Lunar Crustal Mineralogy inferred from Lunar Meteorites and Kaguya Data.

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Introduction: Lunar feldspathic crust is considered to be products of a primordial magma ocean crystallization. Distribution and composition of major minerals co-existing with plagioclase, such olivine and low-Ca pyroxene in the lunar crust provide us with keys to understand the chemical composition and the mode of crystallization of a lunar magma ocean. Previous mineralogical analyses of the Apollo samples and remote sensing studies give us a general idea that the abundance of low-Ca pyroxene far exceeds that of olivine in the lunar crust [e.g. 1, 2]. Thus, a magma ocean composition has been assumed to be saturated with low-Ca pyroxene and plagioclase [e.g. 3]. Yet, recent mineralogical and geochemical studies of feldspathic lunar meteorites indicate that olivines are universally present [4-6]. Thus, an understanding of the true mineral distribution in the lunar global feldspathic crust is required to discuss a magma ocean composition and the lunar crustal genesis. In this study, occurrence, abundance and origin of olivine and low-Ca pyroxene in the lunar crust are discussed on the basis of mineralogical analyses of feldspathic lunar meteorites, and Kaguya Multiband Imager (MI) remote-sensing reflectance spectral analyses of lunar crust.

Analytical methods: Feldspathic lunar meteorites DaG 400 (fragmental breccia), NWA 5000 (fragmental breccia), and Dhofar 908 (impact-melt breccia) are used for this study. Textural observation and analyses of mineral chemistry were conducted with analytical SEM of PERC/ChiTech and EPMA of NIPR. VIS-NIR reflectance spectra of lunar meteorites were done by a spectrometer of NAO. MI multiband spectra (415, 750, 900, 950, 1000, 1050, 1250, 1550 micron) are used for band images and reflectance spectra here. The MI data are calibrated with a method presented in [7]. Photometric correction with detailed topography were made for band images and all spectra presented here.

Results:

Mineralogy of three lunar feldspathic meteorites

The above three samples commonly include clasts of anorthosites and troctolite, which consists of plagioclase and olivine (Fig 1). Unlike the two fragmental breccias, mineralogy of the troctolite clasts in an impact-melt breccia, Dhofar 908, is different, because a variable amount of low-Ca pyroxenes are present as a minor phase. The low-Ca pyroxenes occur as an overgrowth of olivine in the grain boundary between olivine and plagioclase. The rock texture of the clasts indicate that the overgrown low-Ca pyroxenes are resulted from a resorption of olivine in the presence of a silica-rich melt (Fig. 2). These occurrences show that low-Ca pyroxenes do not formed by a simple monotonic cooling of magmas, but by a reaction between disequilibrium pairs of olivine and SiO_2-rich melt. The partial replacement of olivine by low-Ca pyroxene is controlled by a peritectic reaction between the two phases, shown by an equation below:

$$\underset{\text{Olivine}}{(Fe,Mg)_2SiO_4} + \underset{\text{Melt}}{SiO_2} \rightarrow \underset{\text{Low-Ca pyroxene}}{2*(Fe,Mg)SiO_3}$$

Considered the above occurrence of low-Ca pyroxene, and a peritectic relation between low-Ca pyroxene and olivine, low-Ca pyroxene in the lunar feldspathic rock likely formed during the secondary metamorphism of the olivine-bearing initial (igneous-origin) crust. The texture of olivine, low-Ca pyroxene, and plagioclase indicates that olivine crystallizes first, followed by plagioclase crystallization, and subsequently low-Ca pyroxene forms in between the two minerals either during the later course of crystallization or after the completion of crystallization.

Spectroscopy of olivine-bearing crust

In the spectroscopic observation, pyroxenes seem to be dominant in the lunar crust, but olivine is also present globally. Note that the occurrence of olivine is confined to relatively fresh craters on and around basin rings and crater central peaks [8]. Copernicus crater (95 km in diameter) in the central nearside (9.5°N, 20°W) is one of them. Mineral distribution of the central peak of the Copernicus crater is shown in Figs. 3-4. Detection of plagioclase absorption at 1250 nm requires that the abudance of plagioclase is nearly 100 vol%. [7]. Thus, blue areas indicate the presence of purest anorthosites (PAN) [7]. Since an absorption coefficient of pyroxene is far greater than that of olivine and plagioclase, a few to several vol% of pyroxene masks absorptions of olivine and plagioclase. Red areas indicate that pyroxene abundance is greater than several vol%, with possible co-existence of olivine and plagioclase. Green areas are olivine-rich with minor amount of pyroxene (less than a few vol%), and minor or moderate amount of plagioclase, of which abundance is hard to be determined. Therefore, green areas can be dunite or troctolite. The occurrence of PAN in the vicinity of the olivine-rich areas implies the green area is likely trocrolite. An original depth of central peaks is generally greater than that of floor and wall. PAN on the eastern crater floor and olivine-rich rocks at the centeral peaks indicate that the olivine-rich rocks originally occur below the PAN crust. The suggested crustal column is in line with a crust model proposed from mineralogical studies of feldspathic meteorites [9].

