

MELTING CONDITIONS OF PRIMARY LUNAR ULTRAMAFIC GLASSES. S. M. Brown¹ and T. L. Grove²,
¹Massachusetts Institute of Technology, 77 Massachusetts Ave 54-1210, Cambridge MA 02139, brownsm@mit.edu,
²Massachusetts Institute of Technology, 77 Massachusetts Ave 54-1220, Cambridge MA 02139, tlgrove@mit.edu

Introduction: The highly variable compositions of lunar ultramafic volcanic glasses [1] record primary and secondary magmatic processes. The two important secondary melt modification processes for lunar magmas are fractional crystallization and magma mixing / assimilation. When a glass has experienced significant secondary modification such that it is no longer primary, multiple saturation experiments will not faithfully record the conditions (pressures, temperatures, compositions) of melting [2]. To address this problem, we correct for secondary magmatic processes to obtain primary composition(s) of all of the ultramafic glasses and then infer the melting conditions of these true primary melts.

Methods: First, we identify which ultramafic glasses have experienced sufficiently extensive secondary modification such that their multiple saturation points need revision (Figure 1) and then identify their most likely primary melt composition(s). Second, we calibrate a thermobarometer of melting (Figure 2) using the database of currently existing lunar multiple saturation experiments and then apply the thermobarometer to the corrected ultramafic glass primary

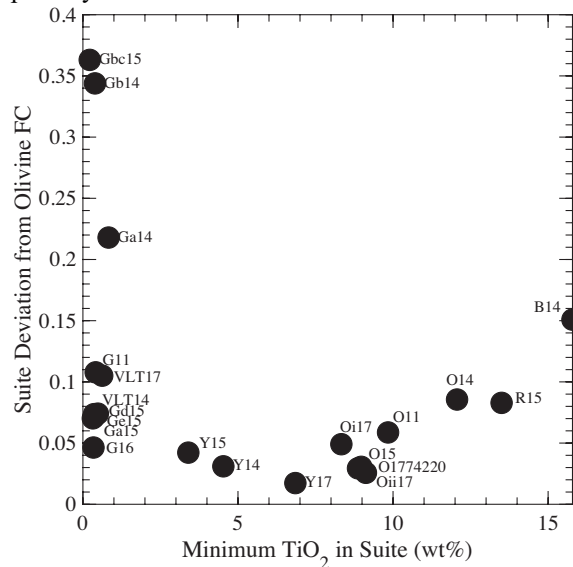


Figure 1 Measure of complex secondary melt modification processes in excess of pure olivine fractionation (olivine FC) of twenty-one ultramafic glass suites from [1]. The deviation (y-axis) is the average composition distance (the Aitchison distance) using SiO₂, TiO₂, Al₂O₃, FeO, MgO, and CaO. The magnitude of secondary processes are not strongly dependent on TiO₂ content.

Identifying and measuring non-primary lunar volcanic ultramafic glasses. The simplest process to generate compositional trends within lunar ultramafic glasses suites is by low-pressure fractional crystallization [1]. The trends; however, often deviate substantially from fractionation of the experimentally determined low-pressure liquidus phase olivine [3] and require more complex processes [e.g., 2,5]. We thus identify glass suites that have experienced magma mixing / assimilation by calculating the deviation of suite from pure olivine-only fractionation (Figure 1). We then use the magma mixing / assimilation model of [2] to calculate best fit primary melt compositions.

Calibrating a lunar thermobarometer. We calculate a thermobarometer for source regions with residual olivine and orthopyroxene according to the Gibbs Phase Rule by multiple linear regression on experimental lunar melt compositions in equilibrium with olivine and orthopyroxene. The multiply saturated melt dataset currently includes 38 experiments [2,4-8]. Given 9 components (SiO₂, TiO₂, Al₂O₃, Cr₂O₃, FeO, MgO, CaO, Na₂O, K₂O) and 3 phases (olivine, orthopyroxene, and liquid), 6 dependent variables are required to uniquely determine pressure and temperature (Figure 2). We use the Grove [9] Tormey mineral components olivine (Ol), clinopyroxene (Cpx), quartz (Qtz), oxide (Ox), in addition to Mg# = molar Mg/(Mg+Fe) and NaK# = Na₂O+K₂O/(CaO+Na₂O + K₂O) in wt%.

