Vapor element transport in the lunar crust. Implications for lunar crustal processes, water on the Moon and lunar ore deposits.

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Exploring the lunar crust

Chemical variation and bulk composition.

Processes at work in the lunar crust.

- Origin of the Earth-Moon system.
- Differentiation of the terrestrial planets.
- Effect of giant impacts on planetary evolution.

Thermal and magmatic history of the terrestrial planets.

Growth, and evolution of planetary crusts.

Role of volatiles in shaping the evolution of the crust of terrestrial planets.
Transport of vapor mobilized elements

- In planetary environments with stable \( \text{H}_2\text{O} \) in the crust (Earth, Mars), large impacts (i.e. Newsom, 1980; Naumov, 2002; Abramov and Kring, 2004 and references within) and emplacement of mantle derived magmas may generate extensive hydrothermal systems.

- Previously the Moon was considered to be dry by most standards, there are textures preserved in the lunar sample collection that imply the mobility of elements in this type of environment.

- Now with the potential for \( \text{H}_2\text{O} \) in the crust and mantle, does \( \text{H}_2\text{O} \) have a role in the mobility of elements in the lunar crust?
Sulfides in Apollo 16 Lunar Breccias

- Fragmental breccia: 67016 and 67915.

- Norman (1981) and Lindstrom and Salpas (1983) reported the existence of troilite fracture-fillings, veins and textures suggesting the replacement of silicates by troilite.

Transport of vapor mobilized elements
Models for S mobility in the lunar crust

A. \(<T_0\)
- Distillation, extraction of vapor-mobilized elements
- C-O-S circulating fluids

B. \(T_0\)
- S directly from impactor
- C-O-S circulating fluids

C. \(>T_0\)
- Distillation, sublimation, extraction of vapor-mobilized elements
- Ejecta blanket
- C-O-S circulating fluids

D. Limited vapor mobility of elements
- Ejecta blanket
- S circulating fluids

Large impact structure
Crust
KREEP
Olivine-pyroxene upper mantle
Upper crust
Lower crust
Analytical Design

- Electron microprobe imaging and x-ray mapping of sulfide veining and replacement features in A16 feldspathic fragmental breccia.
- Electron microprobe analyses of major & minor elements.
- Electron, ion microprobe and synchrotron x-ray microprobe (SXRF) for trace element analyses (Zn, Ni, Mn, Co, Cu, As, Se).
- NanoSIMS 50L used for the analyses of S isotopes.
Sulfide veining and replacement in A16 crustal lithologies
BSE images of S veining and silicate
Sulfide replacement of silicates

67016, 294

67915, 149
Origin of clasts
Potential Replacement Reactions

\[ \text{Olivine} + S_2(g) \rightleftharpoons \text{Enstatite} + 2\text{FeS} + O_2(g) \]

\[ 7(\text{Mg}_{0.6}\text{Fe}_{1.4}\text{SiO}_4) + 4S_2(g) \rightleftharpoons 6(\text{Mg}_{0.7}\text{Fe}_{0.3}\text{SiO}_3) + \text{SiO}_2 + 8\text{FeS} + 4O_2(g) \]

\[ 7 \text{olivine} + 4S_2(g) \rightleftharpoons 6 \text{orthopyroxene} + \text{SiO}_2 + 8 \text{troilite} + 4O_2(g) \]

\[ \text{Cr-rich ulvospinel} + H_2 \rightleftharpoons \text{ilmenite} + \text{Cr-rich spinel} + \text{Fe} + H_2O \]

\[ \text{Ilmenite} + H_2 \rightleftharpoons \text{rutile} + \text{Fe} + H_2O \]

Anhydrous fluid phase
Crustal environment of sulfide replacement

- **Ferroan Suite:** < 25 km
- **Sp Troctolite:** 16-25 km
- **Troct w/ Chm-Aug-Opx symplectite:** 42-50 km
- **Alkali suite:** very shallow, upper crustal emplacement

**Clasts with troilite replacement:**

- $T_{\text{crystallization}} = 1100^\circ\text{C}$
- $T_{\text{pyx. exsolution}} = 800\text{-}750^\circ\text{C}$
- Cooling rate $= 3.0\text{-}3.3 \times 10^{-2} \, ^\circ\text{C/\text{year}}$
- Depth of crystallization $= 0.5\text{-}0.7 \, \text{km}$
- Troilite veins cross-cut reequilibrated mineral phases.
- Olivine-S(g) experiments indicate troilite will form at $800^\circ\text{C}$, whereas pyrite will occur at low T ($600\text{-}650^\circ\text{C}$).
Trace element comparisons between mare basalt, vein, and replacement troilite

![Graph showing trace element comparisons between mare basalt, vein, and replacement troilite.](image-url)
Constrains on models for volatile element mobility

- S-metasomatism occurs in shallow lunar crust (0.5 km) most likely associated with the emplacement of Mg-suite magmas. Perhaps, a fairly large-scale process as it cross-cuts several different crustal lithologies.

- Pyroxene-Sulfide replacement texture is most likely a result of the reaction:

\[
\text{olivine} + S_2 \leftrightarrow \text{orthopyroxene} + \text{troilite} + 4O_2
\]

- “Fluid” phase is S-rich and anhydrous.

- These sulfides appear not be an enrichment in Ni, Co, Cu, Mn, Zn, As, or Sb relative to magmatic sulfides. However, due to changes in the modal abundance of troilite differences between unmodified and modified Mg-suite-FAN lithologies with regards to chalcophile elements are significant. Therefore, an open system existed with these elements being transported with the S.