

SHOCK-INDUCED DECOMPOSITION OF ARMALCOLITE DURING LITHIFICATION OF LUNAR REGOLITH. T. R. Du¹, A. C. Zhang¹, J. N. Chen¹, and Y. Y. Wen². ¹School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China, ²Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China, E-mail: dutianran@foxmail.com

Introduction: Shock lithification of fine-grained regolith is a ubiquitous process on the airless planetary bodies [1, 2]. It can make regolith breccias with high mechanical strengths. Meanwhile, potential thermal effects during shock lithification may modify the mineralogical and isotope features of the constituents in regolith breccias to various degrees, which are critical to precisely decipher the evolution history of planetary bodies. However, quantitatively or semi-quantitatively constraining thermal effects in lithic and mineral clasts during shock lithification of regolith breccias is very challenging. In this study, we report the micro-textures of two types of armalcolite in the lunar meteorite Northwest Africa (NWA) 8182. We suggest that some of the micro-textures are related to shock-induced decomposition into rutile + ilmenite + spinel of armalcolite, which provides a semi-quantitative constraint on the thermal effects in lithic clasts during strong shock lithification of regolith breccias.

Methods: A Zeiss Supra 55 field-emission SEM was used for petrographic observation. Chemical compositions were measured by a JEOL 8530 field-emission EPMA. Two FIB sections were observed using a FEI Tecnai F20 TEM. Selected area electronic diffraction, Fast Fourier Transform patterns of high-resolution TEM images, high angle annular dark-field observation, energy-dispersive X-ray analysis and elemental mapping were performed for structure and composition.

Results: NWA 8182 is a strongly shock-lithified lunar regolith breccia [3]. Lithic clasts and mineral fragments in this meteorite are largely cemented by glassy matrix, which usually contains Mg,Fe-rich tissantite (a high-pressure mineral) and vesicles. Clast-20 is an Mg-suite lithic clast of approximately 1.3 x 0.7 mm in NWA 8182 [4]. It is also surrounded by tissantite- and vesicle-rich glassy matrix; however, the glassy matrix surrounding Clast-20 exhibits a large variation in width (30–200 μm). Clast-20 consists mainly of plagioclase, olivine, and pyroxene. Pyroxene includes both high-Ca pyroxene ($\text{En}_{48.8-51.0}\text{Fs}_{5.1-6.3}\text{Wo}_{42.6-46.2}$) and low-Ca pyroxene ($\text{En}_{84.2-84.9}\text{Fs}_{12.3-12.7}\text{Wo}_{2.5-3.1}$), which are present as discrete grains or intergrowths. The two-pyroxene equilibrium temperature is $\sim 1030^\circ\text{C}$ [4]. Accessory minerals in this lithic clast are Ti-rich oxides (ilmenite, armalcolite, loveringite, and rutile), chromite, Ca-phosphate minerals, Fe-Ni metal, and Fe-sulfide.

Two types of armalcolite grains with similar compositions ($\text{Mg}\# \sim 0.6$) but different micro-textures are present in Clast-20. The first type includes two small grains ($\sim 10\ \mu\text{m}$ in grain size), which are composed of three tiny phases of different brightness in BSE images (Fig. 1). The two grains are close to each other and adjacent within a distance of $< 5\ \mu\text{m}$ to the tissantite- and vesicle-rich thick matrix. The other type contains abundant small grains throughout the lithic clast and is characterized by tiny bright ilmenite inclusions in BSE images (Fig. 2). The second type of armalcolite grains are either homogeneous or heterogeneous in BSE images. The EPMA data shows that both types of armalcolite grains contain a small amount of Al_2O_3 (0.3–1.4 wt%).

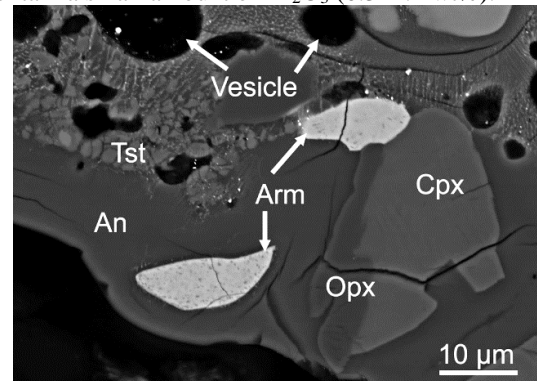


Fig. 1: BSE image of armalcolite pseudomorphs in Clast-20. Tst=tissantite; An=anorthite; Cpx=high-Ca pyroxene; Opx=orthopyroxene; Arm=armalcolite.

