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Viscosity of hydrous Etna basalt: implications for Plinian-style basaltic eruptions

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Abstract Water dissolved in a silicate melt can strongly influence its physical properties and thus magma behavior during crystallization, degassing, foaming and fragmentation. Etna is a basaltic volcano whose activity is dominated by effusive eruptions which have long represented a threat to the densely populated, surrounding area. Recently, recognition of the products of a Plinian eruption (122 B.C.) has raised further issues for hazard assessment at Etna and other basaltic volcanoes. Constraining the behavior of Etna magma under conditions relevant to both effusive and explosive hazards requires viscosity data under conditions near the glass transition. Here we have investigated the viscosity of hydrous Etna lava in order to better understand eruptive processes which characterize this volcano. The experimental methods which have been used include piston cylinder synthesis of the hydrated melts, micropenetration viscometry for low-temperature viscosity measurements, and near-infrared spectroscopy for the evaluation of sample homogeneity and measurements of water content. Additionally, scanning calorimetric determinations were performed to check whether incipient crystallization had occurred. Sample compositions were determined using electron microprobe analysis and ^{57}Fe Mössbauer spectroscopy. Results from this study are compared with previous reports of trachytic, phonolitic and model calc-alkaline rhyolite (HPG8) compositions. The viscosity of the basaltic melt (dry and wet) has been parameterized in terms of temperature and water content via the non-Arrhenian equation: $\log_{10}\eta = -4.643 + (5,812.44 - 427.04 \times \text{H}_2\text{O}) / (T(\text{K}) - 499.31 + 28.74 \times \ln(\text{H}_2\text{O}))$ where η is the viscosity in Pa s, H_2O is the water content in wt%, and T is the temperature in Kelvin. We observe that the viscosity of alkali basalt (at

more than 0.5 wt% H_2O) is similar to that of an alkaline trachyte (Agnano–Monte Spina eruption, Phlegrean Fields) and much higher than that of a peralkaline phonolite (Teide, Tenerife) at similar silica contents and NBO/T. For water contents above 1.5 wt%, the viscosity of the basalt is similar to that of rhyolitic melts with similar water contents. At temperatures ranging from 1,050 to 1,150 °C and with water contents between 0.5 and 2.3 wt% (eruptive conditions), the viscosities calculated using the equation defined in this study are (1) in reasonable agreement with those calculated using Shaw's model, and (2) much lower than those experimentally determined in a previous study. However, outside these temperature and water content ranges, the agreement with Shaw's model (1972) breaks down.

Keywords Basalt · Calc-alkaline · Peralkaline · Viscosity · Eruptive conditions · Fragmentation

Introduction

Viscosity is probably the most important property governing magmatic processes such as the formation, transport and crystallization of magma associated with volcanic activity ranging from explosive to effusive flow. The main factors controlling the viscosity of magmas are temperature and chemical composition, volatile contents (mainly H_2O and CO_2), and crystal and bubble content (Dingwell et al. 1993). Significant advances in modeling the viscosity of multicomponent hydrous melts have been made (Shaw 1972; Hess and Dingwell 1996). Nevertheless, there is no general predictive model available which adequately copes with the non-Arrhenian temperature dependence of melt viscosity. More data in multicomponent space are required to achieve this goal.

In the present study we determine the molten viscosity of an alkali lava flow erupted from Etna in 1992. Etna is the most active volcano in Europe, and it is characterized by quasi-persistent Strombolian activity and frequent lava flows. In the last 20 years the average erup-

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tive rate has been $1 \text{ m}^3 \text{ s}^{-1}$ (Coltelli et al. 1998). Interestingly and, until recently, less well appreciated, is the fact that Etna has also exhibited sub-Plinian and Plinian activity. The most recent such event, dated 122 B.C. in Roman chronicles (Alessi 1830; Ferrara 1835), was a very destructive event, with a conservative estimate of the volume of the exposed deposits of $\approx 0.4 \text{ km}^3$ (Coltelli et al. 1998). Despite its rarity, basaltic Plinian-style activity represents significantly destructive volcanic events, and thus data from such eruptions in the past can yield improved hazard assessment for basaltic volcanoes.

A model for calculating the viscosity of hydrous and anhydrous Etna basalt is provided on the basis of a Tamman-Vogel-Fulcher (TVF) equation composed in the same form as that proposed by Giordano et al. (2000). Comparisons are made with the behavior of hydrous melts and derived viscosity models. Implications for explosive fragmentation of basaltic melts are discussed.

