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

Allan H. Treiman, Michael J. Kulis, and Allen F. Glazner

Appendix D: Equilibria Between Peridotite and Anorthosite in the System Fo-An-Sil

Extending our results toward realistic lunar compositions, we consider the system Fo-An with additional SiO_2, the system Fo-An-Sil (forsterite-anorthite-silica), Figure D1. Its ternary liquidus diagrams are shown in Figure D1a as experimentally determined by Andersen (1915) and Irvine (1975), and Figure D1b as calculated with FactSage. The topographies of the experimental and calculated diagrams are similar with a significant exception. The fields of liquidus pyroxene are nearly identical, although the calculated diagram includes several varieties of $MgSiO_3$ pyroxene (protopyroxene, space group Pbcn; pigeonite, $P2_1/c$; and orthopyroxene, Pbca), which are rarely distinguished in experimental studies. The significant difference is that FactSage calculations yield a significantly larger spinel liquidus field than determined in experiments. The spinel-liquidus field is so enlarged that the calculated diagram has no L + Ol + Pl field (or line, Fig. D1b), which is not consistent with natural occurrences and laboratory experiments.

Rather than investigate the whole ternary system, we focus on the formation of lunar spinel by selecting a binary join in Fo-An-Sil that is relevant to hypotheses that invoke anorthosite assimilation into picritic or Mg-suite magmas (Morgan et al., 2006; Gross and Treiman, 2011; Prissel et al., 2016). The join between anorthite and a model peridotite composition of 88% forsterite by mass and 12% SiO_2 (Figure 3a, see Appendix B) passes close to the projections of the Apollo 14 B ‘green glass’ picrite, Table 1 of main text (Delano, 1986; Elkins-Tanton et al., 2003), and the suggested composition of possible parent magma compositions for the Mg-suite plutonic rocks (Longhi et al., 2010; Prissel et al., 2016). The A14B green glass is appropriate here because it is among the most picritic (i.e., richest in normative olivine; Fig. 3a) and most magnesian (highest Mg#) of the lunar magma compositions.

Figures D1c-f show equilibrium phase relations along that peridotite-anorthite join (at 1 bar), both as T-X and ΔH^*-X diagrams.

Interpretation 2: Peridotite-Anorthosite in Fo-An-Sil

Spinel stability is a problem in the FactSage calculated diagrams, as its stability fields are significantly larger than those constrained by experiments (Figs. D1a, b). Of most importance, the calculated T-X diagram shows a liquidus field of Opx + Sp + L. This difference is significant because Opx + Sp + L is not stable at low pressure (i.e., 1 bar as in the FactSage calculation); instead, Ol + Pl + L are stable together at low pressures in lunar, terrestrial, and experimental systems. The assemblage Opx + Sp + L is stable only at high pressures, i.e. > 0.3 GPa (Presnall et al., 1978), and the effect of pressure on spinel stability underlies several hypotheses for its occurrence on the Moon (Herzberg and Baker, 1980; McCallum and Schwartz, 2001; Prissel et al., 2014). This mismatch has little effect on calculated liqudus equilibria for this binary join (Figs. D1c-f), but is important at sub-liquidus conditions because it implies that spinel could form at temperatures (and in phase assemblages) different from those constrained by experiments. In Figures D1d & f, note that there are calculated stability fields for Px + Sp + Ol + L, Px + Sp + Pl + L, and Px + Sp + Ol + Pl + L; although these fields are small, they are not consistent with experimental data (Fig. 3a) and diagrams derived from them (Figs. 3c, e).

