Element diffusion rates in lunar granulitic breccias: Evidence for contact metamorphism on the Moon

JILLIAN A. HUDGINS, JOHN G. SPRAY, and CHRISTOPHER D. HAWKES

ABSTRACT

Lunar granulitic breccias are a group of clast-bearing impact-melt lithologies that have been brecciated, and then metamorphosed at high temperature (∼1000 °C) to generate annealed (granoblastic to poikiloblastic) textures. They are ubiquitous among lunar samples, but occur in small volumes, typically as clasts in other lunar rocks. We have determined major, minor, and trace element diffusion profiles in olivines, orthopyroxenes, and clinopyroxenes from one Apollo 16 (60035), three Apollo 17 (77017, 78155, 79215), and two paired lunar meteorites (NWA 3163 and NWA 4881) by means of electron microscopy and electron probe microanalysis. The results show that relic igneous clasts exhibit an absence of, or limited, major element zoning, yet retain minor and trace element profiles. We exploit this characteristic to estimate the duration of high-temperature metamorphism responsible for their recrystallization. To achieve this we have completed pyroxene thermometry, element linescans, X-ray mapping, and modeling of heating and cooling of hanging wall and footwall lithologies juxtaposed with a hot body. The high equilibration temperatures, moderately high siderophile contents, and time scales of metamorphism of the lunar granulites indicate that they were metamorphosed in relatively near-surface settings. Diffusion calculations indicate that most granulitic breccias were heated for 13,000–300,000 yr. We conclude that they formed above or beneath superheated impact-melt sheets associated with medium-size (100–200 km) craters.

Keywords: Lunar geology, diffusion, trace element zoning, thermometry, superheated impact-melt sheets, contact metamorphism

INTRODUCTION

Understanding igneous and metamorphic processes on the Moon is challenging due to a lack of in situ material and because most lunar samples have undergone multiple episodes of brecciation and/or thermal re-equilibration after initial formation. Lunar granulitic breccias are metamorphic rocks that have been recovered at most Apollo and Lunar mission sites, and within non-mare lunar meteorites (e.g., ALHA 81005, NWA 3163, SaU 300). They are commonly manifest as lithic clasts in non-metamorphosed host breccias (e.g., Hudgins et al. 2007), though a limited number of monolithic samples have been discovered (e.g., 77017, 78155, and 79215). Both the surface-recovered and meteoritic granulitic breccias possess granoblastic to poikiloblastic textures that require high-temperature annealing at ∼1000 °C, which has resulted in partial to complete recrystalization (Warner et al. 1977; Lindstrom and Lindstrom 1986). They typically comprise >80% plagioclase and <20% mafic minerals, metals, and oxides, and they exhibit elevated siderophile element concentrations, indicating a significant impactor contribution to their chemistry (i.e., a history influenced by impact cratering events). Their bulk compositions are considered by Lindstrom and Lindstrom (1986) to approximate the average lunar highlands crust. Most granulitic breccias are derived from impact-melt breccias generated via multiple bombardments of the anorthositic crust, which were subsequently metamorphosed at high temperature (Cushing et al. 1999). Compositionally, granulitic breccias can be divided into two groups: ferroan (plagioclase > pyroxene > olivine) and magnesian (plagioclase > olivine > pyroxene) (Lindstrom and Lindstrom 1986). The granulitic breccias have low but variable abundances of incompatible trace elements, which distinguishes them from most other Apollo polymict breccias (Warner et al. 1977; Lindstrom and Lindstrom 1986). Metamorphic age data are limited. The granulitic breccias that have been dated from Apollo range from ∼4.2 to ∼3.8 Ga (Hudgins et al. 2008), whereas meteorites can yield younger ages (e.g., ≤3.5 for NWA 3163 and paired stones; Fernandez et al. 2009; Hudgins et al. 2011). Coupled with a lack of contamination by K-, rare earth element, and P- (KREEP)- rich materials, and chemistries indicative of the ancient (>4 Ga) upper crust, the older (>3.8 Ga) granulitic breccias have the potential to provide insight into the Moon’s elusive pre-Nectarian history. In contrast, the younger granulitic breccias require post-late heavy bombardment (LHB) metamorphic processing.

There is negligible evidence of plastic deformation in the granulitic breccias and, in this respect they can be likened to high-temperature terrestrial hornfelses. Two distinct sources of heat for metamorphism have been proposed: (1) juxtaposition with impact-melt sheets or hot ejecta blankets (i.e., near surface at low pressures for short periods of time) and (2) burial within the lunar crust (i.e., higher pressure conditions for longer periods of time). Determining the duration of metamorphism for the granu-