

The widespread occurrence of high-calcium pyroxene in bright-ray craters on the Moon and implications for lunar-crust composition

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[1] We investigated the continuous spectral features of fresh craters on the Moon accompanied by distinctive bright rays, with cavity diameters between 8 and 24 km. We used the data from the Spectral Profiler onboard SELENE (Kaguya) to gain a better understanding of the composition of the lunar highland crust. We found that the observed spectra exhibited strong symmetric absorption around 1 μm and recognizable absorption around 1.3 μm . The spectra around a few craters showed a drastic change in the relative strengths of these two absorption bands $s_{1.3/1.0}$ at different locations in and around the craters, indicating differences in the abundance of plagioclase and mafic minerals. In contrast, the spectra around most of the craters showed no significant variation in spectral shape, with an essentially constant $s_{1.3/1.0}$. We analyzed the absorption features of the craters with an essentially constant $s_{1.3/1.0}$ using the Modified Gaussian Model. We found that the strongest symmetric absorption bands were centered at 0.97–1.01 μm with $s_{1.3/1.0} \approx 0.2$ –0.6. Comparing these values with data from known samples, we concluded that high-calcium pyroxene (HCP) is the most plausible dominant mafic mineral identified from the observed spectra. The fact that we detected such HCP-dominant spectra among rayed craters widely spaced across the lunar highland implies that the major mafic component of some portions of the lunar crust is HCP rather than low-calcium pyroxene (LCP). **Citation:** Ogawa, Y., et al. (2011), The widespread occurrence of high-calcium pyroxene in bright-ray craters on the Moon and implications for lunar-crust composition, *Geophys. Res. Lett.*, 38, L17202, doi:10.1029/2011GL048569.

1. Introduction

[2] The petrologic nature and vertical structure of the lunar highland crust provide important clues for understanding the evolution of the Moon, but the composition of the highlands is not well understood. Many previous studies suggested the

presence of a noritic crust, including low-calcium pyroxene (LCP) as the dominant mafic mineral. This suggestion first came from the Apollo sample data, in which the second most abundant mineral after plagioclase was usually LCP [Papike *et al.*, 1991]. In remote-sensing studies, Pieters [1986] investigated telescopic spectra of immature exposed surfaces on the near side combined with measured spectra from returned lunar rocks and breccias and concluded, based on the 1- μm band positions and spectral shapes, that norites (norite \approx LCP+ plagioclase) are ubiquitous, although some heterogeneity was noted. Tompkins and Pieters [1999] used Clementine data to examine the central peaks of large craters. They indicated that anorthosite near the surface evolves toward more mafic, LCP-rich compositions with depth, suggesting various types of rocks. In contrast, several highland locations with abundant high-calcium pyroxenes (HCP) were discovered from telescopic data [e.g., Lucey and Hawke, 1988; Pieters, 1986]. These were connected to the possible gabbroic plutons (gabbro \approx HCP + plagioclase). Such discrepancy among the observed abundances of materials in the highlands could reflect the intrinsic local diversity of the crustal compositions. Alternatively, this diversity could reflect the insufficiency of information that is derived from observations covering limited areas on the Moon at limited wavelength bands or ranges.

[3] Lately, Ohtake *et al.* [2009] investigated the central peaks of the large basins on the Moon using the latest data obtained by the Multiband Imager onboard SELENE (Kaguya). The authors discovered that the lunar highland crust contains “purest anorthosite” (PAN) globally, possibly at depths of 3–30 km. We focused on the compositional distribution and variation of a shallower part of the highland crust, which probably contains fresh materials, excavated from the deeper regions by cratering.

[4] We investigated continuous spectra from bright-rayed craters. The existence of rays generally suggests that the

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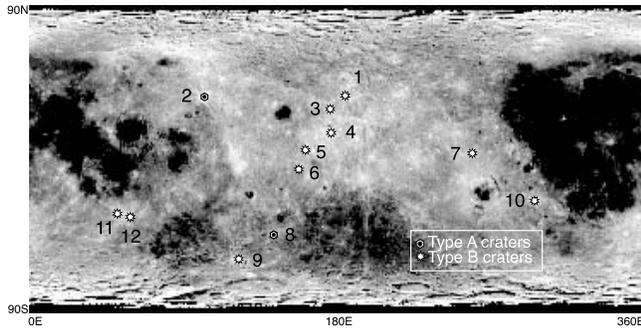


