THE GRANULITE SUITE: IMPACT MELTS AND METAMORPHIC BRECCIAS OF THE EARLY LUNAR CRUST  
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The granulite suite consists of two major types of rocks. One is coarse-grained and poikilitic with many euhedral crystals of olivine and plagioclase. These characteristics indicate crystallization from a melt; the poikilitic granulites are impact melt breccias. The other group is finer-grained and granoblastic, with numerous triple junctions; the granoblastic granulites are metamorphic rocks. Compositional groups identified by Lindstrom and Lindstrom [1] contain both textural types. Two-pyroxene thermometry indicates that both groups equilibrated at 1000 to 1150 °C. Calculations suggest that the granoblastic group, which has an average grain size of about 80 μm, was annealed for < 6 x 10⁴ y at 1000 °C, and for < 2500 y at 1150 °C. Similar equilibration temperatures suggest that both groups were physically associated after impact events produced the poikilitic melts. Granulitic impactites hold important information about the pre-Nectarian bombardment history of the Moon, and the composition and thermal evolution of the early lunar crust.

Granulitic impactites [2] are widely considered to be an important rock type in the lunar crust, but how they formed is poorly understood. Metal compositions and elevated concentrations of meteoritic siderophile elements suggest that most lunar granulites are impact breccias. Their occurrence as clasts in ~3.9 Ga breccias, and ⁴⁰Ar-³⁹Ar ages ≥ 4.2 Ga for some granulites show that they represent a component of the lunar crust which formed prior to the Nectarian cataclysm. Petrographic characteristics of lunar granulites indicate at least two endmember textural variants which apparently formed in fundamentally different ways. One type has granoblastic textures consisting of equant, polygonal to rounded grains, and abundant triple junctions with small dispersions around 120° indicating a close approach to textural equilibrium. As suggested by many authors, granoblastic granulites probably formed by subsolidus annealing and recrystallization of fragmental or glassy protoliths. Examples of this type include 15418, 78155, and 79215.

The other textural type consists of poikilitic to poikiloblastic rocks with euhedral to subhedral plagioclase and olivine enclosed by interstitial pyroxene. In some cases, the texture resembles that of an orthocumulate. Examples of this type include 60035, 67955, and 77017. Rounding of grain edges is common in poikilitic granulites, but the regular crystal shapes and widely dispersed dihedral angles show they are far from textural equilibrium. The textures of poikilitic granulites are more consistent with the formation of these rocks by crystallization from a melt than by subsolidus metamorphism. A few samples have been recognized with textural characteristics transitional between those of the granoblastic and poikiloblastic endmembers (e.g., 72559, 78527) [3].

Pyroxene compositions taken from the literature and determined for this study by electron microprobe were used to calculate equilibration temperatures. The Kretz [4] Ca transfer (solvus) thermometer and the Lindsley and Anderson [5] graphical method both give similar temperatures, which range from ~1000 °C to 1150 °C (Fig. 1). There is no apparent temperature difference between granoblastic and poikilitic varieties, but there is a hint in these data that the more ferroan varieties equilibrated to lower temperatures. Additional studies are in progress to test this possibility.

Although clearly metamorphic, the granoblastic group has a matrix grain size of only about 80 μm. We can constrain the duration of metamorphism by estimating the rate of grain growth from Ostwald ripening, a process in which large grains grow at the expense of smaller ones to minimize surface free energy. If grain growth is controlled by Ostwald ripening, growth would follow a law such as the following [6]:

\[ a^n = a_0^n + \frac{8ν²γCsD}{9RT} t \]

where \( a \) is the crystal size after time \( t \), \( a_0 \) is the initial size, \( ν \) is the molar volume of typical silicate crystals (4.2 x 10⁻⁶ m³/mol for olivine), \( γ \) is the surface free energy of the crystal-crystal interface.
(about 1 J/m²), c is the equilibrium concentration of solute (taken as the Fa content of granulite olivine, 4 x 10⁴ mol/m³), D is the diffusion coefficient, R is the gas constant, and T is temperature. The exponent n is 2 if the process is interface controlled and 3 if volume (diffusion) controlled. Most metamorphic systems seem to be volume controlled. The diffusion coefficient is not really known with certainty; we use that of olivine [7] because it is reasonably well determined and because its use gives self-consistent results for chondrite metamorphism [8] and our unpublished calculations. Results are shown in Fig. 2 for an assumed initial grain size of 10 µm. The two vertical dotted lines provide estimates for the duration of granulite metamorphism. It appears that the present grain size of granoblastic granulites (80 µm) could be attained in a setting that allowed annealing at 1000 °C to 1150 °C for < 10⁵ y.


Figure 1. Pyroxene equilibration temperatures of lunar granulites plotted against the Mg/Mg+Fe of the low-Ca pyroxene. Symbols refer to textural types: granoblastic (+), poikilitic (●), and transitional (■). There is no difference in temperature between the different textural types, but the less magnesian samples may have equilibrated to lower temperatures.

Figure 2. Thermal models for the duration of metamorphism based on the grain size and pyroxene temperatures of granoblastic granulites. Grain growth by Ostwald ripening is assumed. Metamorphic timescales of < 10⁵ years are indicated by these models.