Spinel-Anorthosites on the Moon: Impact Melt Origins Suggested by Enthalpy Constraints

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Appendix C: Selection and Construction of Chemical Compositions

It was not practical to produce and interpret phase diagrams, T-X and ΔH*-X, for all possible compositions that could be relevant to lunar spinels. Our approach then was to find or generate liquidus phase diagrams for simple chemical systems related to basalt and spinel, and then select pseudo-binary joins within those systems that are reasonable analogs to lunar materials and are relevant to assimilation. Because lunar highlands plagioclase is nearly pure anorthite, An95 (molar Ca/(Ca+Na) = 0.95), we chose pure anorthite as an end-member.

Lunar spinel-bearing rocks have been interpreted to represent mixtures of crustal anorthosite and picritic or basaltic magma (Finnila et al., 1994; Morgan et al., 2006; Gross and Treiman, 2011). To model such mixtures, we investigated four simple systems, of increasing complexity and similarity to real lunar magmas: forsterite-anorthite; forsterite-anorthite-silica; forsterite-anorthite-diopside-silica; and forsterite-anorthite-diopside-silica with iron-bearing olivine and pyroxenes..

The simplest chemical system relevant to spinel genesis in both lunar and basaltic systems is Mg_2SiO_4 – $CaAl_2Si_2O_8$, forsterite-anorthite, or Fo-An. Phase relations in Fo-An are known well (Andersen, 1915; Osborn and Tait, 1952; Irvine, 1974), and form a bounding join for more complex chemical systems related to basalt genesis (Longhi, 1987; Libourel et al., 1989; Shi and Libourel, 1991; Soulard et al., 1994). Specifically in connection with the formation of lunar spinel, pure Fo is a first-order proxy for lunar mantle peridotite, and olivine-rich mixtures are possible proxies for lunar peridotitic magmas.

Within the latter three systems, we selected pseudobinary joins that are increasingly realistic approximations to assimilation or mixing of highlands anorthite and basaltic or picritic material. The chosen pseudo-binary join is between anorthite feldspar composition and approximations of the Apollo 14 green glass B composition (Delano, 1986; Elkins et al., 2000),

Table 1 of main text, which is among the most magnesian and picritic (high normative olivine) of known lunar magma compositions. The Apollo 14B green glass has: low abundances of elements outside the system CaO-MgO-FeO-Al_2O_3-SiO_2, CMFAS (i.e., Ti, Cr, Na, and K); among the highest Mg* of lunar glasses (63.2%) suggesting that it is primitive; and among the highest molar ratios (Fe+Mg)/Si, implying that it is closest to olivine in composition and thus more likely to form spinel or interaction with the lunar anorthositic crust.

The Apollo 14B green glass composition is fortuitously relevant to another recent hypothesis that lunar spinel-bearing rocks derive from chemical reaction between anorthosite and Mg-suite magmas (Prissel et al., 2014; Prissel et al., 2016). The Mg-suite represents a diverse group of cumulate igneous rocks (Shearer et al., 2015), some rich in KREEP component (Longhi et al., 2010) and others containing abundant spinel (e.g., samples 67435c77 and t2295 (Prinz et al., 1973; Walker et al., 1973)). Estimates of the chemical composition of a magma parental to the Mg-suite rocks, MgSPM, are provided by both Longhi et al. (2010) and Prissel et al. (2016) are similar, see Table 1 of the main text.

The compositions of the Apollo 14B glass and the inferred MgSPM contain moderate abundances of elements outside CMFAS, and are unnecessary complications to our models. So, we removed these other chemical components as follows, to yield model compositions in CMFAS.

- Molar TiO_2 was paired with equimolar FeO to represent a $FeTiO_3$ component, which was then subtracted.
- Molar Cr_2O_3 was paired with equimolar FeO to represent a $FeCr_2O_4$ component, which was subtracted.
- Molar Na and K were associated with molar Al and Si to represent $NaAlSi_3O_8$ and $KAlSi_3O_8$ components, and both were subtracted.
- Molar MnO was added to FeO.

The remaining composition was normalized to 100% mass to give the model compositions projected into CMFAS and its subsystems (Table 1 of main text). To model these magmas in the Fe-free systems, molar FeO was added to MgO, and the compositions again normalized to 100% weight.