Methods

Basalt was obtained by fusion and homogenization of a sample from the 1992 lava flow on Etna collected by M. Coltelli. Melting, homogenization and low-viscosity-range measurements ($0.1\text{--}1 \text{ Pa s}$) were performed in air at 1 bar in the $1,400\text{--}1,550 \text{ }^\circ\text{C}$ temperature interval using a concentric cylinder apparatus (Dingwell and Virgo 1988). Samples were fused and stirred in a $\text{Pt}_{80}\text{Rh}_{20}$ crucible for several hours until inspection of the stirring spindle indicated that melts were crystal- and bubble-free, as indicated by stable, time-invariant and strain-rate-invariant viscosity readings. After homogenization of the liquid, three samplings of the melt were performed to check the oxidation state of the iron by ^{57}Fe Mössbauer spectroscopy. Samples of the remelted material were collected after homogenization and before viscometry at $1,550 \text{ }^\circ\text{C}$, and during viscometry at $1,400 \text{ }^\circ\text{C}$. The melt was sampled by dipping an alumina rod into the crucible and extracting a wetted liquid drop which was quenched in water to obtain a glass. Values of the $\text{Fe}^{3+}/\text{Fe}_{\text{tot}}$ ratio between 0.66 and 0.68 were observed. In this range the influence of a temperature-dependent oxidation state on viscosity is expected to be negligible (Dingwell 1991). Glasses suitable for micropenetration viscosity determinations were obtained by pouring the basaltic liquid onto a steel plate. Glass compositions so obtained were analyzed using a Cameca (SX50) electron microprobe (analyzing voltage and current conditions are reported in Table 1, together with the standards employed).

Powders from the quenched anhydrous glasses were loaded together with known amounts of doubly distilled water in platinum capsules (outer diameter 5.2 mm, wall thickness 0.1 mm, and length 14 to 15 mm) which were then sealed by arc-welding. To check for any possible leakage of water from the welded capsules, they were dried in an oven at $110 \text{ }^\circ\text{C}$ for at least 1 h and checked for weight loss. This ensured a homogeneous distribution of water inside the capsules. Syntheses of hydrous glass-

Table 1 Electron microprobe analysis of Etna basaltic lava from the 1992 flow compared with other volcanic melts. AMS Agnano–Monte Spina, A.I. agpaite index

Oxide	This study (wt%, $n=42$) ^a	Teide	AMS	Kirgurich basalt
SiO_2	47.03	60.46	59.98	52.05
TiO_2	1.61	0.56	0.39	0.85
Al_2O_3	16.28	18.81	18.01	15.16
FeO_{tot}		3.31	3.82	–
FeO	3.34	–	–	5.16
Fe_2O_3	7.54	–	–	4.48
MnO	0.20	0.20	0.11	0.10
MgO	5.17	0.36	0.88	9.49
CaO	10.47	0.67	2.91	9.29
Na_2O	3.75	9.76	4.06	2.46
K_2O	1.94	5.45	8.37	0.82
P_2O_5	0.59	0.06	0.21	0.13
Total	97.92	99.64	98.74	99.99
H_2O	–	0.02	0.02	0.09
F	–	0.17	–	–
Cl	0.1	0.31	–	–
A.I.	0.58	1.17	0.87	0.325

^a Analytical conditions: 15.0 kV, 10 nA, defocused beam of diameter 20 μm ; standards: albite (Na), spinel (Al), pyrophanite (Mn, Ti), orthoclase (K, Si), Fe_2O_3 (Fe), andradite (Ca), forsterite (Mg), apatite (P), vanadinite (Cl), LiF (F)

es were performed within a piston cylinder apparatus at 10 kbar and $1,450$ to $1,600 \text{ }^\circ\text{C}$. The samples were held under these conditions long enough to ensure complete homogenization of H_2O dissolved in the melts (run durations between 28 and 37 min). After the piston cylinder runs, the samples were isobarically quenched and then slowly decompressed. It proved difficult to obtain hydrated samples without fractures. For those samples exhibiting a strong tendency to fracture, we slightly reduced the pressure during quenching. This enhanced the recovery of non-fractured homogeneous glasses. Doubly polished sections 1 to 1.5 mm thick were prepared from the resulting glasses for FTIR spectroscopy and micropenetration viscometry.

Samples were prepared for micropenetration viscometry using the methods described in Hess et al. (1995) and Dingwell et al. (1996). Initial time provided for the relaxation process was 15 min. The indentation–time traces were processed using the software described by Hess (1996). The viscosity measurements could be performed in a viscosity range from $10^{9.6}$ to $10^{11.6} \text{ Pa s}$ without vesiculation problems. One advantage of the micropenetration technique is that it requires only relatively small samples. The homogeneity and stability of the water contents of the samples were confirmed by FTIR spectroscopy before and after micropenetration viscometry using the methods described by Dingwell et al. (1996). No loss of water was detected. Scanning calorimetric traces of the glass transition before and after viscometry were identical, indicating no phase changes or chemical changes in the samples. The absolute water content was then estimated using the adsorptivity coefficients from Dixon et al. (1985). Water contents were also determined

