

Chlorine distribution and its isotope composition, alteration mineralogy, and micro-textural analysis of “rusty rock” 66095. Implications for the petrogenesis of “rusty rock”, origin of “rusty” alteration, and volatile element behavior on the Moon. C.K. Shearer^{1,2}, Z. D. Sharp², F. M. McCubbin^{1,2}, A. Steele³, P.V. Burger¹, P.P. Provencio¹, and J.J. Papike¹. ¹Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131 (cshearer@unm.edu), ²Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, ³ Geophysical Laboratory, Carnegie Institute of Washington, Washington DC 20015

Introduction: “Rusty Rock” 66095 has produced significant debate concerning its origin, yet it has and will continue to reveal significant insights into the behavior of volatiles on the Moon. Most of 66095 is composed of a fine-grained, subophitic to ophitic impact melt-rock, which also contains a wide variety of lithic clasts [1,2]. Alteration is found in the interior as well as on the surface of 66095. A brownish alteration extends from margins of metallic iron grains into the adjacent silicates and consists of a variety of relatively low-temperature minerals [1-6]. The origin of this alteration, and hydrogen and oxygen isotopic signatures, have been attributed to alteration on the Moon [7,8] as well as to “terrestrial” alteration during or following transport to Earth [4,9]. Another interesting aspect of 66095 is its enrichment in ²⁰⁴Pb, Cd, Bi, Br, I, Ge, Sb, Tl, Zn, and Cl indicating that portions of this sample contains a volatile-derived component [e.g.10-14]. Similar enrichments have also been observed in Apollo 16 (A-16) soils [8,11-14]. The mineralogy of this component has not been fully described [8]. The origins of these enrichments have been attributed to fumarolic-hydrothermal [14], magmatic, or impact processes [11,12]. Here, we examine the Cl isotope composition and distribution of Cl in 66095 and selected soils from the A-16 site, and the alteration mineralogy of 66095 to gain additional insights into the petrogenesis of the rusty rock, the origin of the “rusty” alteration, and transport of volatiles in the lunar crust and on the lunar surface.

Analytical Approach: Three A-16 samples were analyzed in this study: “Rusty Rock” 66095 and two soils: 64501 and 61220. A JEOL 8200 electron probe microanalyzer was used to produce BSE images, X-ray maps, and point analyses of alteration in individual thin sections representing different portions of 66095 and soil samples. The $\delta^{37}\text{Cl}$ (where $\delta^{37}\text{Cl} = (R_{\text{sample}}/R_{\text{standard}} - 1)1000$ and $R = {}^{37}\text{Cl}/{}^{35}\text{Cl}$) was determined for 66095 and A16 soils using the method of Sharp et al. [15]. All data are reported relative to SMOC (Standard Mean Ocean Chloride, with a $\delta^{37}\text{Cl}$ value of 0‰). The alteration mineralogy of 66095 was explored on both thin sections and small sample split using Raman Spectroscopy following the approaches outlined in Steele et al. [16]. Four sample splits from different portions of 66095 are being examined and prepared by a FEI

Quanta 3D Field Emission Gun SEM/FIB for STEM/TEM analysis.

Distribution of Cl in 66095 and soils: Cl is heterogeneously distributed in 66095. Leachable Cl (in H₂O) ranges from 29 to 117 ppm [13,15], whereas bulk (leachable + non-leachable) Cl ranges from 10-400 ppm [17]. In the two soils studied, leachable Cl ranges from 16-19 ppm and non-leachable Cl is approximately 10 ppm [15]. Most likely, the distribution of Cl in thin sections represents the non-leachable components. As shown in BSE and X-ray maps (Fig. 1), Cl is closely associated with both FeOOH and phosphates. In the FeOOH, Cl is lowest directly adjacent to the metal and increases outward. Zinc enrichments are only associated with the troilite. They usually occur on the rim of the troilite and can make up greater than half of the individual grain. Major to minor abundances of phosphorous occurs in two phosphates (apatite, merrillite), schreibersite, metallic Fe, and FeOOH.

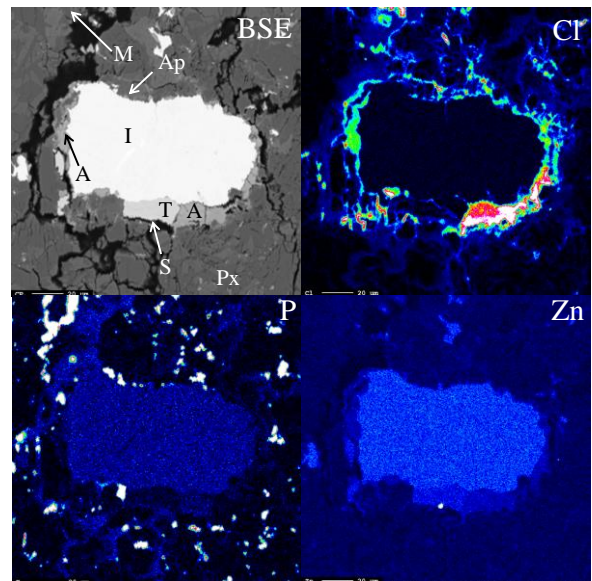


Figure 1. BSE image and Cl, P, and Zn x-ray maps of alteration in 66095. Mineral phases are identified in the BSE image: I=metallic iron, T=troilite, A= FeOOH, Ap=apatite, M=merrillite, S=sphalerite, Px=pyroxene.