Figure 1. Locations of sampled craters 1–12 listed in Table S1. The background image is the SP 750-nm reflectance map of the Moon, developed based on the method of Yokota *et al.* [2010]. See Results for information on the Type A and Type B craters.

craters are young (<1 Ga) [e.g., Wilhelms, 1987] and composed of fresh material. Such material was excavated from depths down to about 1/10 of the diameter, for small to medium craters [e.g., Cintala and Grieve, 1998]. The spectral signature of such fresh material has a high reflectance with a high signal-to-noise (S/N) ratio and generally exhibits strong absorption, all of which enable us to investigate the spectral signature with greater reliability. Such rayed craters are distributed over a wide portion of the lunar highlands. We conducted a hyperspectral survey, taking advantage of a new dataset obtained with the Spectral Profiler (SP) onboard SELENE (Kaguya). Using the new SP data, we analyzed spectra observed around the bright-rayed craters on the Moon. Our results provide new constraints on the distribution of the mineral components in the lunar highland.

2. Data Analysis

[5] The SP is a visible and near-infrared spectrometer with 3 detectors covering wavelengths of 0.5–2.6 μm . The spectral resolution is 6–8 nm, and the S/N ratio is more than 460–2300 under a solar reflectance of 0.06. The footprint on the lunar surface is about 500 \times 500 m along the polar tracks of the SELENE satellite. In total, about 70 million spectra were taken, with an average spacing of 1–2 km in the east–west direction at the equator [Matsunaga *et al.*, 2008].

[6] We surveyed craters with cavity diameters of 8–24 km accompanied by noticeable bright rays on the lunar highlands based on the Clementine UVVIS 0.75- μm base map mosaic (http://starbase.jpl.nasa.gov/archive/archive/clem1-1-u-5-dim-basemap-v1.0/cl_3015/index.htm). Even for small to medium-sized craters, we had enough SP coverage for spectral analyses. Table S1 in the auxiliary material lists our target craters. We examined twelve craters: nine on the far side and three on the near side (Figure 1), distributed globally on the highlands of the Moon. We investigated the optical characteristics of these craters using continuous reflectance spectra covering wavelengths of 0.5–1.7 μm , calibrated based on the laboratory reflectance spectrum of the Apollo 16 soil sample 62231 to maintain consistency with previous studies [Tompkins and Pieters, 1999]. For detailed procedures regarding the calibration and derivation, see Matsunaga *et al.* [2008] and Yamamoto *et al.* [2011].

[7] First, we examined the variations in spectral features for different areas in and around each crater, including the cavity

floor, inner wall, ejecta blanket, rays, and background (see Figures 2 and S1). To eliminate the effect of space weathering and clarify the features of the absorption bands, we removed fitted continua from all the observed spectra. For 5 representative spectra (colored in light red in Figure 3; see Section 3 for details), we adopted the scheme developed by Sunshine *et al.* [1990] for deconvolving spectra using a Modified Gaussian Model (MGM) (see Figure S2). Each spectrum was deconvolved with several Gaussians, which represented the characteristics of the absorption bands and gave critical information on the composition of the observed spot. We set the initial number of absorptions to four, with absorption bands around (i) 0.3, (ii) 1, (iii) 1.3, and (iv) 2 μm . These absorption bands correspond to (i) the intrinsic UV absorption of component minerals combined with a degree of space weathering, (ii) the iron contents of mafic minerals, (iii) high-calcium pyroxene and/or plagioclase, and (iv) high-calcium or low-calcium pyroxene. All of these are expected on the lunar surface [e.g., Noble *et al.*, 2006]. Then, we independently optimized the central position, strength, and width of each absorption band to obtain the best fit to the observed spectrum. If the fit was poor, we added another Gaussian around 1 μm to obtain a fit of sufficient quality, assuming two pyroxenes: low-calcium pyroxene (LCP) and high-calcium pyroxene (HCP). Since natural LCP usually does not show significant absorption around 1.3 μm [Klima and Pieters, 2005], we set a single Gaussian around 1.3 μm for HCP, if any.

3. Results

[8] We found that the spectra of the bright-ray craters commonly showed absorption bands in two regions, around 1 μm and 1.3 μm , after continuum removal. The relative depth of the 1.3- μm to 1.0- μm bands ($s_{1.3/1.0}$) varied by crater. We categorized the examined craters into 2 types, focusing on changes in $s_{1.3/1.0}$, as shown in Figure 2. Type A craters were defined as craters around which the spectral shape drastically changed, with $s_{1.3/1.0}$ between around 0.5–1 at the ejecta, rim, wall, and floor. Type B craters were defined as craters around which the spectra exhibited little variation, having an essentially constant value around 0.5 (see Figure S1 for the observed spectra of all examined craters; Type A/B distinctions are shown in Table S1).

