IMPORTANT LITHOLOGIES OF THE LUNAR FARSIDE CRUST: COARSE-GRAINED GRANULITES OR MAGNESIAN ANORTHOSITES. H. Takeda[1], T. Arai[2], A. Yamaguchi[2] and T. Mikouchi[3], [1]Research Inst., Chiba Inst. of Technology, 2-17-1 Tsudanuma, Narashino City, Chiba 275-0016, Japan, takeda.hiroshi@it-chiba.ac.jp, [2]National Inst. of Polar Res., 1-9-10 Kaga, Itabashi-ku, Tokyo 173-8515, Japan, [3]Dept. Earth and Planet. Science, University of Tokyo, Hongo, Tokyo 113-0033, Japan.

Introduction: Because some lunar feldspathic meteorites are similar in composition to lunar feldspathic highlands and are remarkably KREEP-poor, it has been proposed that they might have been originated from the farside or rims of the nearside [1]. Abundant clast types in them are granulitic breccias. We presented new petrologic descriptions, major and trace element data, and Ar-Ar isotope data on lunar meteorite Dhofar 489 [2,3]. The significance of this lunar meteorite is that it has the lowest concentrations of incompatible trace elements of any lunar meteorites, and plausibly provides a unique sample of large areas of the farside crust of the Moon that have been mapped from orbit but not explored by the Apollo missions. Major clast types in this meteorite are not granulitic breccias. We report mineralogy of clasts found in new PTSs.

Much of their information in the petrologic description of lunar granulites is confusing. According to Papike et al. [4], granulitic breccias and granulites are coherent crystalline rocks that have been recrystallized by heating at temperatures over 1000 ºC for long period of time. The granulitic breccias contain relict clasts and have been studied extensively by many investigators [5,6], whereas granulites, which are much less abundant, do not show breccia textures. Cohen et al. [7] described two strongly shocked, partially melted, granulitic breccias in Dhofar 026 and Apollo sample 15418. We describe textures of clasts in Dhofar 489 in detail in this report.

Samples and Experimental Methods: Five polished thin sections of Dhofar 489 have been employed for mineralogical and petrographic studies. Elemental distribution maps of Si, Mg, Fe, Al, Ca, Ti and Cr were obtained by electron probe microanalysis (EPMA) at the Ocean Research Institute (ORI) of University of Toyo and National Inst. of Polar Res. (NIPR).

Results: Five anorthositic clasts with minor mafic silicates were recognized in PTS ,2-1 and 11-3. They can be coarse-grained granulites or magnesian anorthosites. The shapes of plagioclase fragments are not well defined in the dark matrices. Some large subrounded plagioclase grains have fine dark inclusions. The An values of plagioclase distribute in a much smaller range ($An_{95\sim98}$) than those in common lunar anorthositic meteorites [8]. The An contents of the acicular plagioclase in the crystalline matrix $An_{\sim96}$ also distribute in the same range as large fragments. The An values range from 95 to 98 (mean 96). Many parts of the plagioclase clasts are converted to dark colored, fine-crystalline materials with small amounts of FeO and MgO.

Magnesian anorthosite clasts. The second largest plagioclase-rich lithic clast (MA1), 3.0 x 1.3 mm in size in PTS 2-1contains an aggregate of amoeboidal mafic silicate (olivine) grains (0.7 x 0.4 mm) (Fig. 1). Although some mafic silicates show rounded grain shape, amounts and sizes of plagioclase are large and do not show granulitic texture. Because the twin lamellae of a plagioclase grain, one side attached to the olivine aggregate and the other terminated at the clast boundary reaches up to 1.6 mm, we conclude that this clast is a coarse crystalline anorthosite. Their olivine compositions (Fo_{79}) are still more magnesian than those in the FAN trend. Thus, this clast could be a magnesian anorthosite.

Anorthosite clasts with mafic silicates. The largest angular fragment of plagioclase (MA2) 2.6 x 1.7 mm in size shows shocked appearance, but the original rock could be an anorthosite. At one edge of the clast, one brownish olivine crystal (0.42 x 0.14 mm in size) is attached. Fo_{75} indicates that this clast is also magnesian anorthosite. Some subrounded plagioclases (e.g. AN2) in PTS 11-3 have fine-grained dusty inclusions in rectangular area with a clear rim. One such clast contains a very small olivine with Mg number 78.

Coarse-grained granulite clast. One clast (GR1) in PTS 2-1, 1 x 0.7 mm in size has a chain of mafic silicates 1 x 0.13 mm. Rounded shapes of the olivine grains suggest that this may be a coarse granulite. Another shocked plagioclase-rich clast (GR2) 3 x 2 mm in size includes more than 15 rounded olivine grains less than 0.15 mm in diameter, may be a granulite, but we cannot see the detailed textures because of the shock.

Discussions: We have described major clasts in Dhofar 489, an anorthositic lunar meteorite. The petrology, geochemistry and geochronology of this rock have been partly reported [2,3]. However, the question is whether we have pieces of magnesian anorthosites in Dhofar 489. The proposal that magnesian anorthosites probably existed on the Moon is in support of our inferred knowledge of how igneous systems work and the remote sensing data.

We made the case that the mineral compositions of anorthositic clasts in Dhofar 489 extend the known ferroan anorthosite fractionation trend to more primitive (higher Mg#) compositions. If so, the gap in mineral compositions that distinguishes ferroan anorthosites from Mg-suite rocks on the classic An (plag) vs. Mg# (mafics) diagram [10] would be narrowed considerably. This would be a significant discovery with implications for current concepts of lunar crustal composition, magma ocean evolution, and possible genetic relationships between ferroan anorthosites and the Mg-suite cumulates.

