MINERALOGY AND COOLING HISTORIES OF LUNAR GRANULITES AND RELATED LUNAR METEORITES; Hiroshi Takeda1), Masamichi Miyamoto2) and Hiroshi Mori3),
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We investigated Apollo lunar granulites 79215, 67235, 76230 and granulitic clasts in lunar meteorite Y86032 by mineralogical techniques to gain better understanding of the origin and cooling histories of lunar granulites. Our previous comparisons of lithic clasts in lunar meteorites, Y82192 and Y86032, and those in highland breccias 60019 and 67016 (1, 2) showed higher abundances of granulitic clasts in these breccias and their cooling rates are 0.3 to 3°C/day. In this study we investigated cooling rates of true lunar granulites of the Apollo 17 samples, which were previously well characterized (3). We measured Mg-Fe and CaO chemical zoning profiles of olivines in granulite 79215 with an electron microprobe (JXA-733) to study cooling rates.

Mineralogy. The polished thin section (PTS) of Y86032 studied (76-2) was taken from the opposite side of the previously studied one (51-3) (2). Two granulitic clasts are present in the PTS; one clast (GR2) contains chain of mafic silicates in plagioclase but in another (GR1) rounded small mafic silicates distribute in the matrix of granoblastic plagioclases. Three Apollo granulites show diversity of textures: 67235 is rather similar to the Apollo 16 poliklitic rocks and only the plagioclase-rich matrix portion shows granulite-like texture. The texture of 76230 is similar to GR1, and fragments of plagioclase crystals still can be recognized. 79215 is completely recrystallized and the plagioclase matrix shows transparent uniform texture, but in large scale we can recognize the original texture and chemistry of a feldspathic fragmental breccia. The modes of mafic silicate distribution differ from one place to the other. Many different textures recognized as clasts in lunar meteorites can be identified within 79215. The texture of one portion is similar to that of GR1 in Y86032 and another part is similar to that of GR2. The mafic silicates are mostly orthopyroxene (Ca,Mg,Fe), olivine (Fo) and augite (Ca,Mg,Fe). Plagioclase compositions range from An20 to An28. The grains sizes of mafic silicates and density of distribution differ from one place to another.

Estimation of Cooling Rates from Chemical Zoning of Olivines. The method to estimate cooling rates and burial depths is the same as that used for the previous study (4, 5). Mg/Fe ratios of olivines in 79215 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 for the formation of zoning.

Case 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 3°C/day (1000°C/yr) and the cooling rate to preserve the Ca zoning is faster than 0.3°C/day (1000°C/yr). In this case, we can give only ranges of cooling rate.

Case II: Ca distribution was uniform (CaO ~0.05 wt %) when olivine was crystallized. Then, Ca zoning was produced by diffusion of Ca into olivine
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from the surrounding plagioclase during thermal metamorphism. An approximate cooling rate can be determined uniquely. 40°C/yr gives best fit for the observed profile (Fig. 1). This cooling rate corresponds to a burial depth of 12 m for a rock-like material (thermal diffusivity=0.004 cm²/s) and 60 cm 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. We assumed that the CaO content at the interface between olivine and plagioclase is 0.13 wt %, which gives best fit for the observed profile. This value is supported by the partition coefficient (k) between olivine and plagioclase. Ideally we obtain k of oliv./plag. as 0.01-0.018 (e.g., 9). The CaO content of plagioclase of 79215 is 18 wt %. Then equilibrium CaO content in olivine is about 0.18-0.32 wt %.

Variations of textures from poikilitic (67235) to granulitic (79215) suggest that granulites were formed by thermal annealing of impact heated breccias, which were parts of a hot ejecta blanket. Since no Ca enrichment or depletion at the rim of an olivine, adjacent to Opx were detected, Case II is more likely process to produce the CaO zoning. The estimated burial depth by our calculation implies that the impact deposit was cooled rapidly from high temperature near surface. If this hypothesis is accepted, the similarity in cooling rates of granulites to those in breccia clasts (2) suggests that the prolonged annealing took place before these rocks incorporated into the present breccias as clasts.

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![Fig. 1 Olivine chemical zoning profiles from core to rim of molecular percent Fa [100 X Fe/(Mg+Fe)] (open circles, scale on right) and weight percent CaO (solid circles, scale on left) for 79215 granulite.](image-url)