[9] Following Ohtake *et al.* [2009], plagioclase is known to display its deepest absorption around 1.3 μm . However, when it is mixed with mafic minerals, this significant absorption disappears quite easily and is barely observed. Such mixing of plagioclase and pyroxene was observed on the central peaks of Tsiolkovsky and Jackson in the latest studies [Ohtake *et al.*, 2009; Matsunaga *et al.*, 2008]. The spectra with $s_{1.3/1.0} \approx 1$ observed in some spots around Type A craters in this study are plagioclase-dominant spectra. The significant variety of $s_{1.3/1.0}$ around Type A craters indicates the changeable abundance of plagioclase to mafic minerals. In contrast, Type B craters exhibited no significant difference in spectral shape after continuum removal, only showing variations due to the degree of weathering. The difference between Type A and B craters is due to the difference in the local composition of the distributed material, probably reflecting the different degree of mixing of plagioclase and mafic minerals.

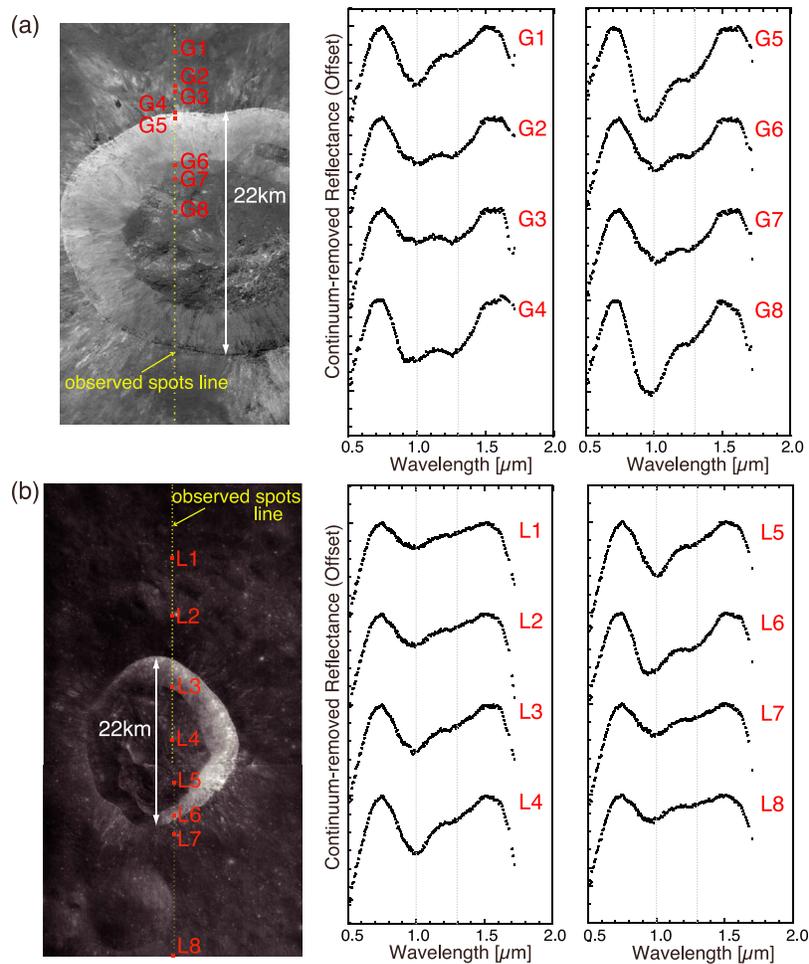


Figure 2. SP spectra with context images around (a) Giordano Bruno crater (Type A, Number 2 in Figure 1) and (b) Larmor Q crater (Type B, Number 3 in Figure 1). We can see marked differences in spectral shape in Figure 2a, where the relative depths of the two absorption peaks at 1 and 1.3 μm ($s_{1.3/1.0}$) vary between the observational spots. In comparison, for Figure 2b, the spectral shapes show no variation and seem to have a constant $s_{1.3/1.0}$. The tick intervals on the vertical axes are 0.02. The contrast of context images is adjusted for viewing.

