Viscosity of Magmatic Liquids: A model for volcanology

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Viscosity of silicate melts is the single most important physical property governing the transport and eruption of magma. The viscosity of naturally-occurring silicate magmas can span more than 10 orders of magnitude ($10^{-1}-10^{14}$Pa s) due to variations in temperature (T), melt composition, and due to varying proportions of suspended solids and/or exsolved fluid phases. Dissolved volatile contents of H_2O and F are of particular importance because small variations in their concentrations generate large ($> 10^5$) and strongly nonlinear changes in melt viscosity. The task of creating a comprehensive model for viscosity of natural melts has long been a goal of earth scientists, but the challenge has been to include these volatile effects, together with multicomponent melt compositional effects, in the framework of a non-Arrhenian model. Here, we present the first empirical model for predicting the viscosity of natural volatile-bearing silicate melts. The model has an oxide mole % basis of SiO_2, Al_2O_3, TiO_2, FeO_{tot}, CaO, MgO, MnO, Na_2O, K_2O, P_2O_5, H_2O, and F_2O_{-1}) and covers over fifteen log units of viscosity (10^{-1}-10^{14} Pa s). Temperature dependence of viscosity (η) is modelled by the VFT equation [$\log \eta = A + B/(T(K) – C)$]. The calibration is based on ~1540 published viscosity measurements at T(K) on melts of known composition. The chemical model uses a total of 18 empirical coefficients. The parameter A is assumed constant and to represent the high-temperature limit to silicate melt viscosity ($A = \eta$ ~$10^{-4.6}$ Pa s). Compositional effects are ascribed to the parameters B and C. Additional attributes of the viscosity model include: i) its experimental basis spans virtually the entire compositional range found in naturally-occurring volcanic rocks, ii) the model captures the effects of 10 major and minor oxide components and the volatile components H_2O and F, iii) it is computationally continuous across the entire

compositional and temperature spectrum of the database, iv) it is capable of accommodating both strong (near-Arrhenian T-dependence) and fragile (very non-Arrhenian T-dependence) behaviour of silicate melts, and v) it reproduces observed relationships between melt composition and transport properties such as glass transition temperature (Tg) and fragility (m). The model reproduces the T(K)-log η relationships for melts not used for calibration purposes indicating that it can be extrapolated past the original database. This attribute makes our model important for predicting transport properties of melts that do not allow direct experimental measurement (e.g., peridotite, kimberlite, or high-T, volatile-rich melts). In addition, because the model uses a single computational strategy independent of whether melts are hydrous or anhydrous and strong or fragile, the model allows for accurate, continuous prediction of melt properties as a function of evolving temperature and melt composition (e.g., volatile loss or gain). This property ensures that dramatic shifts in predicted viscosity are real (e.g., due to Δ(T-X) conditions) as opposed to numerical artefacts. This model will undoubtedly lead to more realistic computational models of volcanic processes. In summary, this computational model transforms a quarter-century of experimental study of melt viscosities, into a parameterisation which can support numerical modelling of magmatic and volcanic phenomena.