Application of new thermobarometers to constraining the origin of magmas on Mars, Venus, Earth, the Moon, and the eucrite parent body.

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Introduction: The most important parameter for understanding the dynamic state of the interiors of rocky planets is the average temperature of the planet (typically referred to as the potential temperature, T_P, which is the fictive temperature the planet would have if it's interior were decompressed along a solid adiabat to the surface of the planet). Because there are no direct ways for estimating interior temperatures of a planet, the next best approach is to use erupted magmas as indirect windows into the mantle. Temperatures of erupted magmas, however, yield minimum bounds on potential temperature for the following reasons. First, erupted magmas have often cooled and chemically fractionated, hence these effects must be corrected for. Second, even in the case of primary magmas, there is substantial cooling during adiabatic decompression melting due to the absorption of the latent heat of fusion. The original temperature of the solid mantle must then be calculated by extrapolating magmatic temperatures back in depth until the mantle solidus is intersected. This requires an estimate of the average pressure of magma extraction from the mantle. While there are a number of existing magma thermometers, we are not aware of robust barometers that are widely applicable to planetary magmas over a range of pressures.

Here, we combine a new method of estimating melting pressures with refined methods of estimating temperatures applicable to a wide range of mafic compositions ranging from Fe-poor (terrestrial) to relatively Fe-rich (e.g., Martian) compositions. The barometer uses the P-dependence of silica activity on the following silica buffer, ol + SiO_2 = opx, which likely dominates mantle-melting on all rocky planets. The thermometer is based on olivine-saturation.

Methods: To calibrate the barometer, we assembled a database (with the aid of the LEPR database http://lepr.ofm-research.org) of 433 experimental basaltic liquid compositions in equilibrium with olivine and orthopyroxene ranging from pressures of 1 atm to 7 GPa and temperatures from 1100 to 1800 °C; the experimental systems included terrestrial mafic and ultramafic compositions, multiple saturation experiments done on lunar, martian, and eucritic meteorite or crustal compositions, as well as water-bearing experiments. Details are presented in [1]. The calibrated barometer is as follows:

$$P = \frac{\ln(Si_4O_8) - 4.019 + 0.0165(Fe_4Si_2O_8) + 0.0005(Ca_4Si_2O_8)^2}{-770T^{-1} + 0.0058T^{1/2} - 0.003(H_{16}O_8)}$$

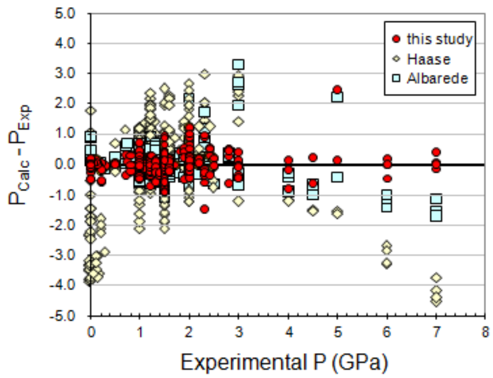

Fig. 1. Calculated P minus experimental P. Red symbols refer to this study. Others refer to [2,3].

where P is in GPa, T is in K, and the compositional terms represent the mole percent of oxides, corrected for various speciation effects discussed in [1]. The robustness of the barometer is shown in Figure 1 in comparison to previous SiO_2-based barometers. Details of our revised thermometers are also discussed in [1].

Results and Discussion: We applied our new thermobarometers to various meteorite or crustal (based on spectral data) compositions from Mars, Venus, the eucrite-parent body, and the Earth's Moon.
In the case of meteorites, we used only those samples that are thought to represent melts and thus avoided any meteorites with a cumulate protolith. Our results are shown in Figure 2.

Because of uncertainties in the mantle compositions of different planets, we chose not to do any fractionation corrections except for Venus. By not correcting for fractionation, our P-T estimates are likely to be minimum estimates on the T-P of melt segregation and hence minimum estimates of potential temperature (assuming fractionation is olivine-controlled).

For the Earth's Moon, we find that Apollo 17 glasses fall mostly between 1250-1360 °C and 0.7-2.0 GPa while the more primitive Apollo 14B green picrite glasses give higher T-Ps, 1500-1630 °C and 1.5-3.2 GPa. The latter calculations are consistent with multiple saturation experiments of Elkins-Tanton on 14B green picrites.