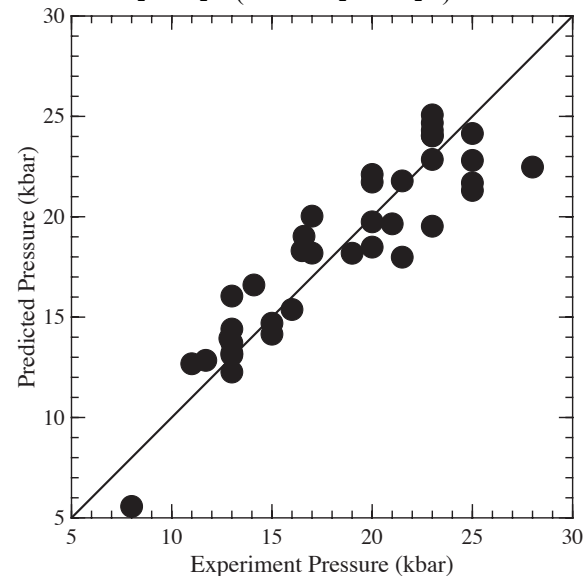


Figure 2 Ol+Opx+Melt barometer for primary lunar magmas; $P(\text{kbars}) = 38.85 + 51.5 \text{ Ol} - 82.87 \text{ Cpx} - 163.14 \text{ Qtz} + 32.17 \text{ Ox} - 18.50 \text{ Mg\#} - 51.41 \text{ NaK\#}$ ($r^2=0.83$, mean absolute error =1.7 kbars).

Results: The intermediate TiO_2 glasses (5–10 wt%) glasses have experienced the least amount of complex secondary modification; however, the magnitude of secondary processes are not strongly dependent on TiO_2 content (Figure 1). In addition, the glass suite that best fits olivine-only fractionation (the Apollo 17 yellow glasses) still likely requires magma mixing to explain its compositional variability [2]. Therefore, complex igneous processes have likely influenced all lunar ultramafic glasses.

Preliminary barometry results for Apollo 14 primary melt compositions indicate deeper melting pressures than graphite-capsule ($f\text{O}_2 = \text{IW}+2$) multiple saturation pressures. Apollo 14 ultramafic glasses span the full range in ultramafic glass TiO_2 content, and so it seems likely that the moon melted at pressures deeper than the range inferred from $f\text{O}_2 = \text{IW}+2$ multiple saturation pressures $\sim 1.5\text{--}2.4$ GPa. The pressures for the primary melts; however, are more consistent with reduced $f\text{O}_2 = \text{IW}-2$ (iron capsules) multiple saturation experiments that extend melting pressures to ~ 4 GPa.

Compared to the Apollo 14 or 15 yellow glasses, the Apollo 17 yellow glasses require higher pressures of melting of earlier formed lunar magma ocean cumulates. If this result holds, then melting in the lunar interior moved to shallower pressures over time. The causes of this magmatism then must be linked to the overturn of dense, titanium rich cumulates [10] or heating due to giant impacts [11]. The absence of overturn would lead to the opposite behavior of deepening melting pressures with time.

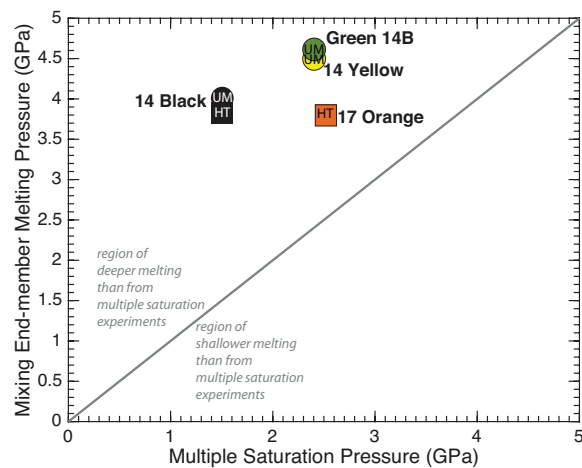


Figure 3 End-member (i.e., primary melt) melting pressures calculated using the barometer (Figure 2) for ultramafic primary melts (“UM”) or taken to be pressures of experiments for high-titanium primary melts (“HT”).

References: [1] Delano JW. (1986) *JGR*, 91, D201–13. [2] Brown SM, Grove TL. (2015) *GCA*, 171, 201–15. [3] Delano J, Lindsley D. (1983) *LPSC*, 88:B3–16. [4] Barr JA, Grove TL. (2013) *GCA*, 106, 216–30. [5] Elkins-Tanton LT, Chatterjee N, Grove TL. (2003) *MPS*, 38, 515–27. [6] Elkins L., Fernandes V., Delano J., Grove T. (2000), *GCA*, 64, 2339–50. [7] Krawczynski MJ, Grove TL. (2012), *GCA*, 79:1–19. [8] Wagner TP, Grove TL. (1997), *GCA*, 61, 1315–27. [9] Grove TL. (1993) *CMP*, 114:422–4. [10] Hess, P.C., Parmentier, E.M. (1995) *EPSL*, 134, 501–514. [11] Elkins-Tanton, L., Hager, B., Grove, T.L. (2004) *EPSL*, 222, 17–27.