LUNAR GRANULITIC BRECCIAS AND THEIR ROLE IN UNDERSTANDING THE LUNAR MANTLE AND LARGE IMPACT EVENTS.

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Introduction: Lunar granulitic breccias are a diverse group of rocks that have been thermally metamorphosed, producing a granular texture from which their name derives. Their compositional diversity is shown by the variation in mg#, the molar ratio Mg/(Mg+Fe) [1], which ranges from 0.56 to 0.89. Their thermal histories and clear evidence for brecciation indicate a connection with impact processes in craters in the 100–200 km size range [2,3]. Coupled with the diversity in composition, it is clear, as Hudgins et al. [3] state that "granulitic breccias are the products of a common process and not a common event." Norman et al. [4] suggest that formation of at least one granulitic breccia, 67955, could have involved crystallization in an impact-melt sea (10-20 km thick) produced during a much larger, basin-forming event. We summarize the current state of knowledge of the lunar granulite suite, focusing on compositional diversity and thermal histories.

Textures: Lunar granulites are all breccias. In most of them minerals are uniform in composition, though two are clearly polymict. They are cataclastic, with remnant clasts set in a finer-grained, metamorphosed matrix; in several cases clasts are granulitic and the matrix is fragmental. More than one episode of breccia makes classification difficult, but the broad categories defined by Cushing et al. [2] are useful. They define three groups: (1) granulitic, which are entirely metamorphic; (2) granulitic-poikilitic, which are very similar to the granulitic samples, but contain poikilitic pyroxene crystals in the matrix (perhaps indicating some partial melting during metamorphism); and (3) poikilitic samples, which are coarse-granied and have igneous textures with pyroxene oikocrysts often 1 mm in length. The coarse poikilitic samples have been interpreted as impact melts [2,4]. Because of the similarty in texture and grain size we combine the first two categories, giving simpler and usable categories of granulitic and poikilitic, which make up the "granulitic suite."

Compositions: The granulitic suite varies in chemical composition and mineral abundances, as show in Fig. 1 (mg# versus modal plagioclase) and Fig. 2 (mg# versus modal olivine in the mafic assemblage). There are distinctive correlations between mg# and decreasing plagioclase and increasing olivine, suggesting that the rocks might be mixtures of a mafic component with ferroan anorthosite. The mafic component could be either troctolic highland rocks or mantle rock excavated by large impacts. The amount of orthopyroxene to high-Ca pyroxene increases with mg# (Fig. 3), indicating that the orthopyroxene was derived from a magnesian noritic or orthopyroxenitic component.

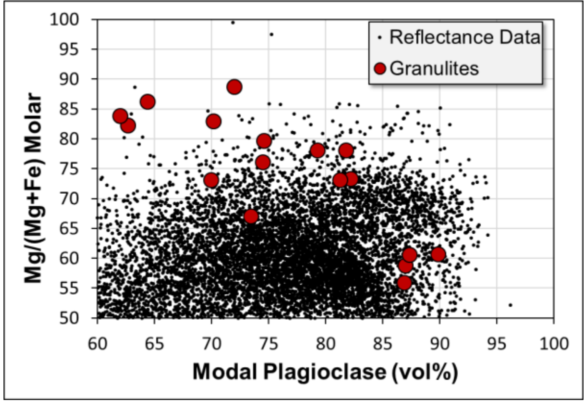

Fig. 1. Modal plagioclase vs bulk mg# in granulite suite rocks [12-14] compared to these parameters in the lunar highlands as determined from reflectance spectra [5].

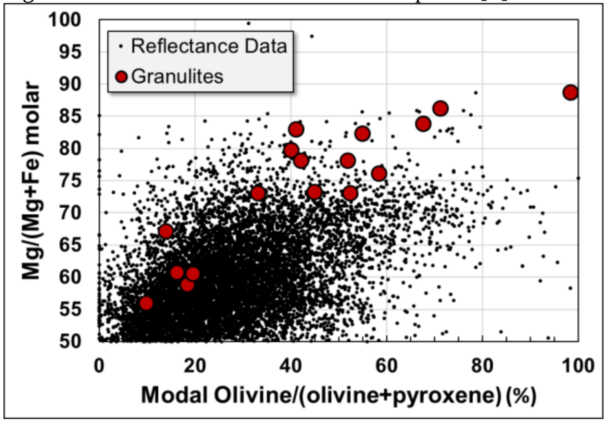

Fig. 2. Modal olivine in mafic assemblage vs mg# in bulk rock for the granulitic suite [12-14] compared to these parameters in the lunar highlands as determined from reflectance spectra [5].