[10] The material around Type B craters should include a much larger amount of mafic minerals with less component variety. The spectra of Type B craters should be dominated by pyroxene exclusively, as seen in Figure 3. No spectral feature characteristic of olivine is observed (compared to pyroxene, olivine has lower absorption coefficient; it should be very hard to detect olivine when it is intimately mixed with pyroxene in reflectance spectra even if the olivine is subequal to pyroxene in the abundance). To retrieve the compositional information of mafic minerals from the spectral features in detail, we chose 5 Type B craters with strong spectra obtained under excellent lighting conditions. We deconvolved the spectra around these 5 craters and investigated the absorption features quantitatively using MGM.

[11] Figure 4 shows the results of the MGM deconvolution of the spectra (all resultant values are available in Table S2). We found that (I) the central wavelengths of the 1- μm absorption band (λ_c) were above 0.97 μm and (II) $s_{1.3/1.0}$ (hereafter re-defined as the strength ratio of the fitted Gaussians of the two absorption bands strictly) ≈ 0.2 –0.6. *Denevi et al.* [2007] clarified the systematic shift of λ_c with composition (i.e., the calcium content) and proposed potential relationships between the absorption strengths at 1 and

1.3 μm and composition. Referring to their results, the fact that $\lambda_c > 0.97 \mu\text{m}$ from our MGM analysis indicates the presence of high-calcium pyroxene (HCP), as does the fact that $s_{1.3/1.0} > 0.2$, as this is too far from the trend for low-calcium pyroxene (LCP) with $s_{1.3/1.0} < 0.05$. Our estimated values for λ_c and $s_{1.3/1.0}$ match those for observed spectra of HCP rather than the LCP of *Denevi et al.* [2007].

[12] Using the newly obtained SP data combined with MGM analysis, we identified the dominant minerals observed around the bright-ray craters. We deduced that anorthosite including HCP are widely distributed in and around the bright-rayed craters on the lunar highlands. These would be accompanied by only minor or negligible amounts of LCP (see Table S2 and compare the strengths of the shorter λ_c -Gaussian with the longer λ_c -Gaussian, corresponding to relative contents of LCP and HCP, respectively).

[13] *Ohtake et al.* [2009] defined PAN as anorthosite of $>98\%$ vol. of plagioclase, of which spectra showed $s_{1.3/1.0} > 1.0$. Based on our analytical results, the spectra around Type B craters had $s_{1.3/1.0} \approx 0.2$ –0.6; therefore, the composition should be $\sim 98\%$ felsic and $>2\%$ mafic minerals. We might further constrain the composition as $\sim 95\%$ felsic and $>5\%$ mafic, considering that anorthosite with $<95\%$ plagioclase