Eucrite meteorite compositions yield T between 1200-1300 °C and pressures that are to within error of 1 atm, though many yield slightly negative pressures. Although within error, the negative pressures could simply imply that these magmas are not primary and hence primary magmas would give slightly higher pressures. In any case, eucrites form at very low pressures,

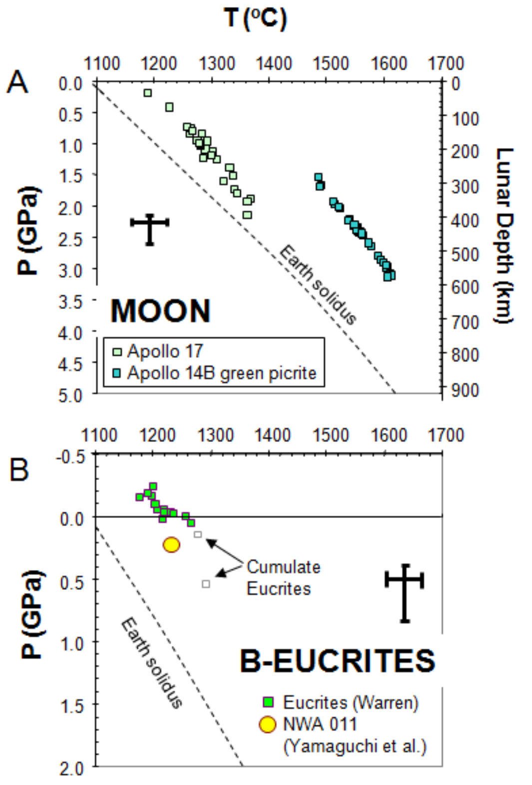

Fig. 2. P-T calculated for lunar glasses (A) and eucrite meteorites. NWA 011 refers to one eucrite with unique oxygen isotopic compositions and may come from a different parent body [4].

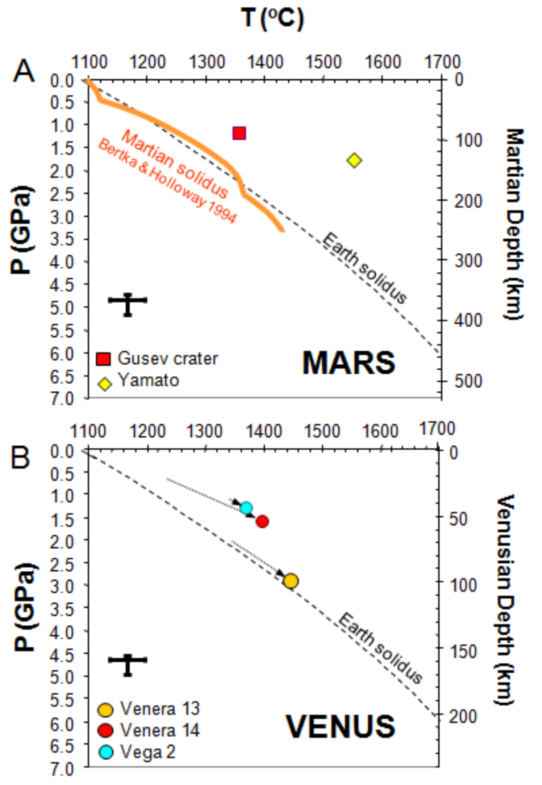

Fig. 3. P-T for Mars (meteorite and spectral data) and Venus (spectral data). Venusian magmas were calculated for fractionation-corrected compositions (symbols) and unfractionated compositions (arrow bases).

consistent with an origin on a small parent body. We note that P estimates for NWA 011, a eucrite-like meteorite whose oxygen isotopes differ from other eucrites, gives a high pressure, suggesting it may have come from a different and slightly larger parent body than the HED parent body. Cumulate eucrites are identified as outliers by their unusually high pressures.

The only primitive Martian meteorite is Yamato and that gives a 1550 °C-1.7 GPa equilibration, consistent with multiple saturation experiments. Martian crust, as represented by Gusev crater spectral data, give lower T and P, 1350 °C and 1.2 GPa. We are in the process of calculating T, P for a compilation of spectral data on the Martian crust.

Our final application was to the Russian Venera and Vega spectral data of the Venusian crust. Two calculations were made. The first was without fractionation correction. The second was with fractionation correction, assuming olivine-only fractionation and back-correction to a Venusian mantle source having an olivine composition of Fo90. Evolved magmas give T-P between 1240-1350 °C and 0.6-2.0 GPa. Fractionation-correct magmas yield 1350-1450 °C and 1.2-3.0 GPa and fall on a possible melting adiabat intersecting a hypothetical Venusian mantle solidus at ~3 GPa nd 1450 °C. This temperatures are similar to that on Earth, though perhaps hotter by ~100 °C compared to mid-ocean ridges on Earth. Average depths of melting on Venus, however, appear to be greater than on Earth (assuming spectral data is representative), perhaps due to a thick stagnant lid on Venus versus the thin, mobile lid on Earth.

Conclusions: The applicability and robustness of our thermobarometers are validated by the good reproducibility of experimental P-T data and the geologically reasonable P-Ts estimated for various planetary magmas. These thermobarometers can be used to constrain lithosphere thicknesses on different planets, and with sufficient spectral data, even allow us to map out variations in lithosphere thickness. The effects of water can also be explored in our thermobarometric formulations.

References: [1] Lee, C.-T. A. et al. (2009) *Earth Planet. Sci. Lett.*, in press.