The granulitic suite rocks are consistent with an origin in the feldspar-rich highlands, as shown by a comparison (Figs. 1 and 2) of the granulite data with mineral abundances extracted from reflectance spectra [5]. The spectral data are binned to 2-degree pixel size. In general, the mg# of the granulites are in the upper range of values found for the global dataset, suggesting a mixing of feldspathic components with a more mafic component with higher mg#. While we cannot rule out the presence of troctolites and norites in the granulite protoliths, the data are consistent with the granulitic suite being an impact mixture of ferroan anorthosite crustal rock and mantle rock rich in forsteritic olivine, implying overturn of early magma ocean cumulates before formation of the granulites.

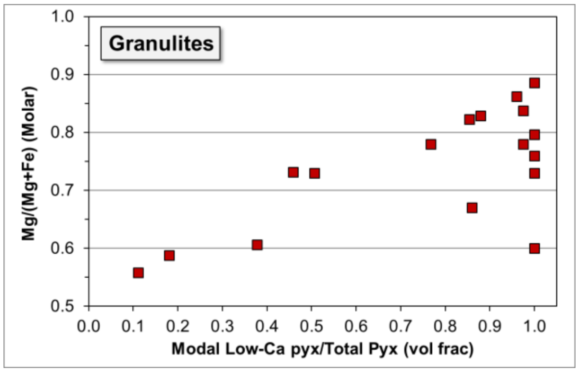

Fig. 3. Modal abundance [12-14] of orthopyroxene to total pyroxene.

Thermal histories: The conditions of metamorphism or melting of the granulitic suite can place constraints on where in a crater or basin setting the rocks were mixed and heated. An origin by contact metamorphism in an impact melt sheet in a ~100 km crater [2,3] implies a drastically different thermal history than an origin as a cumulate in an impact melt sea 10 km thick [4]. Previous work suggests that metamorphic temperatures were high (most >1000°C), as determined by two-pyroxene thermometry [2.3]. In preparation for new measurements of cooling histories, we compiled the published pyroxene data for granulites and calculated their two-pyroxene equilibrium temperatures (Fig. 4). Temperatures were determined using three different techniques [6-8]. All results are the same within stated uncertainties (±50°C), but to avoid scatter caused by the small differences between methods, we report only the temperatures calculated by [6].

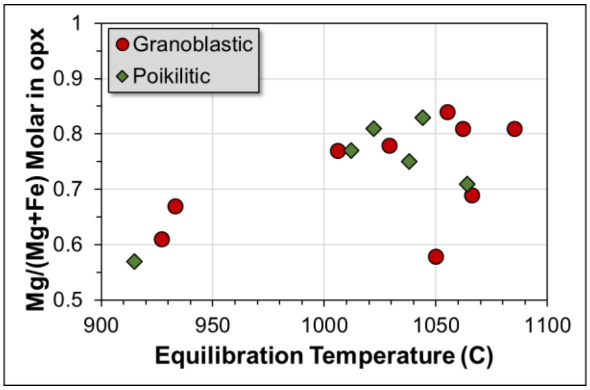

Fig. 4. Two-pyroxene equilibration temperatures plotted against mg# in orthopyroxene. Temperatures calculated using one method [6]; pyroxene data from [2-4,11].

The temperatures for most of the samples exceed 1000°C, and all are >900°C. Most high-Ca pyroxene occurs as exsolution lamellae or small grains in the matrices of the rocks, averaging <10 µm across. Using the augite diffusion coefficient of [9] for the C-direction in a crystal (the rate-determining mineral as diffusion in orthopyroxene is faster), we estimated the cooling rates needed to diffuse 5 µm (half-width of the average lamellae) by calculating the total of the mean-diffusion distance in small isothermal steps using the relation $X^2 = 2Dt$, where X is the mean diffusion distance, D is the diffusion coefficient, and t is time. For a granulite cooling from 1075 °C, the cooling rate needs to be > 100°C/y. Starting at 1025 requires cooling at > 5°C/y, and starting at 925°C requires a cooling rate >1°C/y. All these are much greater than expected for cooling of a cumulate inside a 10-km impact melt sea. Such a body of impact melt is not unlike a terrestrial layered intrusion such as the Stillwater igneous complex, which cooled at about 1°C/My [10], although that value is uncertain because of subsequent metamorphism.

Impact setting: If granulites contain a mantle component excavated during a large (even basin-forming) impact, their final assembly and metamorphism needs to be in a setting compatible with their relatively rapid cooling. One possibility is that during formation of a multi-ring basin, hot mantle-derived rock in the basin interior mixed with crustal rock that flowed towards the basin interior, as suggested by modeling [11]. This does not preclude formation in smaller impact events as proposed previously [2,3].

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