Apollo 15 regolith breccia provides first natural evidence for olivine incongruent melting

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ABSTRACT

The Apollo 15 mission returned various samples of regolith breccias, typical lunar rocks lithified by impact events on the Moon’s surface. Here we report our observations on shock features recorded in a section of the Apollo Sample 15299. We observe the presence of ferropericlase crystals confined in a shock-melt pocket and conclude that their formation is related to a shock-induced incongruent melting of olivine. While predicted by experiments, this phenomenon has never been observed in a natural sample. The incongruent melting of olivine provides an important signature of melting under high-pressure conditions and allows for estimating the pressure-temperature (P-T) experienced by the studied sample during the impact event. We infer that the fracture porosity that likely characterized the studied sample prior to the shock event critically affected the P-T path during the shock compression and allowed the studied sample to be subjected to elevated temperature during relatively low shock pressures.

Keywords: Ferropericlase, olivine incongruent melting, Apollo 15

INTRODUCTION

Collisional processes are integral to the formation and evolution of rocky planets in the Solar System and likely beyond (e.g., Morbidelli et al. 2012). Impacts can result in the propagation of shock waves triggering a temporary but rapid increase in pressure (P) and temperature (T). Such events can leave a record in terms of shock features, including shock-melt pockets and veins in both impactor and impacted bodies (Langenhorst and Hornemann 2005), as shown in recovered meteorites (Gillet and El Goresy 2013). Shock-related phase reactions and transformations can be used to constrain dynamic event(s) in terms of P-T conditions and hence can be used to define the shock event history of the studied sample (Gillet et al. 2007).

The presence of numerous impact craters on the Moon’s surface provides evidence for a long history of dynamic events, and shock-induced phase transformations are relatively common in lunar meteorites (e.g., Kayama et al. 2018; Miyahara et al. 2013; Ohtani et al. 2011). However, the description of high-pressure polymorphs in lunar rocks is limited to the single case of stishovite (Kaneko et al. 2015).

Olivine [α-(Mg,Fe),SiO3] is the most common rock-forming mineral of Earth’s upper mantle (Frost 2008). Along the mantle geotherm, olivine transforms into β-(Mg,Fe),SiO3 wadsleyite at ~410 km depth. Wadsleyite transforms into γ-(Mg,Fe),SiO3 ringwoodite at greater depths (~520 km) (Frost 2008), which eventually dissolves into an assemblage of (Mg,Fe)O ferropericlase + (Mg,Fe)SiO3 bridgmanite in the lower mantle (660–670 km depth) (Ito and Takahashi 1989). Shock-induced phase transitions of olivine into wadsleyite and/or ringwoodite, as well as the dissociation into (Mg,Fe)O ferropericlase + (Mg,Fe)SiO3 bridgmanite, have been previously reported in shocked meteorites and used to constrain the P-T conditions of the impact event that lead to their formation (Miyahara et al. 2011, 2016; Tschauner et al. 2014; Bindi et al. 2020). While this phase transition sequence is expected along a typical geotherm, olivine can melt incongruently at pressures as low as 10–15 GPa when subjected to high temperatures (~2200 °C), leading to the formation of ferropericlase (Mg,Fe)O + liquid (Presnall and Walter 1993; Ohtani et al. 1998).

Here we investigated a shock-melt pocket contained in a lunar rock polished section (Apollo Section 15299,247) combining Raman spectroscopy, field emission gun scanning electron microscopy (FEG-SEM), and transmission electron microscopy (TEM). Our results provide the first observation of ferropericlase with the estimated composition of (Mg0.05–0.08Fe0.95–0.92)O in a lunar rock. By combining our observation with previous findings, we conclude that the lunar ferropericlase has been formed by incongruent melting of olivine induced by a dynamic event. We speculate that the fracture porosity characteristic of lunar rocks translates into elevated temperature even at relatively low shock pressures.

MATERIALS AND METHODS

The Apollo Section 15299,247 (hereafter S247) was obtained from a lunar rock collected during the Apollo 15 mission, Sample 15299, collected in the vicinity of station 6 (Swann et al. 1972). An extensive description of modal petrology, as well as the chemistry of the main mineralogical constituents of this and other Apollo 15...