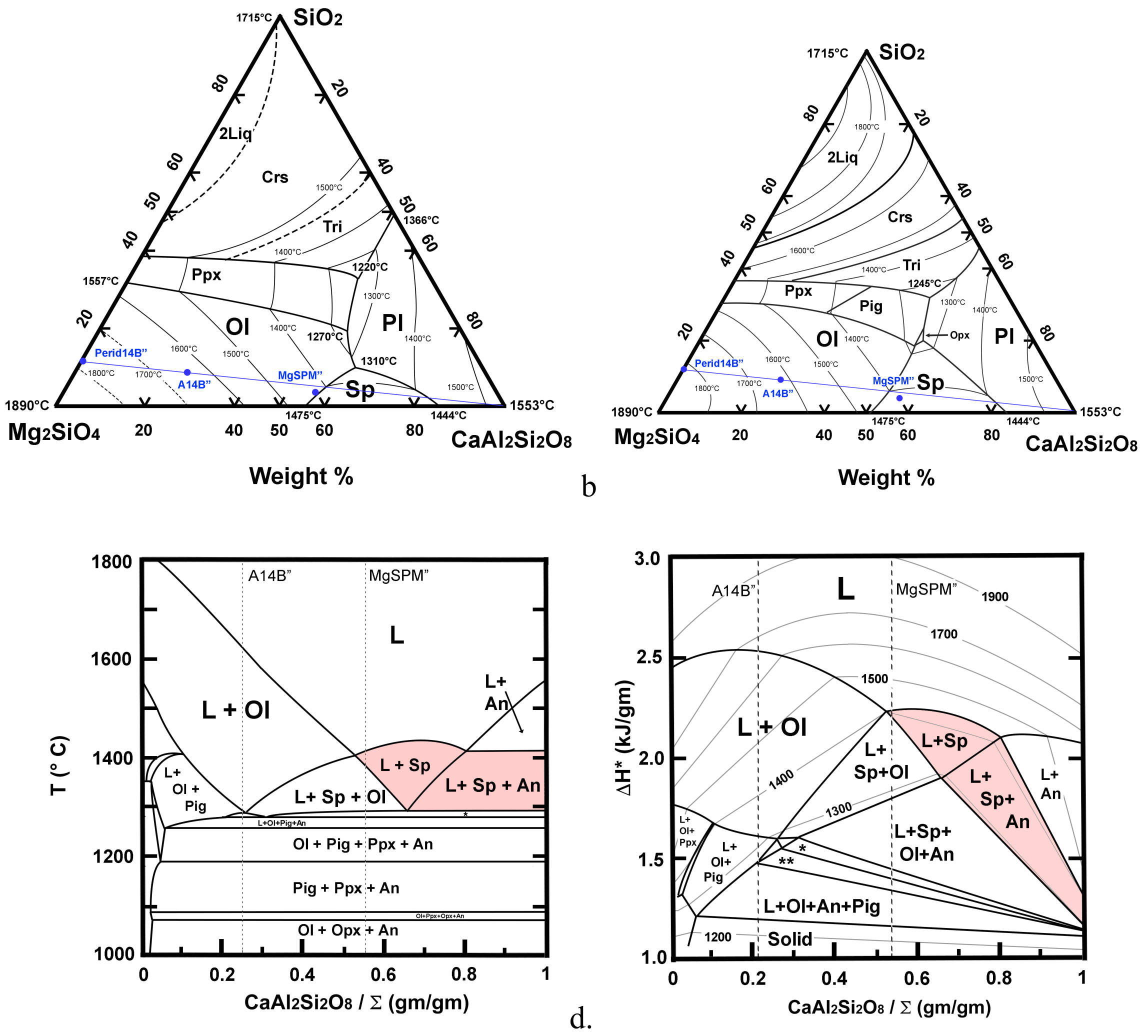

Figure D1. Phase relations in the ternary system Fo-An-Sil (Mg_2SiO_4 – $CaAl_2Si_2O_8$ – SiO_2) at 1-bar pressure.

a. Ternary liquidus surface, as constrained by laboratory experiments (Andersen, 1915; Irvine, 1975). Note that the liquidus fields of olivine and spinel touch, i.e. there are compositions and temperatures where both olivine and anorthite are on the liquidus together, and that spinel and pyroxene are never on the liquidus together. Blue line connects anorthite with a peridotite composition (Perid14B”) such that mixing along it yields model compositions like the Apollo 14 green glass (A14B”) and the Mg-suite parent magma (MGSPM”).

b. Ternary liquidus surface, as calculated in FactSage. Note that the liquidus field of spinel is larger than in part **a**, and implies that spinel and pyroxene can be liquidus phases together. This is contrary to results of laboratory experiments (see Fig. D1a).

c. Temperature-composition phase relations along the join PeridA14B" – Anorthite, (shown as blue lines in Figures D1a & b) calculated in FactSage. Pig = pigeonite pyroxene; Ppx = protopyroxene; Opx = orthopyroxene. The field denoted by * is for L+Sp+Ol+An. Complex relations near the PeridA14B" axis are omitted for clarity.

d. ΔH*-X diagram for the pseudo-binary join Perid14B"-An calculated with FactSage (Bale et al., 2009; Bale et al., 2016) consistent with Fig. D1d. Pink field have phases consistent with remote sensing detection as spinel-peridotite. Pig = pigeonite pyroxene; Ppx = protopyroxene; field marked as '*' is for L+Sp+Opx+Ol+An; field marked as '**' is for L+Opx+Pig+Ol+An. The complex phase relations at lower T and lower An content (mostly involving pyroxenes) are in Figure A4.

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