

**GLOBAL COMPOSITIONAL INVESTIGATION OF MAFIC SILICATE PHASE OF THE LUNAR HIGHLAND CRUST BASED ON REMOTE SENSING REFLECTANCE SPECTRA.** M. Ohtake<sup>1</sup>, S. Yamamoto<sup>2</sup>, T. Matsunaga<sup>2</sup>, Y. Ogawa<sup>3</sup>, <sup>1</sup>Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagami-hara, Kanagawa, 229-8510, Japan (ohtake.makiko@jaxa.jp), <sup>2</sup>National Institute for Environmental Studies, <sup>3</sup>The University of Aizu.

**Introduction:** The composition of the lunar highland crust is among the most important information for understanding the formation mechanism of the lunar highland crust and the composition of the lunar magma ocean. Previously, the composition of the lunar highland crust was estimated mainly based on measurements of the lunar returned samples and the lunar meteorites. These measurements are limited because the sampling locations of the returned samples were limited and may have lateral sampling bias and because the meteorites, which tend to be a relatively younger ejection age, were ejected selectively from shallower depth and may have vertical sampling bias. Therefore, remote sensing approaches to estimate the composition of the lunar highland crust have begun [1]. Recently, the presence of a purest anorthosite (PAN) layer, consisting of rocks with a very high anorthite content (nearly as high as 100%) and tens of kilometers thick, within the lunar highland crust was proposed based on reflectance spectra obtained by Kaguya [2, 3]. The estimated modal abundance of the PAN rocks was significantly higher than previous estimates of 82 to 92 vol.% [4] based on sample measurements. The presence of the PAN rocks within the lunar crust has been confirmed by data obtained by Chandrayaan-1 [5, 6]. To understand the composition of the mafic silicate phase in this layer is an important next study.

Though measurements of returned lunar samples and meteorites indicate that the lunar highland crust typically consists of plagioclase and low-Ca pyroxene [7] with minor amounts of other mineral phases, the presence of high-Ca pyroxene with low-Ca pyroxene within the lunar highland area was reported based on remote sensing data at some fresh craters [8]. However, it is not clear if the reported high-Ca pyroxene really is a major mafic silicate component of the highland crust because the studied fresh craters were small and the excavated shallow mixing layer (up to a few kilometers) and may not be a representative crustal material with a thickness of tens of kilometers [9, 10].

Therefore, this study investigated the mafic silicate phase and estimated its composition within the PAN layer globally by using remote sensing reflectance spectra of the lunar surface.

**Method:** We used reflectance spectra acquired by the Kaguya Spectral Profiler (SP) [11], which has a spectral coverage of 500 to 2600 nm in 300 bands and a spatial resolution of 500 x 500 m. Among the global SP data, all of the 570 PAN spectra identified and reported by [3] were analyzed by using the modified

Gaussian model (MGM) [12]. No smoothing or other treatment was applied to the input spectra. The SP observation covered the 2000 nm mafic silicate absorption band. We used up to 1700 nm data in this study for a preliminary investigation. Several MGM parameters, a number of fitted peak and peak parameters (center wavelength, width, and strength) of each peak at the starting point were tried, and the results were cross-evaluated. The compositions of silicate mafic minerals were estimated by comparing the peak fit results and the known correlation between absorption center wavelength and mineral composition by [13, 14, 15].

**Results:** A representative reflectance spectra and its MGM analyses results are presented in Fig. 1. Absorption features are visible around 900 nm and 1250 nm even in low reflectance without the continuum removed (Fig. 1a), which is uncommon among usual space-weathered lunar highland material. Spectra observed after removing the continuum (black dot), fitted peaks (peak1 as plus and peak2 as white diamond), and the residual of the peak fit (small dot) are presented in

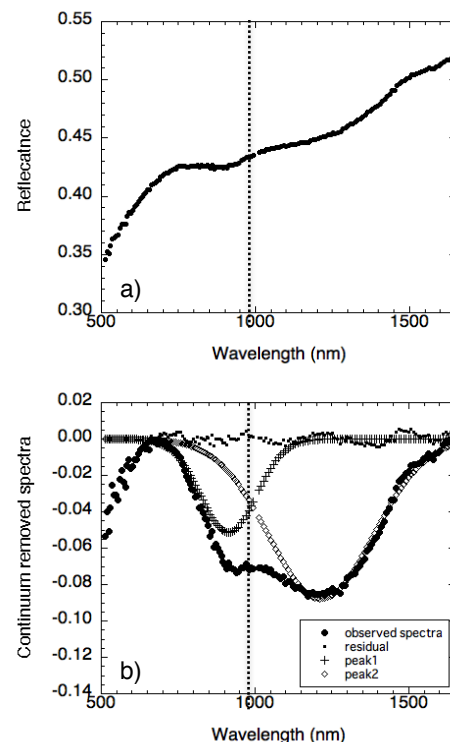


Fig. 1 Representative spectra of purest anorthosite obtained at Jackson crater.

a) Reflectance and b) Results of MGM analysis of the spectra. Dashed lines indicate 980 nm wavelength.

Fig. 1b. Spectra with the continuum removed exhibit clearer combined double peaks; and the fitted absorption center wavelength of this example is 910 nm. The strongest absorption around 1250 nm is caused by anorthite, and the weaker absorption around 910 nm is caused by mafic silicate (low-Ca pyroxene in this example).

