

SUB-MICRON CHEMICAL AND STRUCTURAL COMPLEXITIES WITHIN SHOCKED LUNAR APATITE

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Introduction: Apatite is a key accessory mineral widely used for studying the volatile composition [1-5] and absolute ages of planetary materials [6]. The relevant research mostly focuses on studying its volatile content, considered as a proxy for understanding the history of volatiles in planetary bodies, as well as to fingerprint the sources of volatiles through their isotopic signatures. There is a clear need to contextualize geochemical data with impact-induced features, given that most of the planetary materials experienced at least minimal shock deformation. This study aims at understanding the effect of shock on internal structure of apatite and consequences thereof on distribution of geochemically relevant elements, mostly H, Cl, and Pb.

Sample and methods: This study focuses on an apatite from Apollo 17 heavily-shocked norite of cumulate origin (78236), that experienced shock deformation of stage S5-S6 [>50 GPa], based on existing shock-pressure barometers [7]. Electron Backscatter Diffraction (EBSD) and Transmission Electron Microscopy (TEM) were used to gain insights into sub- μm scale structural complexities. NanoSIMS was used to measure H_2O content and δD values in apatite [after protocols in e.g. 4, 5] whereas Atom Probe Microscopy (APM) was used to analyse structural and chemical variations at nm-scale. APM, however, cannot reliably assess H/ H_2O content.

Results: Based on EBSD mapping we find that apatite in 78236 has degraded crystallinity, high density of low angle grain boundaries within domains of μm - to sub- μm granular crystalline features, as well as significant portions that do not yield indexable diffraction patterns at the lengthscales of EBSD analysis ($\sim 100 \times 50$ nm). No obvious signs of recrystallization were evident at EBSD length-scales. The entire apatite grain appears to preserve one dominant orientation, despite severe crystal-plastic deformation (up 25° of misorientation within a single grain). Stable throughout TEM analysis, shocked apatite indicated good overall crystallinity, appearing finely granular with crystallites ranging in size from $\sim\text{nm}$ to $\sim\mu\text{m}$ scale. Gradual change in grey scale in bright field (BF) images reveals severe deformation of larger crystallites ($\sim 1\mu\text{m}$), whereas a sharp BF contrast of ~ 50 to 100 nm crystallites implies their good crystallinity. The smaller crystallites form grain boundaries meeting at 120° triple junctions. This equilibrium texture is probably accommodated by annealing and nanoscale recrystallization of apatite exposed to post-shock heating from the surrounding impact melt. The atom probe lift outs were selected from the area dominated by smaller crystallites. A total of 8 tips were investigated, all of which were remarkably stable during the acquisition, despite their granular nature. The complex microstructure of the well-developed 50 to 100 nm grains with clear 120° grain boundaries are defined by segregation of Mg, Si and Fe impurities, which possibly diffused from surrounding pyroxene and merrillite. Distribution of Pb is homogenous throughout the grain, with almost undetectable segregation within grain boundaries. Chlorine is detected in high concentrations, and shows homogenous distribution of ^{35}Cl and ^{37}Cl over the length scale of the APM analysis (1 to 500 nm). Homogenous chlorine distribution is in agreement with previous NanoSIMS work [5] on a variety of lunar rocks, suggesting its original distribution is not modified by shock. On the other hand, H_2O composition measured by NanoSIMS in this study, sampling the areas with smaller (recrystallized) and larger crystallites by NanoSIMS separately, reveal ~ 250 and ~ 550 ppm H_2O , respectively. While the measured abundance is consistent with the lower range of reported values for this rock [4], we find that the lower water content is isotopically lighter ($\delta\text{D} = -388 \pm 135$ ‰, CRE corrected) compared to the other spot ($\delta\text{D} = -140 \pm 150$ ‰, CRE corrected) and previously reported values. Low- δD of finely grained apatite could have been influenced by D-poor lunar regolith that was in contact with the impact melt.

Conclusion: Shocked lunar apatite was investigated at unprecedented scale to clarify μm to sub- μm distribution of geochemically relevant elements. The collected dataset suggests that the impact event(s) and related annealing of apatite induced diffusion of impurities (Mg, Fe, Si), probably affected distribution of Pb but did not affect Cl. Although intracrystalline inhomogeneity of H_2O -content and related δD was also observed in unshocked apatites, we argue that in this case low- δD values recorded by apatite with low H_2O -content are accommodated by shock-induced structural degradation. **References:** [1] Hughes J. M. (2015). *Am.Min.* 100, 1033–1039. [2] McCubbin F. et al. (2015) *Am.Min.* 100, 1668–1707. [3] Hauri et al. (2017) *Ann.Rev.* 45, 89–111. [4] Barnes J. et al. (2014). *EPSL* 180, 244–252. [5] Barnes et al., 2013, *Chemical Geology* 337–338, 48–55. [6] Thiessen F. et al. (2017) *MAPS* 52, 584–611. [7] Rubin et al. (1997). *GCA* 61, 847–858.