Table 2 Viscosity data for dry and hydrated 1992 Etna alkali basalt

H ₂ O FTIR ^a (wt%)	T (°C)	log ₁₀ η (Pa s)	H ₂ O KFT (wt%)
0.02	1,544.7	0.18	0.02
0.02	1,520.1	0.26	0.02
0.02	1,495.5	0.34	0.02
0.02	1,470.9	0.43	0.02
0.02	1,446.3	0.52	0.02
0.02	1,421.7	0.62	0.02
0.02	1,397.1	0.72	0.02
0.02	711.9	10.82	0.02
0.02	715.9	10.70	0.02
0.02	731.0	10.23	0.02
0.50	575.2	11.60	0.64
0.50	597.2	10.80	0.64
0.50	601.9	10.74	0.64
0.50	611.6	10.50	0.64
0.50	618.5	10.42	0.64
0.50	619.4	10.33	0.64
1.03	553.2	10.99	1.13
1.03	557.9	10.89	1.13
1.03	564.5	10.73	1.13
1.03	575.3	10.37	1.13
1.50	532.3	11.20	1.64
1.50	544.6	10.88	1.64
1.50	549.2	10.57	1.64
1.50	551.7	10.54	1.64
1.50	556.8	10.25	1.64
1.50	576.8	9.75	1.64
2.29	524.6	10.16	2.31
2.29	534.8	9.77	2.31
2.29	544.9	9.57	2.31

^aThe absolute water contents are derived from infrared spectroscopy using absorptivities from Dixon et al. (1985). Karl-Fischer titration (KFT) measurements are shown for comparison

by Karl-Fischer titration (KFT) prior to the viscosity measurements at Hannover University, following the method described by Behrens et al. (1996). For each sample two analyses were performed. Average values of the two determinations, the difference between which was less than the experimental error, are reported in Table 2. Even though the values recalculated through spectroscopy deviate less than 0.1 wt% from the nominal water contents added to the starting powders (Table 2), they differ from the values obtained by use of the KFT method. The KFT data are used in the following analysis and modeling.

Results

The results of the viscosity measurements are presented in Table 2 and in Fig. 1. Micropenetration viscometry at 1 bar was possible on basaltic samples with up to 2.3-wt% water. Significant water loss can be excluded during measurement via direct determination of water contents by infrared spectroscopy before and after micropenetration viscometry. Any drift in viscosity during the measurement due, for example, to instrumental drift or sample degradation (e.g., water loss, oxidation, crystalli-

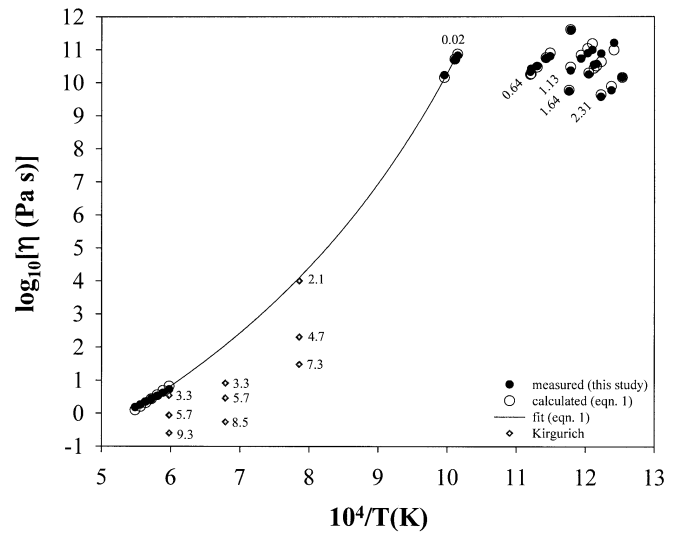


Fig. 1 Viscosity versus reciprocal temperature for the 1992 Etna basalt with varying water content (wt%). *Solid circles* represent the measured viscosities, whereas *open circles* are the viscosities calculated using Eq. (1). The *line* shows the interpolated curve for anhydrous samples. Viscosity measurements for the Kirgurich basalt (Khitrov et al. 1976) are shown for comparison (these measurements were performed at pressures of 1 to 5 kbar)

zation) can also be excluded by observation of the quality of the indentation curves in the micropenetration method. A further check was performed by duplicate viscosity measurements on single samples. Only during the third cycle of measurements for two samples (with 1.64 and 2.31 wt% H₂O, respectively) were very small differences in the viscosity values (on the order of 0.1 log unit) observed. Data from the second and third measurement cycles were not taken into account in the modeling. These tests demonstrated the good reproducibility of the measurements, and the negligible influence of any sample degradation during the experiment.

Comparison of high and low viscosity data for the anhydrous basalt indicates that the viscosity–temperature relationship for the dry Etna melt is strongly non-Arrhenian in the viscosity range 10⁰ to 10^{11.6} Pa s (Fig. 1). A non-Arrhenian dependence of viscosity on temperature is a feature observed in virtually all silicate melts, and it is a fundamental feature of more recent models of melt viscosities (e.g., Hess and Dingwell 1996; Richet et al. 1996).

