Rheology of lava flows on Mercury: an experimental study

Alexander Sehlke and Alan Whittington, Geological Sciences, University of Missouri - Columbia MO, USA
asehlke@mail.missouri.edu

Background

Lava flow morphology is strongly controlled by the **physical properties of the lava**, such as viscosity (η) and yield strength (σ_y) which depend on temperature (T), composition (X), crystal fraction (ϕ_c) and vesicularity (ϕ_b). Moreover, effusion rates, as well as environmental influences such as surface medium, slope and ambient temperature and pressure conditions influence the rheological behavior of multi-phase lava flows developing different morphologies.

For example **basalt flows transition** from smooth pahoehoe to blocky ‘a’a at higher viscosities and strain rates. We have previously quantified the rheological conditions of this transition for Hawaiian basalts [1], but lavas on Mercury are very different in composition and expected crystallization history.

Here we determine experimentally the temperature and rheological conditions of the **pahoehoe-‘a’a transition** for two likely Mercury lava compositions.

By analogy with the rheological conditions of the pahoehoe-‘a’a transition for Hawaiian basalts [1], we can relate the data for Mercury to lava flow surface morphology. These data may allow emplacement temperatures and/or rates to be determined from remote sensing observations of the surface morphology of different volcanic fields on Mercury.

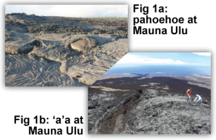

Fig 1a: pahoehoe at Mauna Ulu

Fig 1b: ‘a’a at Mauna Ulu

Methods

We synthesized two likely Mercury compositions: The first is an enstatite basalt, derived from an experimental partial melt of the Indarch (EH4) meteorite composition [2], and assumed to be representative of primitive basalts on Mercury. The second is a Northern Volcanic Plains (NVP) composition based on new data provided by NASA’s MESSENGER mission [3- 5].

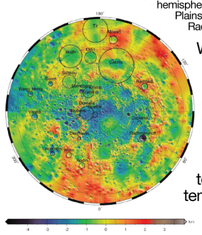

Fig 2: Polar stereographic projection of topography of Mercury’s northern hemisphere with selection of major impact structures. The Northern Volcanic Plains are illustrated in blue and green between Rubens and Rachmaninoff crater (Zuber et al. 2012).

We assesed the full range viscosity of the liquid and supercooled liquids by concentric cylinder and parallel plate viscometry (fig 3). Holding the melts at different temperatures below their liquidus enabled us to determine the rheological response of liquid-crystal suspensions. After each experiment, the sample quenched in water to preserve the texture at measurement temperature.

We then tracked the compositional evolution of the crystals and the residual melt/glass for each experiment by electron microprobe, evaluated crystal volume fraction and crystal aspect ratios. We also checked the Fe-redox state of each experimental product by a combination of wet chemistry and UV/Vis spectroscopy.

And here is what we find

Liquid viscosity:

Mercury compositions are more viscous compared to Hawaiian basalt

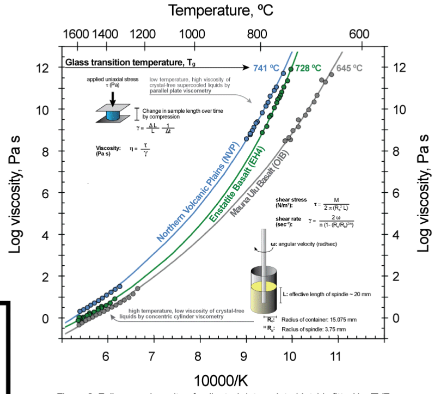

Figure 3: Full range viscosity of collected data points (dots) is fitted by TVF equation, log η = A+B/(T-C) as solid line. Uncertainty of measurement is 0.08 log units.

Melts equilibrated at subliquidus temperatures:

Increase of crystal fraction and crystal aspect ratios with decreasing temperature

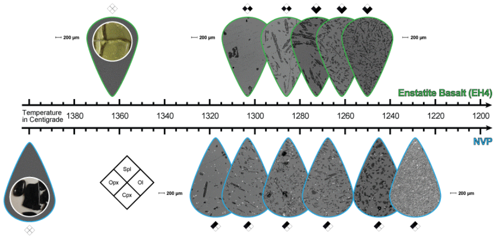

Figure 4: Temperature timeline of crystallization

Here you see what happens when we apply different strain rates to our two-phase suspensions

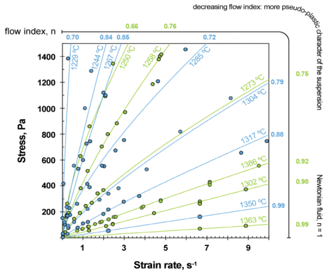

Figure 5: Observed stress as a function of strain rate for Enstatite basalt (green dots) and NVP (blue dots). Every set of points has been fitted by a power-law at higher crystal fractions (0.05).

