Experimental measurements of the thermal conductivity of molten silicates

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Introduction

Although knowledge of the thermal conductivity of magmas is required for any quantitative understanding of heat flow in igneous systems, it remains one of the poorest known properties of molten silicates. Applications range from rates of crystal growth to the cooling of magmatic bodies. Even when convection is the dominant heat-transfer mechanism, thermal conductivity still plays a significant role because of the dependence of the Rayleigh number on thermal conductivity. Here we present measurements of the thermal conductivity of molten $CaMgSi_2O_6$ and discuss some of their implications for magmatic systems.

Experimental methods and results

All thermal conductivity measurements were made using the hot-wire technique modified for high temperature. In this technique, a thin filament of either Rh or Ir is submerged within a molten silicate. This filament serves as both a line source of heat and as a resistance thermometer. At the start of each experiment, a constant, direct current is passed through the filament and the consequent transient temperature rise of the filament is monitored. The rate at which the filament heats up is inversely related to the thermal conductivity of the surrounding medium. Thermal conductivity is then given by the slope (m) of the ΔT *vs.* $\ln t$ curve (where T and t are temperature and time respectively), such that $\lambda = Q/(4\pi m)$, where λ is the thermal conductivity and Q is the power per unit length passing through the filament. Our determinations are independent of Q and the type of filament material used, which is a check that the instrument is operating properly. The hot-wire technique is the most accurate one at high temperature because it nearly eliminates convection (because it is a transient measurement) and significantly reduces thermal radiation (because of the geometry). Heat flow out of the ends of the filament are easily treated by performing paired experiments with two different filament lengths and subtracting the responses.

Thirty-five independent measurements of the thermal conductivity of molten $CaMgSi_2O_6$ were made between 1672 and 1874 K to within an estimated accuracy of 15%. Values range from 0.26 W m^{-1} K^{-1} at 1673 K to 0.03 W m^{-1} K^{-1} at 1873 K. Within error, the values vary linearly with temperature according to an empirical fit: $\lambda = 2.22–1.17 \times 10^{-3}T$ where the thermal conductivity is in W m^{-1} K^{-1} and T is in Kelvins. We emphasize that this fit is only valid within the calibrated temperature range.

Discussion

The measurements reported here indicate two new and surprising results: that the thermal conductivity of molten silicates is approximately an order of magnitude lower than those currently accepted and that it is strongly temperature dependent. The large temperature dependence is unusual for a dielectric liquid, so we did two series of experiments using different filament materials, Ir and Rh. Both sets of experiments gave the same values for thermal conductivity and $\partial\lambda/\partial T$ despite the filaments having very different thermal coefficients of electrical resistivity. This reproducibility confirms the magnitude of the observed $\partial\lambda/\partial T$. We speculate that the large $\partial\lambda/\partial T$ of molten $CaMgSi_2O_6$ is related to the large ΔC_p of melting of diopside and the non-Arrhenius viscosity of its corresponding liquid (i.e., its fragile nature). However, short-range structural similarities between molten $CaMgSi_2O_6$ and natural basic melts suggest that their thermal conductivities should be similar.

To test the applicability of our measurements to natural basic liquids, we have estimated basaltic thermal conductivity from the convective heat fluxes in the Makaopuhi lava lake. These calculations indicate a thermal conductivity of approximately 0.3 W m^{-1} K^{-1} and confirms the relevance of our measurements on molten $CaMgSi_2O_6$ to basic liquids.

The thermal conductivity of molten $CaMgSi_2O_6$ is approximately an order of magnitude lower than the values currently accepted for magmas. This difference evidently does not result from the composition chosen – the thermal conductivity of silicate glasses is only weakly dependent on composition - but rather it is due to the failure of previous measurements to exclude experimental radiative heat fluxes (Murase and McBirney, 1973). But, optical and infrared absorption data, thermal profiles in glass manufacturing tanks and observed cooling rates of lava lakes all indicate that such radiative transfer is quite low in natural, transition-metal-bearing magmas. Moreover, even when radiation may play a role, such as in Fe-poor rhyolites, these previous measurements do not adequately reflect the radiative component in nature because they were done with different geometries and at distances of the order of the photon-mean-free path. Hence, when calculating heat flow in magmas, pure phonic conductivities, like those presented here, should be used for the conductive part and radiation should be treated as a separate, coupled transport mechanism.

The most obvious implication of a low thermal conductivity is the cooling time of magmatic bodies. Since the cooling time of a convecting layer is proportional to $\kappa^{-2/3}$, where κ is the thermal diffusivity ($\lambda = \kappa\rho C_p$), an order of magnitude decrease in the estimate of thermal conductivity implies nearly a five-fold increase in cooling time.

References

Murase, T. and McBirney, A.R. (1973) *Geol. Soc. Am. Bull.*, **84**, 3563–92.