

Vapor element transport in the lunar crust. Open system transport of elements in the shallow lunar crust by anhydrous, isotopically light S-rich vapor. C.K. Shearer¹, P.V. Burger¹, Y. Guan², J.J. Papike¹, and S.R. Sutton³, 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, ³Department of Geophysical Science, Center for Advanced Radiation Sources, University of Chicago, Chicago, Illinois 60637.

Introduction: The existence of troilite fracture-fillings, veins and intergrowths with low-Ca pyroxene in plutonic rock clasts from a variety of lunar breccias (Figure 1) imply that elements have been mobilized in the lunar crust [1-4]. Numerous studies have speculated on the composition and source of these fluids, their capability for the transport of vapor-mobilized elements, and the scale and environment under which these types of process occurred [3,5-8]. These models all assumed a Moon with a very dry mantle, crust, and surface. However recently this assumption has been questioned and the role of H₂O in lunar processes has been investigated. Combining more traditional petrologic analytical approaches (optical microscopy, electron microprobe) with relatively newer instrumental approaches (Nano SIMS, Synchrotron X-ray Microprobe Analysis), we are reexamining these troilite veins and replacement textures in lunar samples to

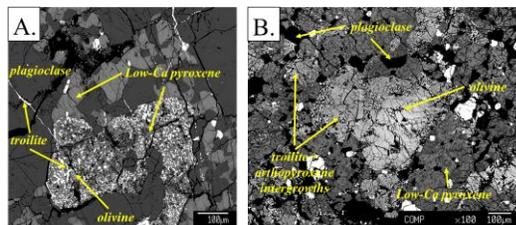


Figure 1. A. BSE image pyroxene-troilite intergrowth in 67016,294. B. BSE image illustrating the relationships between olivine and pyroxene-troilite intergrowths in 67915,149.

(1) differentiate among transport models (Figure 2) proposed by previous studies [3,5-8], (2) examine the potential for the involvement of indigenous (magmatic) or exogenous (solar wind, cometary) H (or OH, H₂O) in these types of models, (3) identify potential sources for the S and heat responsible for driving elemental migration, and (4) identify the potential scale of these processes and the environment under which they oc-

curred. These inquiries may provide a clearer understanding of volatile element transport in the lunar crust, the composition of such volatiles, and the existence of "mineral deposits" on the Moon.

Analysis: Several Apollo samples exhibiting sulfide veining and silicate replacement by sulfides were analyzed in this study: 67016,294, 67915,150, and 67016,297. In addition, sulfides in numerous mare basalts were analyzed and are reported in [9,10]. Sulfides were analyzed and imaged for major and trace elements using electron microprobe (EPMA) at the University of New Mexico and the synchrotron x-ray microprobe at the GeoSoilEnviroCARS sector (SXRF) [11] at the Advanced Photon Source (APS, Argonne, IL, USA). Furthermore, the sulfur isotopic composition of individual sulfides was analyzed using the Cameca nanoSIMS at the California Institute of Technology. In addition to the sulfides, silicate host and reaction phases were analyzed by EPMA and ion microprobe.

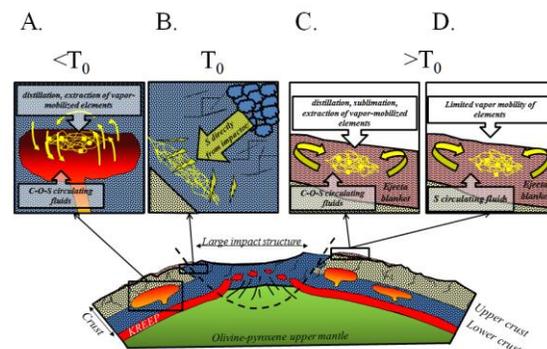


Figure 2. Potential models for the origin of troilite-pyroxene intergrowths observed in lunar breccias. A. Processes associated with the emplacement of intrusions in the shallow to deep lunar crust [3]. Heat and S is derived from the intrusions. B. Closely associated with the impact event that produced the breccias. The heat and S is derived from the impactor [5]. C and D. Process associated with ejecta blankets. The heat and S is derived from the ejecta blanket. The difference between these two models is that model C involves the mobility of numerous elements in addition to S [6], whereas model D requires only the mobility of S [7]. In all images,

the T refers to the time of the impact (s) that formed the breccias.