Rheology experiments:

Crystal-liquid suspensions exhibit pseudo-plastic behaviour meaning they are becoming more fluid with higher strain rates. Development of a yield strength around 200 Pa for crystal fractions > 0.30.

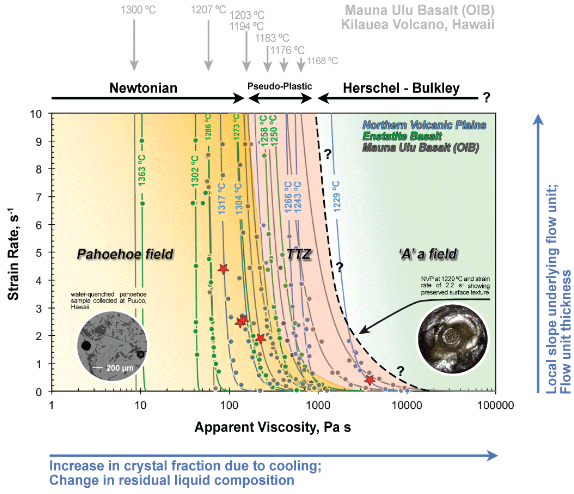

Figure 6: Change of measured apparent viscosities with different strain rates for Mauna Ulu lava (grey), enstatite basalt (EH4) composition (green) and Northern Volcanic Plains (NVP, in blue). Star symbols represent textural analysis of lava flow morphologies from the Muliwai a Pele lava channel at Mauna Ulu (Kilauea) [7]. Lines represent an isothermal power-law fit of the experimental collected data points for each composition. The transition threshold zone (TTZ) is colored in orange, representing a change of lava flow morphology from pahoehoe (yellow field) to ‘a’a (green field, dashed line). Uncertainty of measurement is 0.08 log units.

Rheological evolution of lava flows:

We observe a general apparent viscosity increases with higher crystal fractions and increasing degree of melt polymerization (NBO/T). The fields for Mauna Ulu basalt and NVP overlap, Enstatite basalt is generally more fluid under the same strain rate regimes.

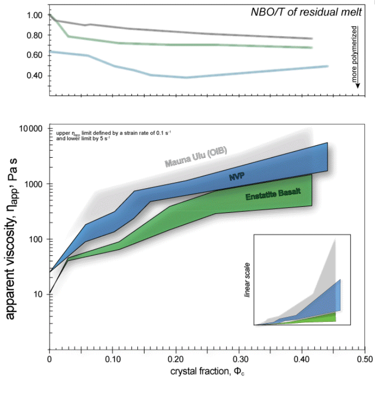

Figure 7: Change of degree of melt polymerization expressed as NBO/T (non-bridging oxygen, NBO, tetrahedrally coordinated cation, T) and apparent viscosities (η_{app}) for different observed crystal fractions in our two-phase suspensions.

Conclusions

Liquid viscosities:
NVP > EH4 > OIB
at fixed temperature

suspension viscosities:
OIB ≥ NVP > EH4
at fixed crystal fraction

Different crystal network with much higher crystal aspect ratios must allow for relatively fluid NVP composition

Smooth northern volcanic plains on Mercury are most likely to develop at temperatures above 1200 °C under similar strain rate regimes

Acknowledgements

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Cited references

[1] Sehlke A. et al. (2013) Concentric cylinder viscometry at subliquidus conditions for Mauna Ulu Lavas, Kilauea Volcano, Hawaii, presented at 2013 Fall Meeting, AGU. [2] McCoy T. J et al. (1999) Meteoritics and Planet. Sci., 34, 735–746. [3] Weider S. Z. et al. (2012) JGR, 117, E00L05. [4] Nittler L. R. et al. (2011) Science, 333, 1847–1850. [5] Stockstill-Cahill K. R. et al. (2012) JGR, 117, E00L15. [6] Ghiorso M. S. and Sack R. O. (1995) Contributions to Mineralogy and Petrology, 119, 197-212. [7] Robert B. et al. Bull. Volc., in review.. [8] Zuber M. R. et al. (2012) Science, 336, 217-220.