The viscosities of Etna alkali basalt melts (dry and wet) were parameterized in terms of temperature and water content via the equation

$$\log_{10} \eta = -4.643 + (5,812.44 - 427.04 \times \text{H}_2\text{O}) / [T(\text{K}) - 499.31 + 28.74 \times \ln(\text{H}_2\text{O})] \quad (1)$$

where η is the viscosity in Pa s, H₂O is the water content in wt%, and T is the temperature in Kelvin. The measured data are compared with Eq. (1) in Fig. 1.

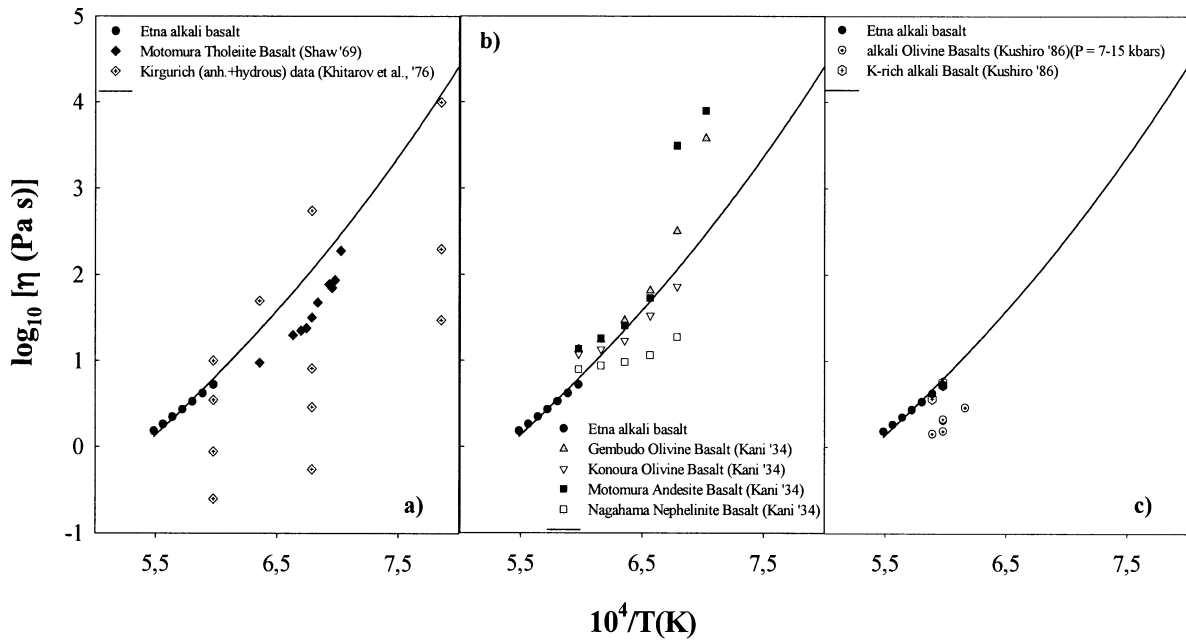


Fig. 2a–c High- and medium-temperature viscosity measurements on basalts from various studies. **a** Shaw (1969) and Khitarov et al. (1976), **b** Kani (1934), **c** Kushiro (1986). The viscosities were obtained under different water and pressure conditions. Details of viscosity, temperature, pressure and water conditions are given in Table 3. The only hydrous viscosity values measured at pressure were obtained by Khitarov et al. (1976). All the other data are from dry samples

Comparison with previous studies

In Fig. 2 our data are compared with those for olivine basalt and alkali-olivine basalts investigated by Khitarov et al. (1976) and Shaw (1969; Fig. 2a), Kani (1934; Fig. 2b), and Kushiro (1986; Fig. 2c). Most of the older data sets (Fig. 2b) show strong deviations from Arrhenian behavior, even in this restricted temperature range. This behavior may be the result of unrecorded progressive crystallization with decreasing temperature.

Viscosities for hydrous basalts are available from Khitarov et al. (1976). These were measured under various conditions with three different high-pressure systems (piston cylinder system up to 23 kbar, internally heated, gas pressure vessel up to 5 kbar, and in nitrogen in a reaction chamber at 1–10 kbar).

The data are shown in Figs. 1 and 3 in terms of reciprocal absolute temperature and water contents, respectively. There is a systematic positive difference between the viscosities obtained at pressures of 1 to 5 kbar (Fig. 1) and those calculated using Eq. (1) (Table 3). Large discrepancies also exist between the high-temperature isotherms calculated using Eq. (1) and those obtained by interpolating the Kirgurich viscosities (Khitarov et al. 1976; Fig. 3). Such large differences may partially be due to pressure and/or compositional differences. However, such a large discrepancy in the high-temperature range for such similar compositions (Table 1) is unlikely because the compositions are similar (Table 1). This is reinforced by the fact that we are dealing with high water contents (greater than 2 wt% H₂O) where viscosities of multicomponent melts typically converge (Giordano et al. 2000; Whittington et al. 2001).