Results: Lunar samples 67016,294, 67915,150, and 67016,297 represent clasts of Mg-suite and ferroan anorthosite lithologies that have interacted with a S-rich vapor. The olivine in these lithologies is partially to totally replaced by troilite and low-Ca pyroxene. The troilite makes up 30 to 54 volume % of the troilite + low-Ca pyroxene pseudomorphs after olivine. Other silicates in the assemblages have experienced post-magmatic, pre-sulfurization reequilibration (pyroxene exsolution, recrystallization) and were not affected by the introduction of S. The troilite also occurs in veins cross-cutting individual phases and metamorphic textures. The sulfide veining and replacement features are restricted to individual clasts and do not cut across the matrix surrounding the clasts, and thus predates the breccia-forming event. The proportion of troilite to low-Ca pyroxene and silicate chemistries indicate that simple reactions (such as olivine + S₂ ↔ low-Ca pyroxene + troilite + O₂) do not adequately represent the replacement process. The sulfides exhibit some compositional variation and exhibit limited exsolution features. The sulfides have compositions that are similar to those found in mare basalts. In particular, the sulfides generally are enriched in Co relative to Ni. Exsolution of Ni-Co-Cu in the sulfides is distinctly different between the breccias and mare basalts and suggests a different cooling or crystallization (melt versus vapor) history. The sulfur isotopic composition of the vein and replacement troilite ranges from approximately $\delta S^{34} = -4.0$ to -8.0 ‰. Spinels in all clasts exhibit “exsolution” of ilmenite suggestive of post-crystallization reduction that appears to be contemporaneous with the sulfurization event.

Discussion: Based on our observations, it appears that the model suggested by Norman et al. [3] is the most appropriate for the origin of the troilite veining and troilite-pyroxene pseudomorphs after olivine. Our data and interpretations add significant definition to this proposed model. Interpretation of pyroxene exsolution indicates this process occurs in the relatively shallow lunar crust on a scale that involves vapor interaction with multiple plutonic lithologies of various ages and compositions. These reactions occur at distinct conditions of f_{S_2} , f_{O_2} , and temperature. The

reacting vapor is S-rich, and low in H. The reduction of the oxides in the clasts was not a product of H-streaming as has been suggested for similar textures in lunar rocks, but more likely related to “S-streaming”. Previous calculations and our modeling indicate that important S species in this vapor were COS, S₂ and CS₂. These vapors had the capability to transport other elements such as Fe and minor chalcophile-siderophile elements. However, a proportion of the minor elements making up the troilite (Fe, Ni, Co) did come directly from the olivine being replaced. The heat source driving the transport of element is closely tied to the emplacement of magmas into the shallow lunar crust. These magmas could be related to episodes of either Mg-suite magmatism or the earliest stages of mare magmatism. The fluids were most likely derived from indigenous sources (magmatic) and do not appear to have exogenous components. The process that drove the derivation of the S-rich volatiles from these intrusions was also instrumental in fractionating the isotopic composition of S from 0‰ in the magmas to -5‰ in the vapor phase. This fractionation was not controlled by the proportions of SO₂⁻² to H₂S, but more likely COS, S₂ and CS₂ species.

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Acknowledgements: GeoSoilEnviroCARS is supported by the National Science Foundation - Earth Sciences (EAR-0622171) and the Department of Energy - Geosciences (DE-FG02-94ER14466). Use of the APS was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract no. DE-AC02-06CH11357. X26A is supported by the Department of Energy (DOE) Geosciences (DE-FG02-92ER14244). Use of the NSLS was supported by DOE under contract no. DE-AC02-98CH10886.