Subsolidus breakdown of armalcolite: Constraints on thermal effects during shock lithification of lunar regolith

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ABSTRACT

Shock lithification of regolith breccias is a ubiquitous process on the surfaces of airless planetary bodies and may induce thermal effects, including melting on regolith breccia minerals. However, potential thermal effects on lithic and mineral clasts in regolith breccias have seldom been quantitatively constrained. Here, we report two types of micro-textures of armalcolite [(Mg,Fe3+)TiO5] in an Mg-suite lithic clast from lunar regolith breccia meteorite Northwest Africa 8182. One type of armalcolite contains oriented fine-grained ilmenite grains; the other occurs as an aggregate of ilmenite, rutile, spinel, and loveringite. We propose that the two types of micro-textures formed through subsolidus breakdown of armalcolite by different processes. The formation of ilmenite inclusions in armalcolite is related to slow cooling after the solidification of its source rock, whereas the ilmenite-rutile-spinel-loveringite aggregates probably formed during the shock lithification event of NWA 8182. The results indicate that the temperature at the margin of lithic clasts could be raised up to at least 600 °C during strong shock lithification of lunar regolith and has profound thermal effects on the mineralogical and isotopic behaviors of lithic and mineral fragments in lunar regolith breccias.

Keywords: Armalcolite, subsolidus breakdown, shock lithification, lunar regolith, lunar meteorite

INTRODUCTION

Lunar regolith is loose, fine-grained material on the surface of the Moon. It holds key information about the formation and evolution of the Moon and the interaction between surface materials and harsh space environments (Heiken et al. 1991). Lunar regolith is inevitably subjected to cycles of fragmentation, comminution, agglutination, compaction, and lithification during its long-term residence on the surface of the Moon. Shock lithification is the major process that generates regolith breccias from fine-grained regolith material (Kieffer 1975; Spray 2016). Kieffer (1975) has qualitatively divided shock lithification into strong and weak shock lithification based on the presence or not of shock-induced glass and new crystalline phases, respectively. The shock metamorphic conditions of strongly shock-lithified breccias may vary from 5–10 GPa to near or in excess of 60 GPa (Kieffer 1975; Schaal and Hörz 1980). Many lunar meteorites and Apollo lunar breccias formed by strong shock lithification (Kieffer 1975; Taylor et al. 1991; Spray 2016; Zhang et al. 2021). The high-temperature melt generated during strong shock lithification can have profound thermal effects on the mineralogical features of the lithic and mineral fragments in lunar regolith breccias (e.g., Gibbons et al. 1975; Simonds et al. 1976; Zhang et al. 2021 and references therein).

Previous investigations have largely discussed the potential thermal effects during strong lithification of lunar regolith, such as fusion-crystallization (Warner 1972; Warner et al. 1973), sintering (Simonds 1973; Uhlmann et al. 1975), diffusion and overgrowth formation (Warner 1972), thermally activated degassing (Williams 1972), and formation of high-temperature and high-pressure minerals (Zhang et al. 2021). However, most of these investigations focused on the thermal effects on the fine-grained matrix phases among coarse-grained lithic and mineral fragments. In contrast, potential shock-lithification thermal effects on lithic and mineral fragments in lunar breccias, which are usually the major materials to be studied to constrain the geological processes and evolution history of lunar rocks, are less constrained.

Armalcolite is a Ti-Mg-Fe oxide mineral (theoretical formula Mg0.5(Fe0.5Ti)xO2, x = 0–1) discovered in Apollo 11 samples with the pseudobrookite structure (Anderson et al. 1970). It is present in many Apollo basaltic samples and lunar meteorites (e.g., Anderson et al. 1970; Haggerty et al. 1970; Steele and Smith 1972; Haggerty 1973; El Goresy et al. 1974; Williams and Taylor 1974; Stanin and Taylor 1979; Treiman and Gross 2015; Zhang et al. 2020). Previous experimental investigations based on the TiO2-FeO system have demonstrated that high-temperature nonstoichiometric ferropseudobrookite [Fe1+2x/3Ti2-(x/3)O3, x = 0–1], which is isostructural with armalcolite, will experience two-stage subsolidus breakdown reactions with decreasing temperature (Lindsley 1991). At high temperatures, nonstoichiometric ferropseudobrookite may transform into stoichiometric ferropseudobrookite (FeTiO3) and ilmenite/rutile, depending on its initial compositions. At lower temperatures, ferropseudobrookite becomes unstable and will break down into ilmenite and rutile (Lindsley 1991). Experiments on the...