We have also compared the high viscosity data for 1992 Etna alkali basalt with rhyolitic melts (Dingwell et al. 1996; Fig. 4), and with trachytic and phonolitic melts (Giordano et al. 2000; Fig. 5). It can be observed that at

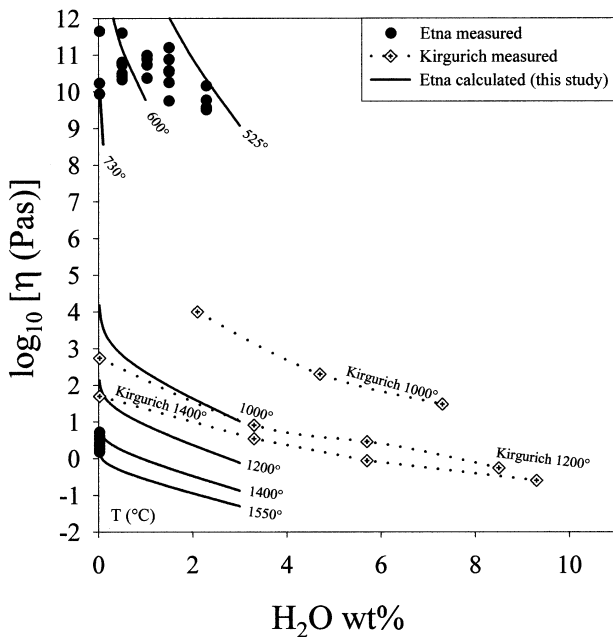


Fig. 3 Calculated isotherms for the Etna basalt (solid lines) and interpolated isotherms for the Kirgurich basalt (dashed lines; Khitarov et al. 1976). The data are clearly discrepant. Partial crystallization of the Kirgurich basalt samples, rather than compositional effects, is the likely origin of this discrepancy. Numbers refer to temperature in °C

Table 3 Viscosities of the Kirgurich basalt under various water pressure conditions (Khitarov et al. 1976)

Pressure (bar)	Kigurich basalt			Etna basalt	
	T (°C)	H ₂ O (wt%)	log ₁₀ η (Pa s)	log ₁₀ η (calc)	Δlog ₁₀ η (Kigurich–calc) ^a
1,000	1,000	2.1	4.00	1.72	2.28
1,000	1,200	3.3	0.91	0.03	0.89
1,000	1,400	3.3	0.54	−0.74	1.29
3,000	1,000	4.7	2.30	0.57	1.73
3,000	1,200	5.7	0.46	−0.76	1.23
3,000	1,400	5.7	−0.06	−1.40	1.34
5,000	1,000	7.3	1.48	−0.46	1.93
5,000	1,200	8.5	−0.26	−1.63	1.37
5,000	1,400	9.3	−0.60	−2.32	1.72

^a Systematic positive difference between the measured data obtained for the Kirgurich basalt and our calculated viscosities (Eq. (1) in text) at the same H₂O and temperature conditions. The effect of pressure is neglected for this comparison

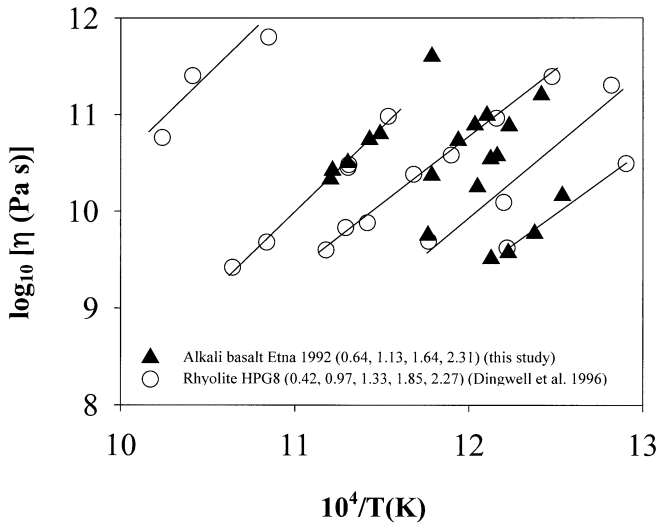


Fig. 4 Viscosity–temperature relationships for the 1992 Etna alkali basalt and a rhyolite (HPG8) melt with silica content at the extremes of the natural eruptive products. Water contents (wt%) are given in parentheses. Note that at water contents >2 wt%, the viscosities are equivalent. The lines are visual guides