To allow the widest use of our results, we extrapolated these model magma compositions to anorthite-free peridotite compositions, olivine + pyroxenes, such that mixtures of these peridotites plus anorthite would include (or be close to) the model picrite and Mt-suite parent compositions. The model peridotite in CMFAS is Perid14B, that projected into Fo-An-Di-Sil is Perid14B', and that projected into Fo-An-Sil is Perid14B". See Table 1 of the main text.

References cited

Andersen, O. (1915) The system anorthite-forsterite-silica. American Journal of Science, 232, 407-454.

Delano, J.W. (1986) Pristine lunar glasses: Criteria, data, and implications. Journal of Geophysical Research: Solid Earth, 91(B4), 201-213.

Elkins, L.T., Fernandes, V., Delano, J., and Grove, T. (2000) Origin of lunar ultramafic green glasses: Constraints from phase equilibrium studies. Geochimica et Cosmochimica Acta, 64(13), 2339-2350.

Finnila, A., Hess, P., and Rutherford, M. (1994) Assimilation by lunar mare basalts: Melting of crustal material and dissolution of anorthite. Journal of Geophysical Research: Planets, 99(E7), 14677-14690.

Gross, J., and Treiman, A.H. (2011) Unique spinel‐rich lithology in lunar meteorite ALHA 81005: Origin and possible connection to M^3 observations of the farside highlands. Journal of Geophysical Research: Planets, 116, E10009.

Irvine, T. (1974) Olivine-pyroxene-plagioclase relations in the system Mg_2SiO_4-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-SiO_2 and their bearing on the differentiation of stratiform intrusions. Yearbook, Carnegie Institution Washington, 74, 492-500.

Libourel, G., Boivin, P., and Biggar, G.M. (1989) The univariant curve liquid = forsterite + anorthite + diopside in the system CMAS at 1 bar: solid solutions and melt structure. Contributions to Mineralogy and Petrology, 102(4), 406-421.

Longhi, J. (1987) Liquidus equilibria and solid solution in the system $CaAl_2Si_2O_8$-Mg_2SiO_4-$CaSiO_3$-SiO_2 at low pressure. American Journal of Science, 287(4), 265-331.

Longhi, J., Durand, S.R., and Walker, D. (2010) The pattern of Ni and Co abundances in lunar olivines. Geochimica et Cosmochimica Acta, 74(2), 784-798.

Morgan, Z., Liang, Y., and Hess, P. (2006) An experimental study of anorthosite dissolution in lunar picritic magmas: implications for crustal assimilation processes. Geochimica et Cosmochimica Acta, 70(13), 3477-3491.

Osborn, E., and Tait, D. (1952) The system diopside-forsterite-anorthite. American Journal of Science, 38, 413-433.

Prinz, M., Dowty, E., Keil, K., and Bunch, T. (1973) Spinel troctolite and anorthosite in Apollo 16 samples. Science, 179(4068), 74-76.

Prissel, T.C., Parman, S., Jackson, C., Rutherford, M., Hess, P., Head, J., Cheek, L., Dhingra, D., and Pieters, C. (2014) Pink Moon: The petrogenesis of pink spinel anorthosites and implications concerning Mg-suite magmatism. Earth and Planetary Science Letters, 403, 144-156.

Prissel, T.C., Parman, S.W., and Head, J.W. (2016) Formation of the lunar highlands Mg-suite as told by spinel. American Mineralogist, 101(7), 1624-1635.

Shearer, C.K., Elardo, S.M., Petro, N.E., Borg, L.E., and McCubbin, F.M. (2015) Origin of the lunar highlands Mg-suite: An integrated petrology, geochemistry, chronology, and remote sensing perspective. American Mineralogist, 100(2), 294-325.

Shi, P., and Libourel, G. (1991) The effects of FeO on the system CMAS at low pressure and implications for basalt crystallization processes. Contributions to Mineralogy and Petrology, 108(1-2), 129-145.

Soulard, H., Boivin, P., and Libourel, G. (1994) Liquid-forsterite-anorthite-spinel assemblage at 1 bar in the CMAS system: implications for low-pressure evolution of high-Al and high-Mg magmas. European Journal of Mineralogy, 6(5), 633-646.

Walker, D., Longhi, J., Grove, T.L., Stolper, E., and Hays, J.F. (1973) Experimental petrology and origin of rocks from the Descartes Highlands. Lunar and Planetary Science Conference Proceedings, 4, p. 1013-1032.