THERMOBAROMETRY OF LUNAR CORDIERITE-TROCTOLITE IN 15295,101: METAMORPHIC TEMPERATURE AND A POTENTIAL BAROMETER.

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A recently discovered clast of cordierite-bearing troctolite [1] in lunar regolith breccia 15295,101 contains mineral assemblages which will define the temperature and pressure of the clast's metamorphic equilibration. Coexisting olivine and ilmenite imply equilibration at 510±40°C [2]. The clast's assemblage cordierite-spinel-olivine-ilmenite-rutile defines a pressure-sensitive reaction; for 510°C, available thermochemical data suggest an equilibration pressure of −0.5±3 kbar. This large uncertainty can be reduced by reversed experiments, and better precision in free energies and activity-composition models.

THERMOMETRY: Silicate and oxide minerals in the clast are chemically homogeneous, consistent with chemical equilibrium at a single pressure and temperature. This equilibrium is inferred to represent a metamorphic event, prior to incorporation of the clast into 15295,101 [1]. The temperature of metamorphic equilibration can be retrieved from the distribution of Fe and Mg between olivine and ilmenite [2]. The cordierite-troctolite is ideal for this thermometer, as very little Mn is present and the ilmenite contains no Fe^{3+} [1]. The mineral compositions given in [1] (Table 1) imply an equilibration temperature of 510±40°C (equation 12 of [2]), within the temperature range of calibration. The uncertainty here derives from uncertainties in thermochemical parameters.

Another potential thermometer is the distribution Fe and Mg between olivine and spinel. The calibration of [3] suggests equilibration near 700°C; this value must be discounted as the spinel activity model of [3] is not consistent with results of more recent studies [4,5].

BAROMETRY: The clast contains forsterite+cordierite, which limits the pressure of equilibration to below about 3 kbar [6]. A potential mineral barometer is present as the assemblage cordierite+spinel+olivine+ilmenite+rutile, which defines the equilibrium:

$$\underset{\text{spinel}}{2\,MgAl_2O_4} + \underset{\text{rutile}}{10\,TiO_2} + \underset{\text{olivine}}{5\,Mg_2SiO_4} \Leftrightarrow \underset{\text{ilmenite}}{10\,MgTiO_3} + \underset{\text{cordierite.}}{Mg_2Al_4Si_5O_{18}}.$$

Both the ΔV (5.525 J/b) and ΔS (55.5 J/K) for this equilibrium are large, and imply a p-T slope of 1 kbar/100K. Thus, the equilibrium can act as a sensitive thermobarometer. The reaction has not been calibrated experimentally, so its location was calculated from published thermochemical data and activity-composition models (Table 2).

The greatest uncertainties in the barometric calculation come from the free energy and activity model for $MgTiO_3$, geikeilite, in ilmenite solid solution; any uncertainty is multiplied tenfold as the above reaction involves 10 moles of geikeilite. In the best available model for ilmenite solid solutions [2], activity coefficients (i.e. Margules parameters) are strongly correlated with free energy of the exchange reaction:

$$MgTiO_3 + 1/2\ Fe_2SiO_4 \Leftrightarrow FeTiO_3 + 1/2\ Mg_2SiO_4.$$

The free energy of this reaction is calculated in [2] and implies [7,8,9] that $\Delta^f G$(geik, 510°C)= -19.53 kJ/mol, while [9] gives -25.38 kJ/mol. This huge discrepancy is unexplained, but use of the activity model of [2] requires also use of $\Delta^f G$(geik) from [2].

At 510°C, the end-member reaction is calculated to lie at -8.0 kbar, or +2.6 kbar using $\Delta^f G$(geik) of [9]. For the natural compositions (Table 1) using reasonable activity models (Table 2), the reaction suggests equilibration at -0.5 kb, or 10.1 kbar using $\Delta^f G$(geik) of [9]. The latter pressure is impossible, as cordierite+forsterite are stable only below about 3 kbar [6]. A pressure of -0.5 kbar is also problematic, but is acceptable given the estimated uncertainty of at least 3 kbar.

INTERPRETATION: When the metamorphic p-T for the cordierite-troctolite clast can be tightly constrained, they will provide an important datum on the selenothermal gradient and possibly the a depth of magma emplacement. Also, the inferred depth of equilibration and the shock effects in the clast may help constrain processes of ejection from large impact basins. Unfortunately, the pressure of metamorphic equilibration is so poorly constrained that interpetations are premature.

FUTURE WORK: The pressure of metamorphism for the 15295,101 clast can be better constrained by locating the position of the pressure-sensitive reaction through reversed experiments. It may be important to quantify Al-Si ordering in the natural and experimental cordierites (e.g. by NMR or X-ray absorption). Further calibration of the thermometric assemblages is important (vis [10]), and would be obtained in the above experiments. Measurement of the enthalpy of formation of $MgTiO_3$ will help clarify the uncertainty in its free energy. Finally, it would be helpful to know when the cordierite-troctolite clast attained its metamorphic equilibrium, both as a constraint on impact ejection and as a constraint on temporal variation of the selenothermal gradient.

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Table 1: Mineral compositions in the clast [1].

Olivine	Fo_{90-92}
Cordierite	$(Mg_{0.967}Fe_{0.033})_2Al_4Si_5O_{18}$
Spinel	$(Mg_{0.78}Fe_{0.22})(Al_{0.87}Cr_{0.13})_2O_4$
Ilmenite	$(Fe_{0.64}Mg_{0.36})TiO_3$
Rutile	TiO_2

Table 2: Sources of Thermochemical Data

	Free Energy	Activity Model
Olivine	[7]	[3]
Cordierite	[9]	[11]
Spinel	[9]	[4]
Ilmenite	[6]	[2]
Geikeilite	[2]	[2]