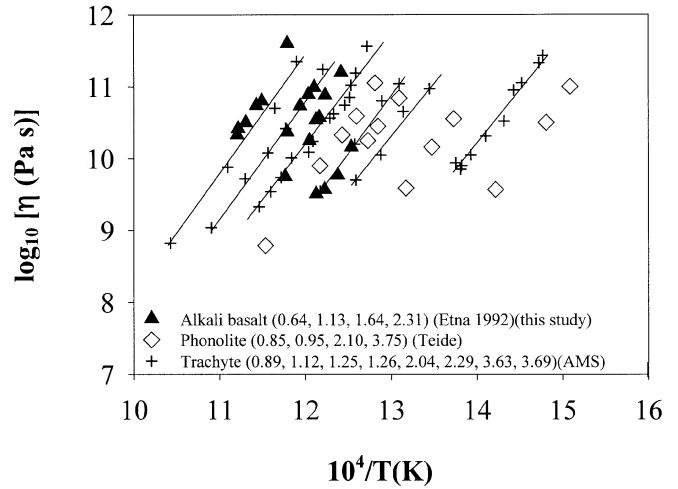


Fig. 5 Viscosity–temperature relationships for the 1992 Etna basalt and products from the Agnano–Monte Spina trachyte (Phlegrean Fields, Italy) and Teide phonolite. Water contents (wt%) for the two liquids are given in parentheses. Lines (at 0.89, 1.12, 1.25+1.26, 2.04, 2.29, and 3.63+3.69 wt% H₂O) are visual guides for each hydrous sample of Agnano–Monte Spina trachyte. The Agnano–Monte Spina alkaline trachyte and the Teide peralkaline phonolite have viscosities which are much lower than those of the Etna basalt and the HPG8 rhyolite at the same temperature

water contents higher than about 0.5 wt%, the viscosity of Etna alkali basalt is similar to that of trachytic melts but significantly higher than that of the phonolitic melts. At water contents above 1.5 wt%, the viscosity of Etna alkali basalt is similar to that of the rhyolitic melt.

The contrast between the behavior of the Etna basalt at the low temperature and high viscosities measured in this study and that predicted by the Shaw model is summarized in Figs. 6 and 7. From this the following points are evident.

1. The Shaw calculation yields very similar viscosities for Kirgurich and Etna alkali basalt, regardless of water content, thereby excluding any strong compositional effect on the viscosity.
2. There is a persistent negative discrepancy, which increases at lower temperatures and water contents, be-

tween the Shaw model and the experimental viscosimetric determinations for Kirgurich.

3. High-temperature (1,400–1,550 °C) anhydrous viscosity as well as the viscosities calculated at close eruptive conditions (1,050–1,150 °C; water contents between 0.5 and 2.5; shaded area in Fig. 7), using our vs. Shaw's (1972) method, are in good agreement, showing +0.2 and −0.4 log units average differences at 0.5 and 2.5 wt% H₂O, respectively. Strong deviations are, however, evident for the dry melts under eruptive temperatures (Fig. 7). Therefore, the Shaw model appears to be acceptable for the low viscosity range, thereby being relevant to many issues of high-temperature eruptive phenomena such as lava flow, conduit flow, and vesiculation.

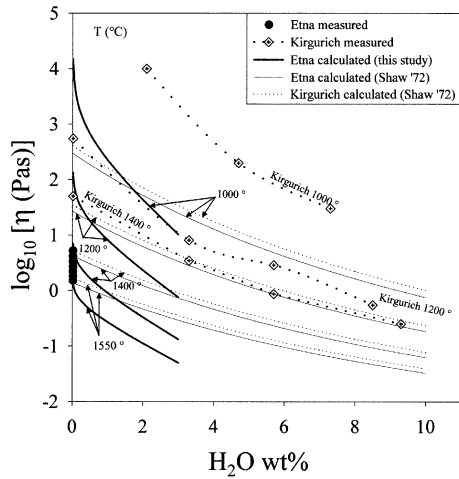


Fig. 6 Measured dry viscosities (*closed circles*) and wet viscosities calculated using Eq. (1) (*bold lines*) for the 1992 Etna basalt in the low-viscosity–high-temperature interval. The viscosity measured for the Kirgurich basalt data (Khitrov et al. 1976) is shown for comparison (*diamonds*). *Thin solid and dotted lines* show the viscosities for the Etna and the Kirgurich basalts, respectively, calculated using the Shaw (1972) method. Viscosities calculated using our Eq. (1) for temperatures ranging from 1,050 to 1,150 °C and water contents up to 2.3 wt% agree well with those predicted by the Shaw model. However, viscosities predicted by the Shaw model for the Kirgurich basalt do not agree with the measurements by Kitharov et al. (1976). The discrepancy becomes larger at low T and water content

