

Vapor Element Transport in the Lunar Crust and Implications for Lunar Ore Deposits. C.K. Shearer¹, P.V. Burger¹, and Y. Guan², ¹Institute of Meteoritics and Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131 (cshearer@unm.edu), ²Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

Introduction: In planetary environments with stable H₂O in the target (Earth, Mars), large impacts will generate extensive hydrothermal systems associated with the ejecta blankets [i.e. 1,2 and references within]. Although the Moon's crust is considered to be dry by most standards (with the possible exception of the polar deposits), there are textures preserved in the lunar sample collection that imply the mobility of elements in this type of environment. As an example, Norman [3] and Lindstrom and Salpas [4] reported the existence of troilite fracture-fillings, veins and textures suggesting the replacement of olivine and pyroxene by troilite. Haskin and Warren [5] speculated that C-O-S compounds of various forms might serve as circulating fluids in ejecta blankets, causing fractional distillation, sublimation, or extraction of individual vapor-mobilized elements. A detailed theoretical analysis of these lunar replacement textures by Colson [6] indicated that they may be described by the reaction: Olivine + S₂(g) ⇌ Enstatite + 2FeS + O₂(g) with the oxygen fugacity (f_{O₂}) being internally buffered. In contrast to Haskin and Warren [5], Colson [6] concluded that such textures only required the mobility of S and not other chalcophile elements. This contrast in models for the mobility of chalcophile elements (and other elements such as H and C) in such an environment has significant implications for the presence or absence of "ore deposits" on the Moon. The goal of this study is to differentiate between the transport models proposed by Haskin and Warren [5] and Colson [6] and thereby gain a clearer understanding of volatile element transport in the relatively dry lunar crust.

Analytical Methods: During the initial stage of this study, thin section 67016,294 was documented using backscattered electron imaging (BSE). BSE maps were used to identify individual phases for follow-on analyses and to document textural relationships between sulfides and silicates. Following phase identification, quantitative electron microprobe (EMP) point analyses were conducted on the phases of interest, using an accelerating voltage of 15 kV, a beam current of 20 nA and a ~1 μm spot size. Analyses were standardized using Taylor mineral and metal standards. A trace element analysis of sulfides via EMP was accomplished using trace element sulfide standards and analytical methodology documented by Donnelly and Brearley [7]. The sulfides were further analyzed for a suite of trace elements using a Cameca 4f ims ion microprobe (UNM). The precision of most of the trace

elements was approximately 10%. Sulfur isotope analysis of the sulfides was accomplished with a Cameca nanoSIMS 50L at the California Institute of Technology. The precision on δS³⁴ measurements is approximately 0.8 per mil for 2-5 μm sulfide grains.

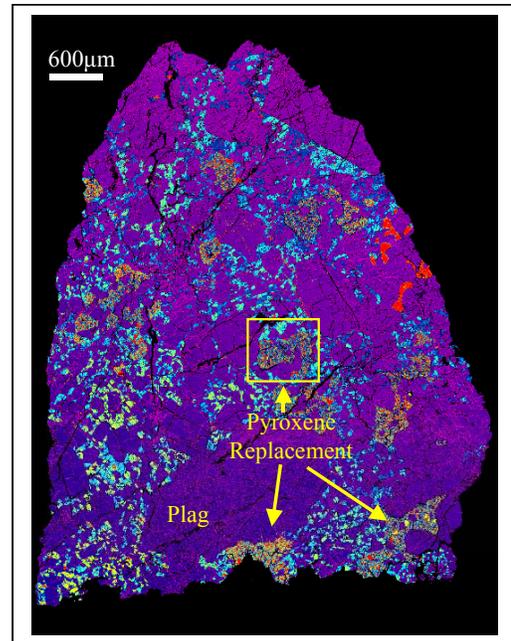


Figure 1. False color BSE image of 67016,294. Plagioclase = purple, pyroxene = blue and blue-green, yellow=olivine, Fe-Ti oxides or sulfides = red.

Alteration petrography: Both Norman [3] and Lindstrom and Salpas [4] described the extensive troilite veins and replacement textures in fragmental breccia 67016. Figure 1 illustrates the distribution and textural variability of the troilite on a thin section scale. The troilite veins are 4-10 μm wide and have a length on the order of 100-1000 μm (Figs. 1 and 2). They appear not to crosscut silicates that are replaced by troilite. Orthopyroxene is the most common silicate associated with the troilite. The replacement remains within the pyroxene grain boundaries. Very minor amounts of olivine are closely associated with this reaction texture (Fig. 2).

Silicate mineral chemistry: Both orthopyroxene and high-Ca-clinopyroxene occur in 67016,294. The distribution of the pyroxenes is illustrated in Figure 1 and the compositions of the "unaltered" pyroxenes are represented in a pyroxene quadrilateral in Figure 3. Pyroxenes intergrown with troilite are more magnesian

than the unaltered pyroxene and have a lower wollastonite component ($Wo_{1.3}$ compared to $Wo_{2.5}$). The olivine that is associated with the troilite-pyroxene has a variable composition ranging from Fo_{45-30} (Fig. 3).

