Trace element partitioning between olivine and melt in lunar basalts

SHA CHEN1, PENG NI1, YOUXUE ZHANG1,*, AND JOEL GAGNON2

1Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, Michigan 48109, U.S.A.
2School of the Environment, University of Windsor, Windsor, Ontario N9B 3P4, Canada

ABSTRACT

Mineral/melt partition coefficients have been widely used to provide insights into magmatic processes. Olivine is one of the most abundant and important minerals in the lunar mantle and mare basalts. Yet, no systematic olivine/melt partitioning data are available for lunar conditions. We report trace element partition data between host mineral olivine and its melt inclusions in lunar basalts. Equilibrium is evaluated using the Fe-Mg exchange coefficient, leading to the choice of melt inclusion-host olivine pairs in lunar basalts 12040, 12009, 15016, 15647, and 74235. Partition coefficients of 21 elements (Li, Mg, Al, Ca, Ti, V, Cr, Mn, Fe, Co, Y, Zr, Nb, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) were measured. Except for Li, V, and Cr, these elements show no significant difference in olivine-melt partitioning compared to the data for terrestrial samples. The partition coefficient of Li between olivine and melt in some lunar basalts with low Mg# (Mg# < 0.75 in olivine, or <~0.5 in melt) is higher than published data for terrestrial samples, which is attributed to the dependence of DLi on Mg# and the lack of literature DLi data with low Mg#. The partition coefficient of V in lunar basalts is measured to be 0.17 to 0.74, significantly higher than that in terrestrial basalts (0.003 to 0.21), which can be explained by the lower oxygen fugacity in lunar basalts. The significantly higher DLi can explain why V is less enriched in evolved lunar basalts than terrestrial basalts. The partition coefficient of Cr between olivine and basalt melt in the Moon is 0.11 to 0.62, which is lower than those in terrestrial settings by a factor of ~2. This is surprising because previous authors showed that Cr partition coefficient is independent of fO2. A quasi-thermodynamically based model is developed to correlate Cr partition coefficient to olivine and melt composition and fO2. The lower Cr partition coefficient between olivine and basalt in the Moon can lead to more Cr enrichment in the lunar magma ocean, as well as more Cr enrichment in mantle-derived basalts in the Moon. Hence, even though Cr is typically a compatible element in terrestrial basalts, it is moderately incompatible in primitive lunar basalts, with a similar degree of incompatibility as V based on partition coefficients in this work, as also evidenced by the relatively constant V/Cr ratio of 0.039 ± 0.011 in lunar basalts. The confirmation of constant V/Cr ratio is important for constraining concentrations of Cr (slightly volatile and siderophile) and V (slightly siderophile) in the bulk silicate Moon.

Keywords: Partition coefficients, lunar basalts, olivine, melt inclusions, Cr/V ratio

INTRODUCTION

Mineral/melt partition coefficients have been widely used to provide insights into magmatic processes. Olivine is one of the most abundant and important minerals in the lunar mantle and mare basalts. Olivine fractionation in the lunar magma ocean (LMO) and during lunar basalt differentiation plays a significant role in the evolution of the magma (Wood et al. 1970; Longhi 1977; Solomon and Longhi 1977; Snyder et al. 1992; Elardo et al. 2011; Lin et al. 2017; Charlier et al. 2018; Rapp and Draper 2018). Olivine-melt partitioning also plays a role in controlling the composition of mantle-derived basalts. Hence, quantifying olivine-melt partitioning is critical to understanding and modeling magma evolution of the LMO and lunar basalts.

Although numerous partitioning studies have been published for olivine and basaltic melt, they show significant variability for most elements due to the wide range of compositions, conditions, and methods involved. For example, the Ti partition coefficient between olivine and melt varies by more than two orders of magnitude, ranging from 0.0019 to 0.43 (Duke 1976; Rollinson 1993; McDade et al. 2003; Spandler and O’Neill 2010; Papke et al. 2013; Laubier et al. 2014; Burnham and O’Neill 2016; Leitzke et al. 2016). In addition, these studies often focus on terrestrial samples and physicochemical conditions. Though lunar and terrestrial basalts share many similarities in terms of their chemical composition, they are distinct in several aspects. Compared to typical terrestrial basalts, lunar basalts have highly variable TiO2, lower Al2O3 and alkalis, and often higher FeO and Cr2O3 concentrations. For example, terrestrial basalts rarely contain ≥5 wt% TiO2 in the melt due to FeTi oxide saturation at ~1100 °C (Toplis and Carroll 1995), whereas lunar basalts may contain up to 14 wt% TiO2. Such compositional differences have been shown to affect the physical properties of the melt, metal solubility in silicate melts (Borisov et al. 2004), and mineral/melt partition coefficients of...