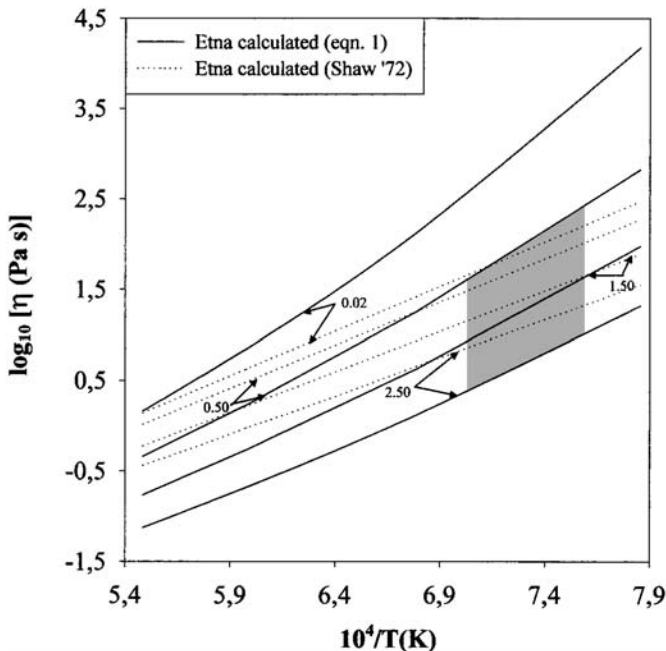


Fig. 7 Comparison between viscosities calculated using Eq. (1) and viscosities calculated using the Shaw method for the Etna basalt at high temperatures (1,000–1,550 °C) with water at contents of 0.02, 0.5, 1.5 and 2.5 wt% (*numbers*). Dry viscosities calculated using our equation at high temperatures (1,400 to 1,550 °C) are consistent with those predicted by the Shaw model. However, at lower temperatures, there is a large difference

Volcanological implications

Papale (1999) has suggested that “strain-induced” fragmentation is only possible for tholeiitic melts if unusual conditions, providing for either very high viscosity of the magma and/or very high strain rate, occur during eruption. One possibility to increase the viscosity is a high crystal content. Possibilities to increase the strain rate include such external forcings as a rapid magma chamber depressurization through edifice collapse, or quenching through magma–water interaction.

Papale (1999) relied on the predictions of the Shaw model to simulate the ascent of a basaltic magma along conduit. Our comparison of measured viscosities with those provided by the Shaw (1972) scheme confirm that, despite somewhat higher experimental viscosities, fragmentation of basalt melt by brittle failure cannot be generated using the “strain-induced” scenario suggested by Papale (1999) unless further forcing mechanisms are added.

This raises the question as to which adaptations of the fragmentation scenario are likely to have generated this sub-Plinian event. We consider it unlikely that the crystallinity observed in the eruptive products of the 122 B.C. eruption, together with the hawaiitic chemistry, can shift the viscosity to high enough values to generate brittle failure during a strain(-rate)-induced fragmentation. The same amount of crystals which were observed in the products of such Plinian-style eruptions at Etna is commonly present in lava flows normally occurring at Etna. We must therefore refer to some other additional cause producing a strain-rate-induced fragmentation.

The strongly non-Arrhenian viscosity of the alkali basaltic melts measured in this study indicates that, where the magma cooled rapidly to much lower temperatures, for example, by rock–water interaction, there would be ample opportunity for brittle fragmentation due to the relatively high viscosities at moderate temperatures. However, a crystalline ground mass of the sub-Plinian products of 122 B.C. would appear to rule out such a scenario.

Alternatively, the external forcing via edifice collapse discussed by Coltelli et al. (1998) could conceivably generate the enormous decompression rates necessary for brittle fragmentation of a moderately crystalline hawaiitic magma during a Plinian-style eruption. More data on the viscosity of basalt in the crystallization interval, together with accurate phase diagrams for these eruptive products (Pompilio et al. 1998) and a careful examination of the kinetic background of sample crystallinity in the eruptive products from the 122 B.C. eruption, should help to clarify this matter.

Conclusions

The comparison under eruptive conditions – typically in the temperature range 1,050–1,150 °C (Archambault and Tanguy 1976; Armienti et al. 1987; Pinkerton and

Norton 1995; Pompilio et al. 1998) and for 0.5–2.3 wt% H₂O (Metrich and Rutherford 1998) – between the viscosities calculated using interpolations of data determined here (Eq. 1) and the viscosities experimentally determined from Khitarov et al. (1976) and those calculated with the Shaw (1972) model demonstrate (1) a reasonable agreement of our results with those calculated using the Shaw method in the T range 1,050–1,150 °C, (2) much lower viscosities than those obtained experimentally by Khitarov et al. (1976), and (3) that extrapolation of Shaw's method outside this temperature and water content range fails for these basaltic compositions.

This study confirms that fragmentation of basalt melt (like, for example, that which occurred during the 122 B.C. sub-Plinian eruption) by brittle failure cannot be generated using the “strain-induced” scenario suggested by Papale (1999), unless further forcing mechanisms, other than the high crystallinity commonly shown by Etna lava flows, has occurred. Possible scenarios, like those discussed by Coltelli et al. (1998) relative to the 122 B.C. eruption of Etna, are possible, although a more careful examination of the eruptive products (kinetic background of sample crystallinity) is required for clarification.

