, D.B., 2003a. Non-Arrhenian multicomponent melt viscosity: a model. *Earth Planet. Sci. Lett.* **208**, 337–349.
- Giordano, D., Dingwell, D.B., 2003b. Viscosity of hydrous Etna basalt: implications for Plinian-style basaltic eruptions. *Bull. Volcanol.* **65**, 8–14.
- Giordano, D., Dingwell, D.B., Romano, C., 2000. Viscosity of a Teide phonolite in the welding interval. *J. Volcanol. Geotherm. Res.* **103**, 239–245.
- Giordano, D., Nichols, A.R.L., Dingwell, D.B., 2005. Glass transition temperatures of natural hydrous melts: a relationship with shear viscosity and implications for the welding process. *J. Volcanol. Geotherm. Res.* **142**, 105–118.
- Giordano, D., Romano, C., Papale, P., Dingwell, D.B., 2004. The viscosity of trachytes, and comparison with basalts, phonolites, and rhyolites. *Chem. Geol.* **213**, 49–61.
- Goto, A., Oshima, H., Nishida, Y., 1997. Empirical method of calculating the viscosity of peraluminous silicate melts at high temperatures. *J. Volcanol. Geotherm. Res.* **76**, 319–327.
- Goto, A., Taniguchi, H., Kitakaze, A., 2005. Viscosity measurements of hydrous rhyolitic melts using the fiber elongation method. *Bull. Volcanol.* **67**, 590–596.
- Gottsmann, J., Giordano, D., Dingwell, D.B., 2002. Predicting shear viscosity during volcanic processes at the glass transition: a calorimetric calibration. *Earth Planet. Sci. Lett.* **198**, 417–427.
- Hess, K.-U., Dingwell, D.B., 1996. Viscosities of hydrous leucogranitic melts: a non-Arrhenian model. *Am. Mineral.* **81**, 1297–1300.
- Hess, K.-U., Dingwell, D.B., Gennaro, C., Mincione, V., 2001. Viscosity–temperature behavior of dry melts in the Qz–Ab–Or system. *Chem. Geol.* **174**, 133–142.
- Hess, K.-U., Dingwell, D.B., Webb, S.L., 1995. The influence of excess alkalis on the viscosity of a haplogranitic melt. *Am. Mineral.* **80**, 297–304.
- Hess, K.U., Dingwell, D.B., Webb, S.L., 1996. The influence of alkaline-earth oxides (BeO, MgO, CaO, SrO, BaO) on the viscosity of a haplogranitic melt: systematics of non-Arrhenian behaviour. *Eur. J. Mineral.* **8**, 371–381.
- Hummel, W., Arndt, J., 1985. Variation of viscosity with temperature and composition in the plagioclase system. *Contrib. Mineral. Petrol.* **90**, 83–92.
- Kozu, S., Kani, K., 1944. Viscosity measurements of the ternary system diopside–albite–anorthite at high temperatures. *Bull. Am. Ceram. Soc.* **23**, 377–378.
- Kushiro, I., Yoder Jr., H.S., Mysen, B.O., 1976. Viscosities of basalt and andesite melts at high pressures. *J. Geophys. Res.* **81**, 6351–6356.
- Lange, R.A., 1994. The effect of H<sub>2</sub>O, CO<sub>2</sub>, and F on the density and viscosity of silicate melts. *Rev. Mineral.* **30**, 331–360.
- Lange, R.A., 1997. A revised model for the density and thermal expansivity of K<sub>2</sub>O–Na<sub>2</sub>O–CaO–MgO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub> liquids from 700 to 1900 K: extension to crustal magmatic temperatures. *Contrib. Mineral. Petrol.* **130**, 1–11.
- Lange, R.A., Carmichael, I.S.E., 1987. Densities of Na<sub>2</sub>O–K<sub>2</sub>O–CaO–MgO–FeO–Fe<sub>2</sub>O<sub>3</sub>–Al<sub>2</sub>O<sub>3</sub>–TiO<sub>2</sub>–SiO<sub>2</sub> liquids: new measurements and derived partial molar properties. *Geochim. Cosmochim. Acta* **53**, 2195–2204.
- Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali–silica diagram. *J. Petrol.* **27**, 745–750.
- Liebske, C., Behrens, H., Holtz, F., Lange, R.A., 2003. The influence of pressure and composition on the viscosity of andesitic melts. *Geochim. Cosmochim. Acta* **67**, 473–485.
- Lillie, H.R., 1939. High-temperature viscosities of soda–silica glasses. *J. Am. Ceram. Soc.* **22**, 367–374.
- Mackenzie, J.D., 1957. The discrete ion theory and viscous flow in liquid silicates. *Trans. Faraday Soc.* **53**, 1488–1493.
- Neuville, D.R., Richet, P., 1991. Viscosity and mixing in molten (Ca, Mg) pyroxenes and garnets. *Geochim. Cosmochim. Acta* **55**, 1011–1019.
- Neuville, D.R., Courtial, P., Dingwell, D.B., Richet, P., 1993. Thermodynamic and rheological properties of rhyolite and andesite melts. *Contrib. Mineral. Petrol.* **113**, 572–581.
- Persikov, E.S., 1991. The viscosity of magmatic liquids: experiment, generalized patterns; a model for calculation and prediction; application. *Adv. Phys. Geochem.* **9**, 1–40.
- Persikov, E.S., 1998. Viscosities of model and magmatic melts at the pressures and temperatures of the Earth's crust and upper mantle. *Russ. Geol. Geophys.* **39**, 1780–1792.
- Persikov, E.S., Epel'baum, M.B., Bukhtiyarov, P.G., 1986. The viscosity of a granite magma interacting with an aqueous chloride fluid. *Geochem. Int.* **23**, 21–30.

- Poole, J.P., 1948. Viscosité à basse température des verres alcalino-silicatés. *Verres Réfract.* **2**, 222–228.
- Richet, P., 1984. Viscosity and configurational entropy of silicate melts. *Geochim. Cosmochim. Acta* **48**, 471–483.
- Richet, P., Lejeune, A.-M., Holtz, F., Roux, J., 1996. Water and the viscosity of andesite melts. *Chem. Geol.* **128**, 185–197.
- Richet, P., Robie, R.A., Hemingway, B.S., 1986. Low-temperature heat capacity of diopside glass (CaMgSi<sub>2</sub>O<sub>6</sub>): a calorimetric test of the configurational-entropy theory applied to the viscosity of liquid silicates. *Geochim. Cosmochim. Acta* **50**, 1521–1533.
- Riebling, E.F., 1966. Structure of sodium aluminosilicate melts containing at least 50 mol% SiO<sub>2</sub> at 1500 °C. *J. Chem. Phys.* **44**, 2857–2865.
- Romano, C., Giordano, D., Papale, P., Mincione, V., Dingwell, D.B., Rosi, M., 2003. The dry and hydrous viscosities of alkaline melts from Vesuvius and Phlegrean Fields. *Chem. Geol.* **202**, 23–38.
- Scaillet, B., Holtz, F., Pichavant, M., Schmidt, M., 1996. Viscosity of Himalayan leucogranites: implication for mechanisms of granitic magma ascent. *J. Geophys. Res.* **101**, 27691–27699.
- Scarfe, C.M., Cronin, D.J., 1986. Viscosity–temperature relationships at 1 atm in the system diopside–albite. *Am. Mineral.* **71**, 767–771.
- Scherer, G.W., 1984. Use of the Adam–Gibbs equation in the analysis of structural relaxation. *J. Am. Ceram. Soc.* **67**, 504–511.
- Schulze, F., Behrens, H., Holtz, F., Roux, J., Johannes, W., 1996. The influence of H<sub>2</sub>O on the viscosity of a haplogranitic melt. *Am. Mineral.* **81**, 1155–1165.
- Shartsis, L., Spinner, S., Capps, W., 1952. Density, expansivity, and viscosity of molten alkali silicates. *J. Am. Ceram. Soc.* **35**, 155–160.
