Development of a New Method for Calculating Viscosity at High Pressures

J.S. Pigott, D.M. Reaman, Wendy R. Panero

Abstract

Fluids released by a subducting plate 100 km below the Earth’s surface cause melting in the overlying mantle, leading to arc volcanism, such as that found in the Andes mountains. The viscosity of the released fluid is a first-order constraint on the transport of material from the plate to the mantle. Accurate determination of fluid viscosity at appropriate pressures (1-10 km and temperatures ~900°C) is hampered by the geometry of high-pressure devices. The goal of this research is to construct a new method for quantifying the viscosity of water at pressures similar to those in subduction zones. By observing the Brownian motion of polystyrene spheres suspended in fluid contained in a diamond anvil cell (DAC), the viscosity of the fluid can be calculated. Preliminary results yield an accuracy within half an order of magnitude of published values. Future experiments plan on measuring the viscosity of water up to 50GPa and 800°C. To further refine conditions of subduction zones, dissolved hydrated minerals such as chlorite will be added to the water.

Geologic Background

Arc volcanism can be attributed to ‘flux melting’ of the mantle wedge caused by release of H2O during dehydration reactions involving hydrated minerals at depth. The water released from dehydration reactions interacts with the surrounding material, thereby lowering its melting point. Most of the H2O is released from serpentinite and chlorite (Havill, 1993).

Results and Discussion

Brownian Motion

Brownian motion is the random movement of particles in a gas or liquid medium due to the interaction with the molecular forces of the fluid. Einstein described the movement as a diffusion process and equated the mean-square displacement to the diffusion coefficient to derive an equation for Avogadro’s number (Einstein, 1905). The equation for MSD as a function of time is:

\[ \text{MSD} = 2kT \eta t \]

where \( k \) is Boltzmann’s constant, \( T \) is temperature in Kelvin, \( \eta \) is the viscosity of the fluid, and \( t \) is time.

Fig. 3. Vector position of a polystyrene sphere suspended in distilled water within a diamond anvil cell at STP. Position of the particle was generated by a particle-tracking velocimetry program written in MATLAB.

Method

Two samples were prepared for analysis. 30-µm polystyrene spheres were added to distilled water and a 0.078% sucrose solution. Each solution was loaded into a diamond anvil cell with a small Cr-doped ruby chip for pressure measurement. The loaded DAC was placed under a microscope with a digital camera connected to the oculars of the microscope. Brownian motion of the polystyrene spheres was videoed for 30-40 seconds. The videos were then run through a particle tracking velocimetry (PTV) program written in MATLAB. The program tracks the positions of the particle at every frame and assigns a distance value proportional to the length of a pixel. By summing the squares of the vector distance at each time step, the MSD is calculated.

\[ \text{MSD} = \sum (x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2 \]

for \( i = 0 \) to \( n-1 \), where \( (x_i, y_i, z_i) \) is the position of the particle at time \( t_i \).

Fig. 4. Gaskets (stainless steel) are indented and drilled to form a strong sample chamber. The gasket is situated between two diamonds and loaded with water. Pressure is induced by applying a moderate force across the culets of the two diamonds.

Fig. 5. Representative graph of peaks obtained by ruby fluorescence. Two distinct peaks, R1 and R2, are emitted when Cr-doped ruby is excited by a 488nm Ar-ion laser. The peaks shift to higher wavelengths with increasing pressure.

Results

The values of water viscosity are within a factor of 2 of the published data. Values for the sucrose aqueous solution are within half an order of magnitude for the sucrose solution. Data in which the cursor in the PTV program lost track of the particle were discarded.

Conclusions

• The resulting viscosities obtained from the experiments are within an acceptable range of published values to continue experimentation.

• Better accuracy in data analysis can be obtained by tracking more particles.

• The pressure measurements usingruby fluorescence might not be precise enough for these purposes. These problems could be solved by using a hydrothermal diamond anvil cell. The temperature is regulated so the pressure can be determined by following the phase diagram of water.

• Density of the particles in suspension plays an important role. If there are too many particles, they interact with each other and lead to inaccurate viscosity measurements. Too few particles, and the bulk of them settle before pressure measurements can be made.

• Brownian motion combined with the DAC may be a useful method for calculating viscosity at conditions related to subduction zones.

References