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References

- Alessi G (1830) Storia critica delle eruzioni dell'Etna. Atti Accad Gioenia Sci Nat Catania 4:23–74
- Archambault C, Tanguy JC (1976) Comparative temperature measurements on Mount Etna lavas: problems and techniques. *J Volcanol Geotherm Res* 1:113–125
- Armienti P, Clocchiatti R, Innocenti F, Pompilio M, Villari L (1987) 1984–1985 Mount Etna effusive activity. *Rend Soc It Mineral Petrol* 43:877–891
- Behrens H, Romano C, Nowak M, Holtz F, Dingwell DB (1996) Near infrared spectroscopic determination of water species in glasses of the system MAlSi₃O₈ (M=Li, Na, K): an interlaboratory study. *Chem Geol* 128:1–63
- Coltelli M, del Carlo P, Vezzoli L (1998) Discovery of a basaltic Plinian eruption of Roman age at Etna volcano, Italy. *Geology* 26:1095–1098
- Dingwell DB (1991) Redox viscometry of some iron-bearing silicate liquids. *Am Mineral* 76:1560–1562
- Dingwell DB, Virgo D (1988) Melt viscosities in the Na₂O-FeO-Fe₂O₃-SiO₂ system and factors controlling the relative viscosities of fully polymerized silicate melts. *Geochim Cosmochim Acta* 52:395–403
- Dingwell DB, Bagdassarov NS, Bussod GY, Webb SL (1993) Magma rheology. Mineral Assoc Can Short Course Handbook on Experiments at High Pressure and Applications to the Earth's Mantle 21
- Dingwell DB, Romano C, Hess KU (1996) The effect of water on the viscosity of a haplogranitic melt under P-T-X conditions relevant to silicic volcanism. *Contrib Mineral Petrol* 124:19–28
- Dixon JE, Stolper EM, Holloway JR (1985) An experimental study of water and carbon dioxide solubilities in Mid-Ocean Ridge Basaltic liquids. Part I. Calibration and solubility models. *J Petrol* 36:1607–1631
- Ferrara F (1835) Sopra l'eruzione dell'Etna segnata da Orosio nel 122 innanzi G.C. *Atti Accad Gioenia Sci Nat Catania* 10:141–158
- Giordano D, Dingwell DB, Romano C (2000) Viscosity of a Teide phonolite in the welding interval. *J Volcanol Geotherm Res* 103:239–245
- Hess KU (1996) Zur Temperaturabhängigkeit der Viskosität von haplogranitischen Schmelzen. Doctoral Thesis, University of Bayreuth
- Hess KU, Dingwell DB (1996) Viscosities of hydrous leucogranitic melts: a non-Arrhenian model. *Am Mineral* 81:1297–1300
- Hess KU, Dingwell DB, Webb SL (1995) The influence of excess alkalis on the viscosity of a haplogranitic melt. *Am Mineral* 80:297–304
- Kani K (1934) The measurements of the viscosity of basalt glass at high temperature, I and II. *Proc Imp Acad Tokyo* 10:29–32, 79–82
- Khitarov NI, Lebedev YB, Slutsky AM, Dorfman AM, Soldatov IA, Revin NI (1976) The pressure dependence of the viscosity of basaltic melts. *Geochem Int* 13:126–133
- Kushiro I (1986) Viscosity of partial melts in the upper mantle. *J Geophys Res* 91:9343–9350
- Metrich N, Rutherford MJ (1998) Low pressure crystallization paths of H₂O-saturated basaltic-hawaiitic melts from Mt Etna: Implications for open-system degassing of basaltic volcanoes. *Geochim Cosmochim Acta* 62:1195–1205
- Papale P (1999) Strain-induced magma fragmentation in explosive eruptions. *Nature* 397:425–428
- Pinkerton H, Norton G (1995) Rheological properties of basaltic lavas at sub-liquidus temperatures: laboratory and field measurements on lavas from Mount Etna. Water and the viscosity of andesite melts. *J Volcanol Geotherm Res* 68:307–323
- Pompilio M, Trigila R, Zanon V (1998) Melting experiments on Mt. Etna lavas. I. The calibration of an empirical geothermometer to estimate the eruptive temperature. *Acta Vulcanol* 10:67–75
- Richet P, Lejeune AM, Holtz F, Roux J (1996) Water and the viscosity of andesite melts. *Chem Geol* 128:185–197
- Shaw HR (1969) Rheology of basalt in the melting range. *J Petrol* 10:510–535
- Shaw HR (1972) Viscosities of magmatic silicate liquids: an empirical method of prediction. *Am J Sci* 272:870–893
- Whittington A, Richet P, Linard Y, Holtz F (2001) The viscosity of hydrous phonolites and trachytes. *Chem Geol* 174:209–223