**HIGH-TEMPERATURE RHEOLOGY MEASUREMENTS ON PLANETARY ANALOG MAGMAS AND LAVAS.** A. Sehlke, NASA Ames Research Center and Bay Area Environmental Research Institute, Moffett Field CA, 94035 (alexander.sehlke@nasa.gov).

**Introduction:** Reconstructing the conditions of planetary magma ascent and lava emplacement (e.g., timescale, effusion rate, temperature) is challenging from observations alone because their modeling requires knowledge of the viscosity and the rheological properties of the magma/lava. Planetary magma and lava viscosities are often treated as if they were crystal-free melts throughout their emplacement. However, most emplacement occurs at temperatures below the liquidus due to cooling to ambient temperature. Treating magmas and lavas as liquids is insufficient because the rheological properties drastically change during cooling and crystallization. At the same time, effective viscosities increase up to six orders of magnitude within the first thirty to forty degrees of undercooling, as shown by numerous studies on terrestrial [1, 2, 11–13, 3–10] and planetary analog lavas [14–16]. Some attempts are made to acknowledge complex aspects of magma/lava rheology by using bulk properties of the magma/lava due to the presence of crystals and bubbles. Two-phase rheology was reviewed by [17], who also suggested a series of "rheological recipes" for use in modeling. However, these recipes are approximations, and no magma/lava rheology model [18–20] yet exists that captures all these parameters correctly, and deviations from these models at crystal fractions < 0.1 has been known for decades [21].

Therefore, without knowing the rheological evolution of planetary magmas and lavas, modeling most likely underestimates the magma and lava viscosity several orders of magnitude, which in turn significantly impacts the calculated dynamics and timescales of magma ascent and volcanic eruptions, favoring fluid, fast-moving, and violent volcanic eruptions as shown by [22] for lunar KREEP basalt.

To close the knowledge gap about the rheology of cooling and crystallizing magmas/lavas, NASA funded the high-temperature rheology facility at NASA Ames Research Center (PI Sehlke) through its Planetary major Equipment & Facilities and Solar System Workings program. The facility is integrated within the PLANETAS (PLANetary Exploration Through Analog Science) laboratory in Building N245.

**Background:** Viscosity is the measure of a liquid's resistance to flow. It is defined as the ratio of applied shear stress (Pa) to the liquid's deformation rate (strain rate, in $s^{-1}$). The SI unit of viscosity is Pa s. Rheology refers to the response of a bulk material (rather than just a fluid) to applied stress.

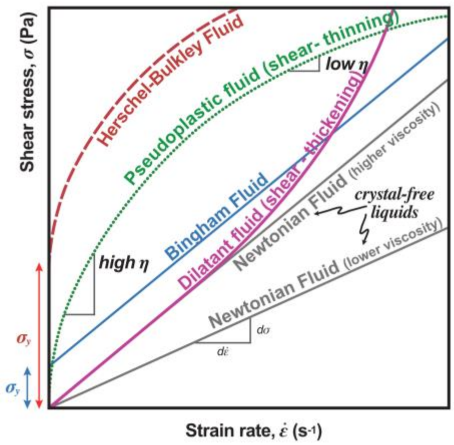


**Figure 1: Stress vs strain rate relationship of crystal-free and crystal-bearing magma or lava.**

Silicate melts, either as a pure liquid or with entrained particles (e.g., crystals and bubbles), are modeled as Maxwell viscoelastic fluids (spring and dashpot in series; [23]). The spring represents the instantaneous, recoverable elastic response of a melt to applied stress. The dashpot represents the viscous, non-recoverable flow as a response to the applied stress.

Silicate melts can respond differently to the applied stress, described either as Newtonian, Bingham, or non-Newtonian fluids. Figure 1 illustrates several ways in which silicate melts can respond to applied shear stress. Pure silicate liquids are Newtonian substances and will flow even when infinitesimal small shear stress is applied. A Bingham material, in contrast, will only flow once sufficient shear stress is applied, commonly called yield strength ($\dot{\gamma}$). For a Newtonian and Bingham material, the relationship between applied shear stress and strain rate is linear once flow is established.