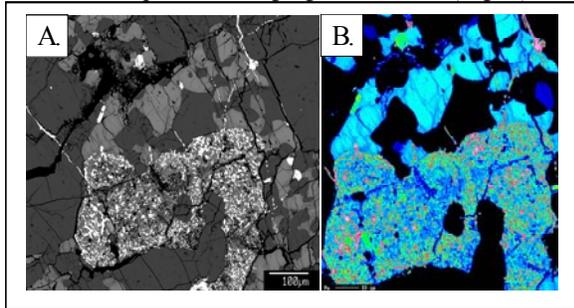


Figure 2. BSE image and Fe x-ray map of troilite veins and pyroxene-troilite intergrowth marked in Figure 1.

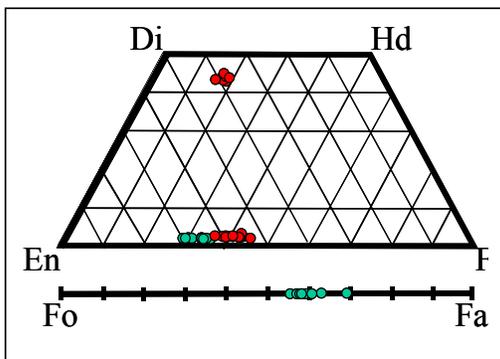


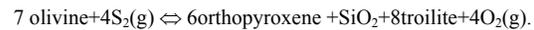
Figure 3. Pyroxene and olivine compositions. Red=unaltered pyroxenes. Green=pyroxene and olivine intergrown with troilite.

Sulfide chemistry: All sulfides analyzed by electron microprobe (EMP) are troilite. In the troilite, Co ranges from 0.11 to 0.13 wt.%, Cu ranges from less than 0.01 to 0.03 wt.%, and Ni, Zn, and As are less than 0.01 wt%. Manganese is the only element that is different between the two textural types of troilite with Mn in the sulfide vein ranging between <0.01 to 0.017 weight percent and the replacement sulfide ranging between 0.025 and 0.054 wt.%. Compared to troilite in mare basalts, the sulfides in 67016,294 are lower in Ni, equivalent in Co, and higher in Mn.

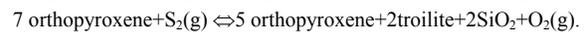
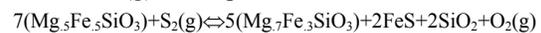
Sulfur Isotopes: The preliminary results of the sulfur isotopic analysis suggest that there may be compositional differences between the troilite veins and troilite associated with the orthopyroxene. The sulfur isotopic composition of the vein troilite is approximately $\delta S^{34}=0$ to 2.0 per mil, whereas the isotopic composition of the troilite associated with the orthopyroxene may be as high as 20 per mil. These results will be confirmed prior to the LPSC.

Discussion: There are at least two interpretations of the replacement textures. One interpretation is that the reaction preserved is olivine reacting with S gas to

form low Ca pyroxene. Based on the mineral chemistries, the reaction is approximately:



This reaction is similar to that proposed by [6] except that SiO_2 is required on the right side of the reaction. Starting with a more iron-rich olivine composition ($\sim Fo_{18}$) would produce much smaller amounts of SiO_2 and intergrowths consisting of a higher proportion of troilite (rather than 57% suggested in the above reaction). Alternatively, a reaction involving orthopyroxene and S (g) could produce the observed textures:



This reaction would produce a troilite/(troilite+opx) of 30% and excess SiO_2 . The latter is not observed in the intergrowths. All of these reactions require only S to be transported into the system. Closed-system behavior is also suggested for Mn, Cr, Co, and Ni, whereas the behavior of As and Sb have not yet been documented.

The preliminary S isotopic data suggest that S in the troilite-opx intergrowths has a isotopic composition that is enriched in S^{34} compared to the S in the troilite veins. If this is correct, it would suggest that the S veining and troilite-orthopyroxene intergrowths represent two different episodes of S transport with the S from each episode being derived from different reservoirs. The S isotopic composition of the troilite veining indicates an unfractionated S source similar to all magmatic S on the Moon [5]. This is consistent with models for S transport proposed by [6]. On the other hand, the enrichment in S^{34} in the intergrowths implies a source that has undergone S fractionation. Such an enrichment has been documented in lunar soils [8] and has been attributed to vaporization and ion sputtering during the evolution of the soil [8]. Sulfur derived from such a source could be accompanied by C-O-S (-N) as speculated by [5]. To confirm the initial measurements of S compositions will require further analyses of the sulfur isotopic compositions of the troilite in both the veins and intergrowths.

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