Cl isotope composition of 66095 and A16 soils:

In 66095, the leachate had a Cl isotope composition of +14.0‰, whereas the non-leachable Cl has a composi-

tion of +15.6‰. The A-16 soils that were analyzed included mature soil 64501,232 ($I_s/FeO=61$) and immature soil 61220,39 ($I_s/FeO=9.2$). The leachate from mature soil (64501) had a Cl isotope composition of +5.6‰ and a non-leachable Cl composition of +15.7‰. The immature soil has a similar Cl isotope composition: the leachate has a Cl isotope composition of +6.1‰ and the non-leachable Cl component has a composition of +14.3‰. Like all the other lunar lithologies analyzed [15], the leachates have a lower $\delta^{37}Cl$ than the non-leachable Cl. (Fig. 2). There is no apparent correlation between $\delta^{37}Cl$ and soil maturity or other stable isotopes ($\delta^{34}S$, $\delta^{13}C$) (Fig. 3).

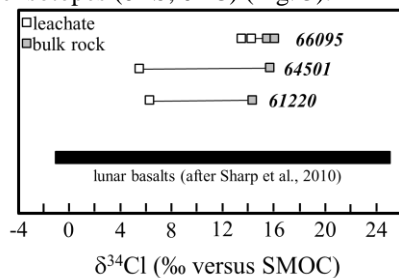


Figure 2. Cl isotopic composition of lunar basalts and A16 samples.

Alteration mineralogy: Taylor et al. [6] concluded that $\beta FeO(OH,Cl)$ (akaganeite) was the dominant iron hydroxide in 66095. Raman spectra collected on fracture surfaces of 66095 indicate the presence of other

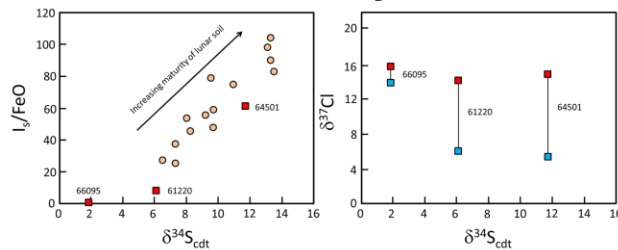


Figure 3. Relationships among Cl and S isotopic compositions and soil maturity.

low-temperature phases associated with the alteration veins. In addition to akaganeite, the Raman spectra indicate the occurrence of goethite ($\alpha FeOOH$), hematite, and rutile. Raman imaging indicates an intimate textural relationship between goethite and akaganeite. As illustrated in Fig. 1, the $FeOOH$ is the dominant non-leachable source of Cl in 66095. The textural relationships among these phases and their origin is further being studied by FIB-TEM. Carbon ranges from 10-90 ppm in 66095 and ~100 ppm for 61221[8]. Soil 61221 is special in that it has a relatively high carbon content and low maturity. Carbon compound cohenite (Fe_3C) in metallic iron was previously described by [5]. Thus far C-compounds associated with the alteration in 66095 have not been confirmed.

Discussion: The new data gathered on 66095 do provide some additional insights into the behavior of Cl on the Moon, and the origin of the volatile element enrichments and alteration in 66095 and A16 soils. There is no evidence that the Cl isotopic composition observed in the A-16 samples are a result of either the high-temperature event caused by impact or a contribution from the impactor. A high-T impact event should not have resulted in stable isotope fractionation. Further, Sharp et al. [15,18] has shown that volatile rich primitive meteorites exhibit fairly limited variation in $\delta^{37}Cl$. Volatile element enrichments in these A-16 materials (66095 and soils) are much more similar to enrichments observed in pyroclastic deposits at the A-15 and A-17 landing sites. Although these enrichments are similar, the Cl isotopic composition is distinct with the coatings on the orange glass exhibiting limited fractionation ($\delta^{37}Cl = -0.7\%$). Sharp et al [15] observed that unlike the Earth and most other materials in the solar system, samples from the Moon exhibited an extremely wide range of $\delta^{37}Cl$. They concluded that the bulk Moon had a $\delta^{37}Cl$ that was similar to Earth (~ 0 ‰) and that the wide variation of $\delta^{37}Cl$ (-0.7 to 24.5‰) was produced by volatilization of metal halides during the eruption of low-H basalts and/or following the loss of H from lunar basalts.

Unlike the lunar basalts, 66095 represents an impact melt rock produced by near-surface processes rather than mantle melting. The enrichments observed in 66095 may reflect near-surface fumarolic activity with the driving heat source being linked to either shallow emplacement of basalts or impact derived melt sheets. This activity could be somewhat analogous to much more recent surface degassing phenomena observed by [19]. The difference in Cl isotopic composition between 66095 and lunar pyroclastic deposits may be the result of the extent and timing of Cl loss during fire-fountaining as opposed to fumarolic activity.

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