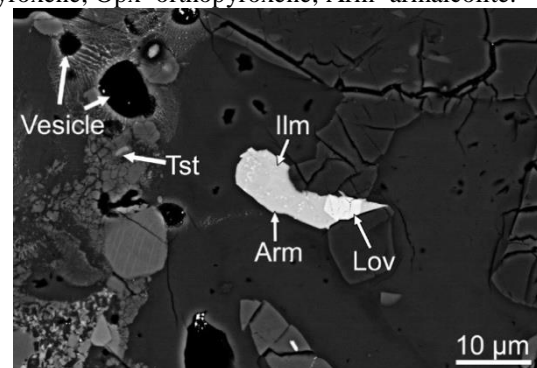


Fig. 2: BSE image of one heterogeneous armalcolite grain containing ilmenite inclusions. Arm=armalcolite; Ilm=ilmenite; Lov=loveringite; Tst=tissantite.

Two FIB sections were prepared from both types of armalcolite grains with roughly similar distances from the glassy matrix. The TEM observations show that the first type of armalcolite in fact is an assemblage of granular ilmenite, rutile and spinel with the triple-junction

texture, indicating that the two grains are armalcolite pseudomorphs. Locally, a few loveringite grains are also present. The other FIB section is dominated by armalcolite with minor ilmenite, which also shows the triple-junction structure in some regions. No rutile and spinel grains were observed.

Discussion and conclusion: Previous investigations show that the Fe-Ti-O and Mg-Ti-O systems have similar phase diagrams [5, 6]. The Ti-deficient pseudobrookite phase may decompose into an assemblage of pseudobrookite + ilmenite and ilmenite + rutile at different temperatures, respectively [5, 6]. It is reasonable to assume that Ti-deficient armalcolite, which has a pseudobrookite structure, may also have a similar phase diagram, although no similar phase diagram near liquidus temperatures has been reported for the Mg-Fe-Ti-O system. Due to the similar mineral assemblages, the micro-textures of armalcolite in Clast-20 can be explained by the decompositions of Ti-deficient armalcolite at different temperatures. The ilmenite inclusions in armalcolite are the decomposition products of Ti-deficient armalcolite at relatively high temperatures. However, the ilmenite and rutile in armalcolite pseudomorphs are the decomposition products of armalcolite at relatively low temperatures; the spinel in pseudomorphs is a byproduct of this process. Phase diagram of ferropseudobrookite-karrooite shows that Mg-rich armalcolite ($Mg\#=0.6$) is stable above 950 °C and will completely decompose into rutile plus ilmenite at ~780 °C [7]. However, the presence of trivalent cations (e.g., Al^{3+} , Cr^{3+} , and Ti^{3+}) may enhance the stability field of armalcolite to the lower temperatures by 50–100 °C [8]. Therefore, in Clast-20, the lower limit of the temperature for the formation of the ilmenite inclusions in armalcolite would be 850–900 °C. And, the upper limit of the temperature for the formation of rutile + ilmenite + spinel is ~700 °C.

Different spatial distributions of the two types of armalcolite in Clast-20 may require one uneven thermal event or two different thermal events. Thermal metamorphism and shock metamorphism are the two important heat-related processes during evolution of planetary rocks [9]. The presence of exsolution in pyroxene indicates that Clast-20 did experience a thermal metamorphic event at ~1030 °C [4]. However, thermal metamorphism usually has a homogeneous temperature distribution at a scale much larger than that of Clast-20. During thermal metamorphism of Clast-20, the relatively low-T (~700 °C) decomposition of armalcolite is not expected to occur. Therefore, thermal metamorphism cannot account for the presence of the armalcolite pseudomorphs in Clast-20. Impact event can produce heterogeneous temperature rises in rocks. Given the absence of local melting in Clast-20, if the formation of

the ilmenite inclusions in armalcolite was caused by an impact event, its widespread presence may require a rather high post-shock temperature across Clast-20. This would contradict with the presence of armalcolite pseudomorphs, which formed at a relatively lower temperature. Meanwhile, the absence of maskelynite and local melting of plagioclase and pyroxene in Clast-20 also argues against a post-shock temperature up to ~900 °C, instead suggest a post-shock temperature < 300 °C [10]. Therefore, it is highly unlikely that both types of decomposition textures of armalcolite in Clast-20 were produced by a common impact event.

Instead, the two types of decomposition textures could be attributed to two different thermal events. The thermal metamorphic event that Clast-20 experienced may account for the formation of the ilmenite inclusions in armalcolite. This interpretation is consistent with the temperature range (> 850–900 °C) inferred from phase diagram of ferropseudobrookite-karrooite. Subsequently, an impact event caused the formation of the two armalcolite pseudomorphs at the margin of the clast, but did not affect most of the armalcolite grains in the clast. Since the glassy matrix contains high-pressure mineral tschermakite and vesicles is closely adjacent to the two armalcolite pseudomorphs, the impact event may be the one that caused the lithification of NWA 8182.

The formation temperature of the armalcolite pseudomorphs should be lower than ~700 °C. However, considering the efficiency of elemental diffusion in armalcolite during the short impact event and the stability of rutile [11], the real decomposition reaction probably took place around 600 °C or at slightly higher temperatures. Such a high temperature rise at the margin of lithic clasts in strongly shock-lithified regolith breccias may have an important effect on elemental diffusions and isotope systems whose closure temperatures are lower than or approaching 600 °C.

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