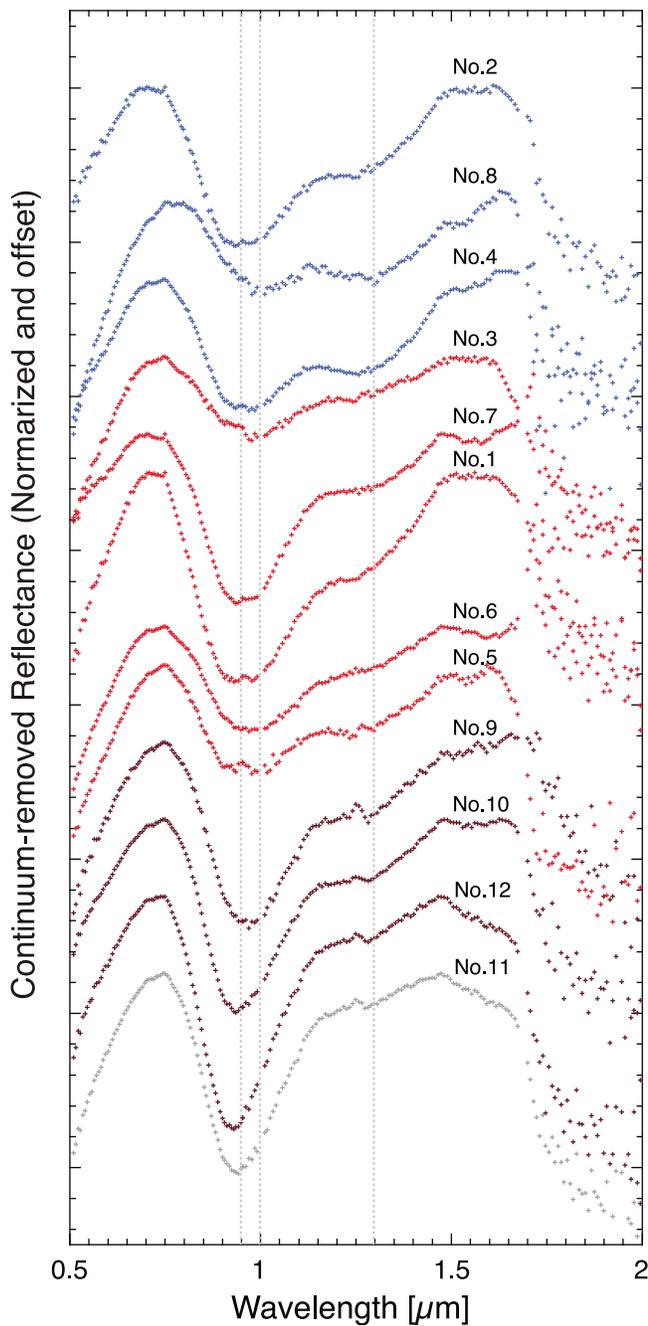


Figure 3. SP spectra at the inner walls of sampled craters 1–10, 12 in Figure 1: blue plots mark Type A craters, and red plots mark Type B craters (the spectrum of the ejecta blanket for 11 is plotted in gray because we have no data for the inner wall). The five Type B craters used in the MGM analysis in Figure 4 are represented in light red. The small changes in spectral shape among Type B craters are due to slight variations in composition. This composition is a minor mixture of LCP, with dominant HCP. The plots are presented in order of increasing LCP contamination toward the bottom. The reflectance is normalized to 1 at $0.75 \mu\text{m}$ for comparison. The tick intervals on the vertical axes are 0.02.

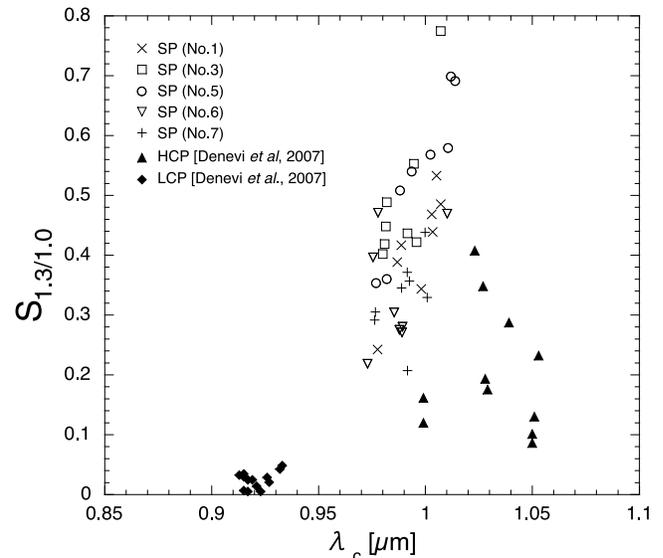


Figure 4. Absorption centers of the $1\text{-}\mu\text{m}$ band and the strength-ratio of the 1.3- to $1\text{-}\mu\text{m}$ bands for the observed SP spectra (Numbers 1, 3, 5, 6, and 7 in Figure 1 and Table S1). Given 2 Gaussians around $1 \mu\text{m}$, the values of the stronger Gaussian are plotted. Reference data for LCP and HCP from *Denevi et al.* [2007] are shown for comparison. Note that we excluded the data for the synthetic LCP of *Denevi et al.* [2007] because it gives an artificial absorption band of $1.3 \mu\text{m}$ due to rapid cooling, which does not occur in nature [*Klima and Pieters, 2005*], except for some special cases. A few of the spectra for Number 3 with a high $S_{1.3/1.0} \sim 0.78$ (>0.6) are exceptional for Type B craters, implying a contribution by plagioclase, such as is observed around Type A craters.

shows very little signature of plagioclase. We propose that a ratio of $<\sim 95\%$ felsic and $>\sim 5\%$ HCP-dominant mafic components could represent the composition of the lunar highland crust in the zone 2–3 km in depth around the bright-ray craters.