- Shaw, H.R., 1963. Obsidian–H<sub>2</sub>O viscosities at 1000 and 2000 bars in the temperature range 700 to 900 °C. *J. Geophys. Res.* **68**, 1512–1520.
- Shaw, H.R., 1972. Viscosities of magmatic silicate liquids: an empirical method of prediction. *Am. J. Sci.* **272**, 870–893.
- Stein, D.J., Spera, F.J., 1993. Experimental rheometry of melts and supercooled liquids in the system NaAlSi<sub>3</sub>O<sub>8</sub>–SiO<sub>2</sub>: implications for structure and dynamics. *Am. Mineral.* **78**, 710–723.
- Stein, D.J., Spera, F.J., 2002. Shear viscosity of rhyolite–vaporemulsions at magmatic temperatures by concentric cylinder rheometry. *J. Volcanol. Geotherm. Res.* **113**, 243–258.
- Stevenson, R.J., Bagdassarov, N.S., Dingwell, D.B., 1998. The influence of trace amounts of water on the viscosity of rhyolites. *Bull. Volcanol.* **60**, 89–97.
- Stevenson, R.J., Dingwell, D.B., Webb, S.L., Sharp, T.G., 1996. Viscosity of microlite-bearing rhyolitic obsidians: an experimental study. *Bull. Volcanol.* **58**, 298–309.
- Stolper, E., 1982. The speciation of water in silicate melts. *Geochim. Cosmochim. Acta* **46**, 2609–2620.
- Tammann, G., Hesse, W., 1926. Die abhängigkeit der viscosität von der temperatur bei unterkühlten flüssigkeiten. *Z. Anorg. Allg. Chem.* **156**, 245–257.
- Taylor, N.W., Dear, P.S., 1937. Elastic and viscous properties of several soda-silica glasses in the annealing range of temperature. *J. Am. Ceram. Soc.* **20**, 296–304.
- Taylor, N.W., Doran, R.F., 1941. Elastic and viscous properties of several potash-silica glasses in the annealing range of temperature. *J. Am. Ceram. Soc.* **24**, 103–109.
- Taylor, T.D., Rindone, G.E., 1970. Properties of soda aluminosilicate glasses: V, low-temperature viscosities. *J. Am. Ceram. Soc.* **53**, 692–695.
- Toplis, M.J., Dingwell, D.B., Libourel, G., 1994. The effect of phosphorus on the iron redox ratio, viscosity, and density of an involved ferro-basalt. *Contrib. Mineral. Petrol.* **117**, 293–304.
- Urbain, G., Bottinga, Y., Richet, P., 1982. Viscosity of liquid silica, silicates and alumino-silicates. *Geochim. Cosmochim. Acta* **46**, 1061–1072.
- Whittington, A., Richet, P., Holtz, F., 2000. Water and the viscosity of depolymerized aluminosilicate melts. *Geochim. Cosmochim. Acta* **64**, 3725–3736.
- Whittington, A., Richet, P., Holtz, F., 2001. The viscosity of hydrous phonolites and trachytes. *Chem. Geol.* **174**, 209–223.
- Whittington, A., Richet, P., Behrens, H., Holtz, F., Scaillet, B., 2004. Experimental temperature–X(H<sub>2</sub>O)–viscosity relationship for leucogranites and comparison with synthetic silicic liquids. *Trans. R. Soc. Edinb. Earth Sci.* **95**, 59–71.
- Zhang, Y., 1994. Reaction kinetics, geospeedometry, and relaxation theory. *Earth Planet. Sci. Lett.* **122**, 373–391.
- Zhang, Y., Xu, Z., Behrens, H., 2000. Hydrous species geospeedometer in rhyolite: improved calibration and application. *Geochim. Cosmochim. Acta* **64**, 3347–3355.
- Zhang, Y., Xu, Z., Liu, Y., 2003. Viscosity of hydrous rhyolitic melts inferred from kinetic experiments, and a new viscosity model. *Am. Mineral.* **88**, 1741–1752.