MINERALOGY AND COOLING HISTORY OF MAGNESIAN LUNAR GRANULITE 67415;
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We investigated Apollo granulite 67415 by mineralogical techniques to gain better understanding of cooling histories of lunar granulites. We estimated cooling rates from chemical zoning of olivines in magnesian granulitic clasts by computer simulation of diffusion processes. The cooling rate of 10 degrees °C/yr obtained is compatible with a model of the granulite formation, in which the impact deposit was cooled from high temperature or annealed, at the depth of about 25 m beneath the surface.

Our previous mineralogical studies of lunar granulites [1], granulitic clasts in lunar meteorites and highland breccias [2] showed that granulites are common lithologies of the ancient highlands and their cooling rates are 0.3 to 3°C/day. In this study we investigated cooling rates of magnesian granulite 67415, which was well characterized [3], but not available in our previous study. We measured CaO chemical zoning profiles of olivines in 67415 with an electron probe microanalyzer (EPMA JCA-733) to estimate the cooling rates of granulitic clasts by the same computer method as previously used [1].

The polished thin section (PTS) of 67415,14 was supplied from NASA. Four large granulitic clasts (GR1-GR4) are present in the PTS; GR1 (2.6x1.5 mm in size) contains rounded olivine crystals (up to 0.4 mm in diameter) and minor orthopyroxene and augite in granoblastic plagioclase. GR2 (1.3x0.96 mm) is similar to GR1, but the mafic silicates are thinner in GR3 and GR4 than those in GR1, and the grains are connected. 67415,14 is classified as a monomict cataclastic noritic anorthosite and consists of abundant angular mineral fragments and a few lithic clasts in a matrix of very fine-grained crushed material [3]. Lithic clasts have annealed plutonic textures and consist of polygonal plagioclase crystals (up to 1 mm) with scattered rounded olivine crystals. Some crystals are joined together to form an aggregate of two to three crystals.

The mafic silicates in GR1 are mostly olivine (Fa22), and minor orthopyroxene (Ca,Mg,Fe$_6$) and augite (Ca$_{48}$Mg$_{48}$Fe$_2$). Plagioclase compositions range from An$_{91}$ to An$_{92}$. The zoning profiles of olivine were obtained by point analyses along a line form core to rim of a crystal. The enrichment of CaO was detected along the rims towards plagioclase, but not towards the olivine to olivine grain boundaries.

The method to estimate cooling rates and burial depths is the same as that used for the previous study [1,4,5]. Mg/Fe ratios of olivines in 67415 are constant, but Ca zoning with Ca enrichment towards the rim has been detected (Fig. 1). The temperature of equilibration estimated from coexisting orthopyroxene and augite chemistries [8] is about 1000°C. We calculated cooling rates from 1000°C based on the following two mechanisms (Case I and II) for the formation of zoning as:

(I) The zoning profiles were assumed to have been established during crystallization. During subsequent annealing process, the Mg-Fe zoning is homogenized but the Ca zoning is not. This can be explained by the fact that the diffusion coefficient of Ca in olivine is smaller than that of Fe in olivine [6,7]. The cooling rate to homogenize the Mg-Fe zoning in olivines is slower than about 200°C/yr and the cooling rate to preserve the Ca zoning is faster than 1°C/yr. In this case, we can give only ranges of cooling rate.
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(II) Ca distribution was uniform (CaO ~0.04 wt %) when olivine was crystallized. Then, Ca zoning was produced by diffusion of Ca into olivine from the surrounding plagioclase during thermal metamorphism. An approximate cooling rate can be determined uniquely. 10°C/yr gives best fit for the observed profile (Fig. 1). This cooling rate corresponds to a burial depth of 25 m for a rock-like material (thermal diffusivity=0.004 cm²/s) and 1 m for a regolith-like one (0.00001 cm²/s). Mg-Fe homogenization is taken place at this cooling rate by a process considered in Case I, if Mg-Fe zoning was initially present. The assumption on the CaO content at the interface between olivine and plagioclase, which gives best fit for the observed profile is supported by the partition coefficient (k) between olivine and plagioclase. k of oliv./plag. are the same as our previous work [e.g., 9]. The CaO content of plagioclase of 67415 is 18 wt %.

Textures of 67415 is granulitic but more coarse-grained and look like a plutonic rock. The facts suggest that this granulate was formed by thermal annealing of a more igneous textured rock than impact heated breccias, which were parts of a hot ejecta blanket. Since no Ca enrichment or depletion at the rim of an olivine joined together were detected, Case II is more likely process to produce the CaO zoning. The estimated burial depth by our calculation implies that the GR1 clast in 67415 was cooled from high temperature or annealed about 25 m beneath the surface.

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Fig. 1 Olivine chemical zoning profiles from core to rim of weight percent CaO (solid circles)