In contrast, the deformation rate of non-Newtonian materials depends on the amount of applied shear stress, thus following a non-linear relationship. Pseudoplastic behavior is commonly observed in natural lavas, where low applied shear stresses result in lower deformation rates, which become larger as the amount of shear stress increases. Therefore, its effective viscosity decreases with increasing deformation rate. A Herschel-Bulkley fluid can be viewed as a hybrid between a Bingham and pseudoplastic fluid: Its viscous flow is initiated as a yield strength is overcome, and its viscosity is governed by the strain rate. At very high strain rates, materials can fail and rupture [23].

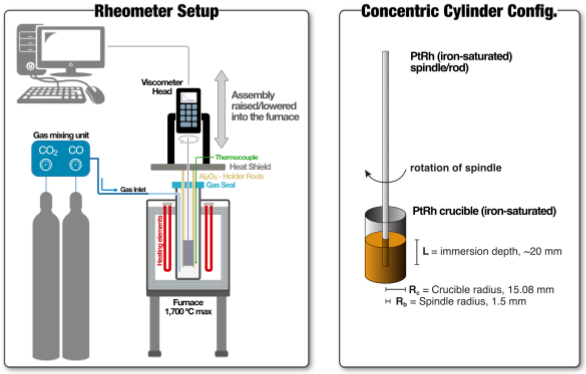


**Figure 2: Left: Schematic diagram of rheometer setup. Right: details on concentric cylinder viscometry configuration.**

**Measurement Principle:** The concentric-cylinder technique consists of a cylindrical spindle immersed in the center of a cylindrical crucible containing the sample, which is held stationary by alumina rods and can be lowered into the high-temperature furnace (Figure 2, right-hand site for details). A rheometer head attached to the spindle measures the torque required to maintain a defined angular velocity applied by the motor above the furnace and protected by a heat shield.

**Rheometer Facility Specifications:** The facility enables rheology measurements up to 1,700 ºC in an inert or reducing atmosphere achieved by gas mixing and allows for in-situ sampling.

*Atmosphere and Gas Mixing:* The current gas mixing setup with CO-CO2 mixtures reaches reducing conditions below the Iron-Wustite (IW) buffer. Inert atmospheres are achieved using Argon. However, the rheometer can also be operated in ambient atmosphere (air). The gas composition can be changed throughout the experiments to mimic changes in oxygen fugacity.

*Viscosity Range:* The setup has several rheometers that can be exchanged based on the anticipated viscosity range. *A* Brookfield DV3TLV low-viscosity rheometer can measure the viscosity between ~$10^{-3}$ to $10^3$ Pa s, whereas the high-viscosity DV3T5xHB rheometer enables viscosity measurements between ~10 to $10^6$ Pa s. The strain rates can be varied during an experiment while at a constant temperature, during cooling, and during heating, allowing a variety of rheological tests of the material.

*Temperature Controls:* Measurements can be done between 800 ºC to 1,700 ºC, and a B-type thermocouple monitors the sample/crucible temperature. Heating rates of 10 degrees per minute can be employed. Cooling rates can vary between degrees per days to seconds. Temperature can be held for weeks, and temperature variations (heating and cooling cycles) can be employed. In short, the complex thermal history of magma and lava in nature can be replicated with the setup.

*In-situ Sampling Capability:* It is possible to rapid-quench the entire sample crucible by raising the spindle out of the melt, raising the assembly out of the hot furnace, removing the crucible from the holder rods, and submerging it into an ice/water bath. The cooling rates are several hundred degrees per minute, preventing further crystallization. Rapid quenching can be done at any desired temperature at any time during the experiment, allowing one to study the petrology of the sample while also knowing its rheological properties. The lab provides a drill press with a 1-inch diameter diamond-coated core drill bit to remove the quenched sample from the crucible. About 60 to 80 grams of material can be recovered.

*Facility Access:* To facility is open to anyone interested in conducting viscosity and rheology measurements on planetary and terrestrial magmas/lavas. Informal requests can be sent to PI Sehlke (alexander.sehlke@nasa.gov).

**Acknowledgments:** The funding for the facility was provided by NASA's Planetary Major Equipment & Facilities and Solar System Workings grant 80NSSC19K1010.

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