Discussions:

Mineralogical studies of feldspathic lunar meteorites show that low-Ca pyroxenes are likely the secondary product after olivine and plagioclase crystallized from a magma. Replacement of the primary olivines by low-Ca pyroxenes during the secondary heating events, such as multiple impacts and subsequent volcanic activities after the magma ocean solidification may have altered an initial abundance of olivine in the primary crust.

This hypothesis also seems to work for the crustal mineralogy revealed by Kaguya remote-sensing data. Plagioclase and olivine are major constituents of the crust in the Copernicus and other fresh craters associated with basin rings and centeral peaks [8]. Olivine could be a major mafic minerals in the feldspathic crust. The apparent paucity of olivine in the FHT may be attributed to the lower detectability of olivine relative to pyroxene due to the smaller absorption coefficiency smaller than that of pyroxene.

A magma ocean composition has been previously estimated to crystallize low-Ca pyroxene and plagioclase, because a noritic crust has been generally assumed from studies of Apollo samples and pre-Kaguya remote-sensing data. Yet, a magma ocean would be more aluminious by a factor of two or three than the previous estimate, when a troctolitic crust is considered.

References: [1] Hawke B. R. et al. (2003) *JGR 108,* DOI:10.1029/2002JE001890. [2] Lucey, P. G.(2004) *GR*L 31, L08701. [3] Longhi J. (2003) *JGR 108,* doi:10.1029/2002JE001941. [4] Korotev R. L. et al. (2003) *GCA 67,* 4895-4923. [5] Takeda et al. (2006) *EPSL 247,* 171-184. [6] Korotev R. L. et al. (2006) *GCA 70,* 5935-5956. [7] Ohtake M. et al. (2009) *Nature 461,* 236-240. [8] Yamamoto S. et al. (2010) *Nature geosciences 3,* 533-536. [9] Arai T. et al. (2008) *Earth Planet Space 60,* 433-444.

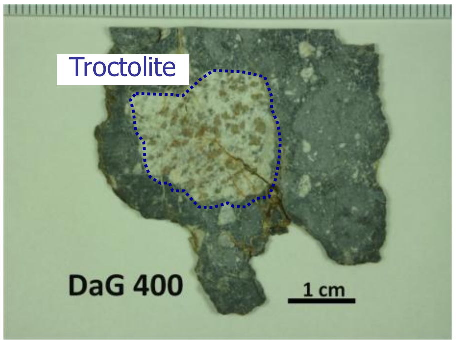

Fig. 1. Photograph of a chip of lunar felspathic meteorite DaG 400, with a coarse-grained troctolite clast.

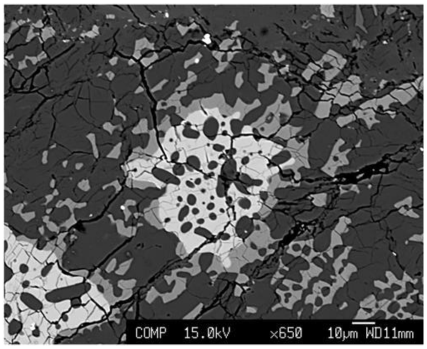

Fig. 2. Back-scattered electron image of low-Ca pyroxene as an overgrowth of olivine, showing a corona texture in a feldspathic lunar meteorite Dhofar 908. Bright phase: olivine, light-grey phase: low-Ca pyroxene, and dark-grey phase: plagioclase.

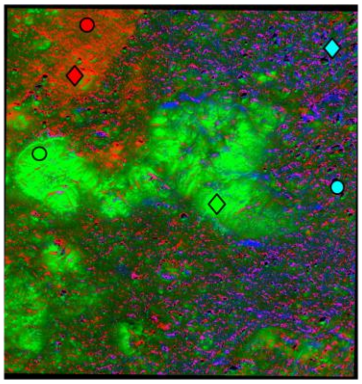

Fig. 3. Color-composite image of a central peak of crater Copernicus. Field of view is 20 km. Red:Pyroxene-rich Green:Olivine-rich, Blue:Plagioclase-rich. Solid circles and diamonds indicate points for the spectra which are shown in Fig. 4.

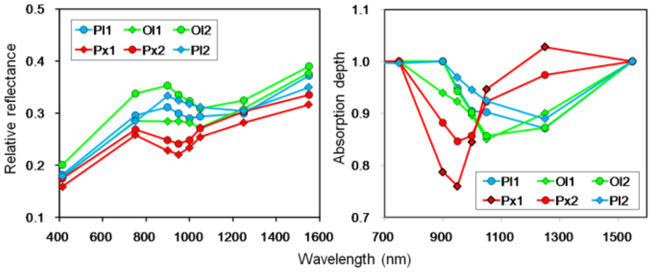

Fig. 4. (a) MI eight band spectra for points given in Fig. 3 (b) the spectra of (a) after the continuum removal.