High-Pressure Falling Sphere Viscosimetry of Basaltic and Dacitic Rocks in Conjunction with Synchrotron Radiation


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The viscosity of silicate melts is of vital importance for the transport of mass and energy inside the Earth. Using short- and long-period precursors of PKP phases ultra-low velocity zones (ULVZ) even at the core-mantle boundary beneath the Western Pacific [1] and central Africa [2] were observed. The elastic properties of these zones correspond to partial molten state.

Multi-anvil apparatus (MA), also known as large volume presses (LVP), have been proved to be highly successful tools for measuring the physical properties of Earth’s materials under experimentally simulated mantle conditions. First falling sphere viscosimetry was successfully used in quench experiments [3] using piston cylinder devices, later also with multi-anvil apparatus [4]. But this technique require a sequence of quench experiments to measure the viscosity of one sample and the time resolution is limited because of the heat capacity of the set-up with the adjacent anvils.

The installation of large volume presses at synchrotron X-ray facilities represented a huge progress for in-situ viscosity measurements, because the falling sphere could be observed and monitored in real time now. This eliminated the problems of accurately determining time-distance-relationships of the quench experiments. Additionally by placing a pressure standard close to the sample inside the set-up the pressure could be determined much more precisely by X-ray diffraction [5, 6].

We used powdered glass samples of basalt, dacite, and diabase for our experiments. The basalt and the dacite samples were dredged along the neo-volcanic zone of the Pacific-Antarctic-Rise during the SONNE 157 cruise. The experiments were performed in the single-stage multi-anvil DIA-device MAX80 installed at beamline F2.1 [7, 8, 9, 10]. The apparatus is made up of a 2500 N hydraulic ram with two load frames driving four reaction bolsters for the lateral anvils. For these experiments we used a tungsten carbide anvil set with 6 mm truncation. The maximum pressure of about 7 GPa corresponds to the measurement problem. The maximum temperature is about 2000 K. The viscosity was measured at pressures of 0.5 and 1 GPa. Each experiment started with compression at room temperature. Then the temperature was ramped slowly by about 100 K per minute up to 1500K. Afterwards the temperature was risen much faster by ~ 50 K per second to the run temperature of 1890K. The falling spheres were monitored by the digital camera with a frame rate of 25 fps. The X-radiography images were analyzed to determine a distance versus time plot of the sphere. We used a modified Stokes’ Law to calculate the viscosity, $\eta$.

$$\eta = \frac{2g\pi^2 \Delta \rho}{9 \nu} \left[ 1 - 2104 \left( \frac{r}{r_o} \right) + 2.09 \left( \frac{r}{r_o} \right)^3 - 0.95 \left( \frac{r}{r_o} \right)^5 \right]$$

where $g$ is the gravitational constant, $r$ is the radius of the falling sphere, $\Delta \rho$ is the density contrast between the sphere and the melt, $\nu$ is the settling velocity, and $r_o$ is the internal radius of the sample capsule. The X-radiography movies were analyzed by image processing frame per frame. Fig. 2 shows such a sequence as an example. Between all the displayed images is a time interval of 2 seconds each. Because of the much higher density of the platinum sphere in comparison to the surrounding silicate melt the sphere appears as black. Measuring the position of the sphere at all images of the sequence taken with a constant time interval allows to deduce a distance versus time plot of the falling sphere. Fig. 3 shows such a plot with the reduced time interval of 1 second for.
demonstration. The sigmoidal shape of the distance data is indicative of the acceleration, terminal velocity, and deceleration phases of the sphere motion. The terminal velocity of the sphere, used to calculate the viscosity of the samples, was determined as the maximum slope at the centre of the linear part. For the example of Fig. 3 this is at about 8.5 seconds.

Fig. 4 shows our results for basalt, diabase, and dacite at 0.5 GPa and 1 GPa. In addition to our results we display published data. Our dacite results are in good agreement with the corresponding data of Tinker et al., 2004. The slightly lower viscosity of our dacite sample might probably be the result of the high water and chlorine contents (3.2 wt.% H$_2$O and 8400 ppm Cl).

References