Now, we discuss which clasts described above are in agreement with magnesian anorthosites. Among five clasts described above, none of them shows relict of breccia textures. Modal abundance of plagioclase is within the range of "pure anorthosite" [11] except for GR2 clast, which could be coarse-grained granulite of [4]. The chemical compositions of their olivine grains are more magnesian than common FAN trend [10]. Although the shape of olivine grains in MA1 is rounded, the presence of large plagioclase grain 1.6 mm up to the clast boundary with one continuous twin lammelae clearly indicate that this clast is not granulite. The rounded olivine shape may be produced during slow cooling after crystallization in the crust. A large olivine crystal attached to AN1 does not show granulitic appearance. Thus, both MA1 and AN1 can be highly likely magnesian anorthosites.

The recrystallized matrix, the lack of sharp boundaries between clasts and matrix, and "dusty" material in the plagioclase grains (indicative of devitrifying maskelynite) suggest that Dhofar 489 is a metamorphosed breccia. In this case, Mg# of mafic minerals in the matrix may have been all homogenized and does not now indicate anything about early lunar igneous processes. However, the ranges of the olivine compositions Fo_{71} to Fo_{89} do not support such interpretation.

Cushing et al. [7] and Cohen et al. [6] give a more thorough discussion of the granulitc breccia rocks and their mechanism of formation. Takeda and Miyamoto [12] estimated cooling rates from Ca chemical zoning of olivine crystals by computer simulation of diffusion processes. The cooling rate of 10 ºC /yr thus obtained is compatible with a model of the granulite formation, in which the impact deposit was cooled from high temperature or annealed at depth of about 25 m beneath the surface. Possible crustal rocks such as Dhofar 489 experienced much slower cooling rate.

In this abstract we did not discuss the importance of spinel troctolite clast in Dhofar 489 [13]. It may be the precursor to granulites, because it is feldspathic and magnesian, but spinel troctolites are in fact in the Apollo collection and spinel is not in most granulites.

The magnesian granulites have been argued by Korotev [14] to be a special product of the PKT [15]. Our conclusion, that mixtures of magnesian anorthosites with spinel troctolites on the lunar farside can produce these rocks, proposes that the petrologic formation of these rocks is older and more widespread. This is an important point and deserves some more consideration and comment in future. Because textures of plagioclase are disturbed by shock events, experiments performed by Mikouchi et al. [16] will be useful to gain shock information. If Dhofar 489 is a representative rocks of the farside and the polar regions, its properties will be useful in producing lunar simulant for these regions.

Acknowledgments: This work was carried out as a part of "Lunar simulant project" (PI: H. Kanamori) supported by Shimizu Corp. and JAXA and partly supported by NIPR, Research Project Fund, P-8 (Evolution of the early Solar System Materials).

References: [1] Takeda H. and Miyamoto M. (1988) *Proc. 21st ISAS Lunar Planet. Symp.*, 161-165, ISAS., Tokyo. [2] Takeda H. et al. (2003) *LPS XXXIV,* Abstract #1428. [3] Karouji Y. et al. *Antarct. Meteorites*, *XXVIII*, 29-30. [4] Papike J. J. et al. (1998) *In Planetary Materials.,* 5-158 - 5-161, Miner. Soc. Amer., Washington, D.C. [5] Lindstrom M. M. and Lindstrom D. J. (1986) *JGR, 91,* Suppl., D263-D276. [6] Cohen B. A. et al. (2004) *Meteoritics & Planet. Sci., 39*, 1419-1447. [7] Cushing J. A. et al. (1999) *Meteoritics & Planet. Sci., 34*, 185-195. [8] Cahill J. T. et al. (2004) *Meteoritics & Planet. Sci., 39*, 503-529. [9] Warren P. H. (2005) *Meteoritics & Planet. Sci., 40*, 477-506. [10] Warren P. H. (1985) *Earth Planet. Sci., 13*, 201-240. [11] Hawke et al. (2003) *JGR Planets*, *108*, 5050-5066. [12] Takeda H. and Miyamoto M. (1996) *LPS XXIV,* 1391–1392. [13] Takeda H. et al. (2004) *LPS XXXV,* Abstract #1222. [14] Korotev R. L. et al. (2003) *GCA, 67*, 4895-4923. [15] Jolliff B. L. et al. (2000) *JGR, 105* No. E2, 4197-4216. [16] Mikouchi T. et al. (2002) *Meteoritics & Planet. Sci.,* 37, A100.

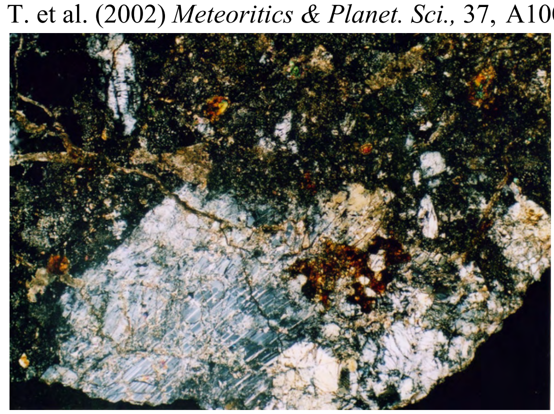

Fig. 1. Photmicrograph of the MA1 clast in Dhofar 489, cross polarized light, width 3.3mm. Note the presence of a large plagioclase with twin lamellae.