Data screening were applied to the MGM results based on the size of the residual after peak fitting and an absorption depth ratio of peak1 to peak2 (this ratio should exceed 1 if the analyses finished correctly but in some cases is abnormally high because of an error in the peak fitting). Figure 2 summarizes the MGM analyses. It is clear that most (93%) of peak1, which corresponds to the mafic silicate phase, has a center wavelength shorter than 980 nm, suggesting that these mafic silicate in the PAN rocks are low-Ca pyroxene (65% are shorter than 950 nm). Note that the low-Ca pyroxene in this study implies pyroxene having less than a 0.2 molar ratio of  $\text{Ca}/(\text{Ca}+\text{Mg}+\text{Fe})$  smaller than 0.2. Figure 2 also demonstrates that data points having a center wavelength shorter than 980 nm are spread widely along the y axis, indicating that these data points had a strong absorption band and were not a product of weak ambiguous absorption spectra. Six percent of the data have center wavelengths between 980 nm and 1040 nm, which correspond to the high-Ca pyroxene composition. The remaining 1% of the data with longer center wavelengths around 1050 nm possibly correspond to olivine or glass.

No apparent phase difference (low-Ca and high-Ca pyroxene difference) is observed between the nearside and the farside. Results of other MGM analyses that used different parameters are similar to the results presented here, supporting the validity of the results described above.

**Discussion:** Our results indicate that the majority of the PAN layer in the lunar highland crust globally consists of anorthite and small amounts of low-Ca pyroxene, the major mafic silicate component, rather than high-Ca pyroxene or olivine. This result is consistent with the previous work based on measurements of the lunar material from the lunar surface mixing layer with limited global coverage and confirms the homogeneous modal abundance within the lunar highland crust. Our intention is to identify low-Ca pyroxene as the most abundant mafic silicate phase, not to deny the presence of high-Ca pyroxene and olivine as a less abundant phase within the highland rocks.

Whether the several percent of the exceptional PAN rocks we detected are minor components of the highland crust or correspond to a composition of different depth within the highland crust, or are caused by other secondary processes such as impact melt, or are simply caused by lateral mixing of PAN rock with

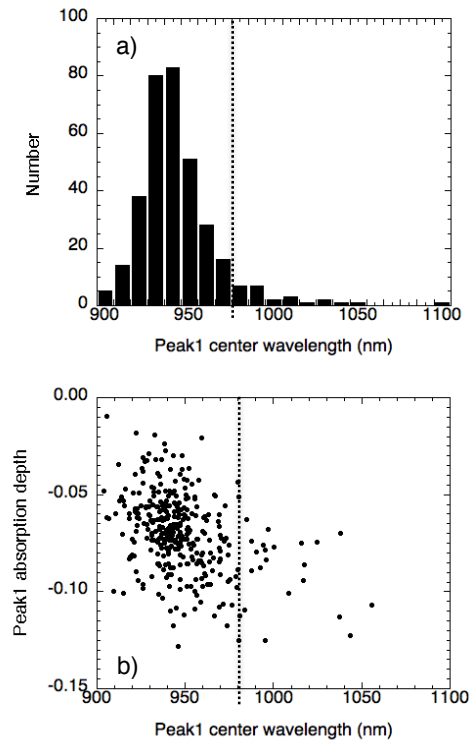


Fig. 2 Derived peak center wavelength of the analyzed PAN rock spectra.

a) Histogram of peak1 (mafic silicate band) center wavelength. b) Correlation between peak1 center wavelength and absorption depth.

different geologic units such as lunar regolith is not clear.

The short center wavelengths of the PAN rocks at Jackson crater suggest relatively higher Mg# ( $\text{Mg}/(\text{Mg} + \text{Fe})$  in mole per cent) (around 70) in this region in good agreement with previous work [16], which suggests the presence of magnesian anorthosite in the farside highland, though accurate estimation of Mg# by using the correlation between absorption center wavelength and Mg# requires more detailed study.

**References:** [1] Tompkins, S. and Pieters, C. (1999) *Meteoritics & Planetary Sci.*, 34, 25-41. [2] Ohtake, M. et al. (2009) *Nature*, 461, 236-240. [3] Yamamoto, S. et al. (2012) *Geophys. Res. Lett.*, 39, L13201. [4] Warren, P. (1993) *Am. Mineral.* 78, 360-376. [5] Pieters, C. et al. (2009) *Lunar Planet. Sci. Conf. XXXX*, 2052. [6] Cheek, L. et al. (2013) *J. Geophys. Res.* 118, 1805-1820. [7] Papike, J. et al. (1991) *Lunar minerals, in Lunar Sourcebook: A User's Guide to the Moon*, 121-181. [8] Ogawa, Y. et al. (2011) *Geophys. Res. Lett.*, 38, L17202. [9] Ishihara, Y. et al. (2009) *Geophys. Res. Lett.*, 36, L19202. [10] Wiczcerek, M. et al. (2013) *Science*, 339, 671-675. [11] Matsunaga, T. et al. (2008) *Geophys. Res. Lett.*, 35, L23201. [12] Sunshine, J. et al. (1990) *J. Geophys. Res.* 95, 6955-6966. [13] Denevi, B. et al. (2007) *J. Geophys. Res.* 112, E05009. [14] Klima, R. et al. (2011) *Meteoritics & Planetary Sci.*, 46, 379-395. [15] Sunshine, J. (1998) *J. Geophys. Res.* 103, 13675-13688. [16] Ohtake, M. et al. (2012) *Nature GeoSci.* 5, 384-388.