Formation of the lunar highlands Mg-suite as told by spinel

TABB C. PRISSEL1,*, STEPHEN W. PARMAN1, and JAMES W. HEAD1

1Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, Rhode Island 02912, U.S.A.

Abstract

Two competing hypotheses suggest lunar Mg-suite parental melts formed: (1) by shallow-level partial melting of a hybridized source region (containing ultramafic cumulates, plagioclase-bearing rocks, and KREEP), producing a plagioclase-saturated, MgO-rich melt, or (2) when plagioclase-undersaturated, MgO-rich melts were brought to plagioclase saturation during magma-wallrock interactions within the anorthositic crust. To further constrain the existing models, phase equilibria experiments have been performed on a range of Mg-suite parental melt compositions to investigate which composition can best reproduce two distinct spinel populations found within the Mg-suite troctolites—chromite-bearing (FeCr2O4) troctolites and the more rare pink spinel (MgAl2O4 or Mg-spinel) troctolites (PST).

Phase equilibria experiments at 1 atm pressure were conducted under reducing conditions (log fO2 ~IW-1) and magmatic temperatures (1225–1400 °C) to explore the spinel compositions produced from melts predicted by the models above. Additionally, the experimental data are used to calculate a Sp-Ol, Fe-Mg equilibrium exchange coefficient to correct natural spinel for sub-solidus re-equilibration with olivine in planetary samples: Sp-Ol $K_{Fe-Mg}^s$ = 0.044Cr# + 1.5 ($R^2 = 0.956$). Melts from each model (≥50% normative anorthite) produce olivine, plagioclase, and Mg-spinel compositionally consistent with PST samples. However, chromite was not produced in any of the experiments testing current Mg-suite parental melt compositions. The lack of chromite in the experiments indicates that current estimates of Mg-suite parental melts can produce Mg-spinel bearing PST, but not chromite-bearing troctolites and dunites. Instead, model calculations using the MAGPOX equilibrium crystallization program predict chromite production from plagioclase-undersaturated melts (<20% normative anorthite). If so, experimental and model results suggest chromite in Mg-suite crystallized from plagioclase-undersaturated parental melts, whereas Mg-spinel in the PST is an indicator of magma-wallrock interactions within the lunar crust (a mechanism that increases the normative anorthite contents of initially plagioclase-undersaturated Mg-suite parental melts, eventually producing Mg-spinel). The constraints for magmatic chromite crystallization suggest Mg-suite parental melts were initially plagioclase-undersaturated. In turn, a plagioclase-undersaturated Mg-suite parent is consistent with mantle overturn models that predict Mg-suite parent magmas resulted from decompression melting of early ultramafic cumulates produced during the differentiation of a global lunar magma ocean.

Keywords: Mg-suite, lunar highlands, spinel, petrogenesis, magma-wallrock interactions

Introduction

The lunar highlands Mg-suite samples are comprised of plutonic to hypabyssal igneous rock fragments and clasts including dunites, troctolites, pink spinel troctolites, norites, and gabbrointrites (e.g., James 1980; Warren 1993; Papike et al. 1998; Shearer et al. 2015). Primitive olivine, orthopyroxene (high-Mg# = Fo# = Mg/[Mg+Fe]×100), and calcic-plagioclase (high-An# = Ca/[Ca+Na+]×100) dominate the mineralogy of Mg-suite samples. Mg-suite rocks are also among the most ancient samples returned from the Moon, dating to >4.1 Ga (e.g., Nyquist and Shih 1992; Borg et al. 2013; Carlson et al. 2014). The primitive mineralogy combined with ancient ages indicate Mg-suite samples can provide insight into the early lunar interior and magmatic activity post-dating the differentiation of a global magma ocean (Wood et al. 1970; Smith et al. 1970; Walker et al. 1975; Drake 1976; Norman and Ryder 1979; James 1980; Nyquist and Shih 1992; Warren 1993; Shearer et al. 2006; Elardo et al. 2011; Borg et al. 2013; Carlson et al. 2014; Shearer et al. 2015).

A positive correlation between the Mg# of mafic silicates and the An# of plagioclase suggests that Mg-suite rock types are comagmatic (i.e., related by a common parental magma crystallizing at <0.3 GPa) (e.g., Walker et al. 1976; James 1980; Warren 1986; Shearer and Papike 2005; Carlson et al. 2014). Consistent with a common source, Mg-suite whole-rock analyses fall along a Lu-Hf isochron (Carlson et al. 2014). However, Mg-suite samples also contain an evolved trace element signature (KREEP = K, rare earth element, and P) (e.g., Warren 1986; Hess 1994; Papike et al. 1998; Shervais and McGee 1998; Shearer and Papike 2005; Longhi et al. 2010; Elardo et al. 2011). The pairing of primitive major element chemistry with an evolved trace element signature indicates a more complex origin than crystal fractionation alone (e.g., Hess 1994; Longhi et al. 2010; Elardo et al. 2011; Shearer et al. 2015).