4. Discussion and Conclusions

[14] The origins of the observed HCP are exogenous (physical mixing) and/or endogenous (intrinsic or transformed geneses). The exogenous hypothesis includes 3 possibilities: (A) contamination by basaltic ejecta from the near-side maria [e.g., *Papike et al., 1991; Hawke et al., 2003*], (B) mixing with the material from original deeply distributed gabbroic layer, and (C) intrusion of gabbroic pluton within the crust [*Lucey and Hawke, 1988; Nyquist et al., 2006; Takeda et al., 2006*]. The endogenous hypothesis includes (D) re-differentiation of the impact melt and (E) original crust composition.

[15] Case A holds that impact events involving the near-side maria deposited the basalt ejecta on the observed surface of the lunar highlands. However, we see no systematic shift in the spectral features correlated with thickness of the ejecta or distance to the maria [*Petro and Pieters, 2008*]. Therefore, this case seems unlikely.

[16] Cases B presumes a gabbroic layer at the lower crust or upper mantle. This case holds that an extensive mafic layer of gabbroic composition originally formed from the lunar

magma ocean (LMO) under the upper anorthosite crust. An important assumption for this case is that the originally stratified or inhomogeneous material was well mixed by large impacts reaching the presumed gabbroic layer at depth. The material subsequently migrated from the deeper zone to the near-surface zone. Such mixing in the vertical direction seems probable [e.g., Araki *et al.*, 2009] and this case explains the laterally extended distribution of HCP.

[17] Case C postulates an igneous intrusive melt (e.g., Mg-suite rocks) within the crust. The same assumption of the vertical migration of the material as was used in Case B is necessary. This case, however, rather supports laterally localized distribution of HCP. It would be difficult to explain the widely distributed HCP under Case C.

[18] Case D invokes impact events involving the anorthosite crust, which contains mafic minerals. Heating by impacts causes partial melt of the crust. In this scenario, the partial melt crystallizes HCP as a liquidus mineral for a given range of bulk composition. The observed spectra in this study might be related to impact melt and the local redifferentiation of the original crust. A single impact or its repetition of impact events over lunar history possibly leads to the observed distribution of HCP on the surface.

[19] Case E assumes trapped liquid. This case holds that the mafic trapped liquid within the anorthositic cumulates of LMO would be squeezed upward by the pressure of the overburden of the overlying anorthosite when plagioclase is generated in the late stage of LMO solidification. While Ohtake *et al.* [2009] stated that PAN may exist at depths of 3–30 km, our results are indicative of a wide distribution of HCP at depths of around a few kilometers. If the purity of anorthosite increased consistently with depth from a few to several kilometers, the mafic component trapped within anorthosite would increase near the surface. We expect future studies will investigate the vertical distribution of mafic elements, clarifying the mafic minerals that accompany the anorthosite to test this hypothesis.

[20] We suggest that Cases B and E are most strongly indicated by our results because they seem consistent with the extensive distribution of HCP. Both cases potentially relate to aspects of the evolution of LMO and the crystallization of plagioclase, which are not fully understood [e.g., Hess, 2000]. It is possible that HCP is originally formed at the stage just before plagioclase formation [Snyder *et al.*, 1992] (Case B) or at the same stage as plagioclase formation (Case E). The lunar meteorite Yamato-86032, which was proposed to come from the lunar far side, includes gabbro in a sodic anorthositic clast, probably formed at the deep region [Nyquist *et al.*, 2006; Yamaguchi *et al.*, 2010]. This could be supporting evidence for Case B (and also Case C). We also suggest Case D is possible, which could easily explain the common occurrence of HCP at the bright-ray craters, just assuming impacts on the lunar highlands.

[21] We also found exposed LCP, at the same location as reported by Spudis *et al.* [1988] based on their telescopic observation (23.6°N, 4.5°E; Aratus crater). The SP spectra were in excellent agreement with the telescopic spectra and at a higher S/N ratio.

[22] Our processed SP data allow us to detect LCP as well as HCP. Our results showed that the mafic component now exposed on the surface of most of the bright-ray craters is HCP rather than LCP. Combining with the fact that the

bright-ray craters distribute widely, HCP could exist more extensively than previously proposed [Bussey and Spudis, 2000; Hawke *et al.*, 2003; Tompkins and Pieters, 1999]. Although some studies referred to the heterogeneity of the composition of the lunar highlands and the existence of material of gabbroic composition [e.g., Lucey and Hawke, 1988; Pieters, 1986], they considered that such gabbroic material represents gabbroic pluton and concluded that the noritic composition is ubiquitous. Such an interpretation was possibly biased by data from the Apollo samples, which were conclusive at that time. We now have new global data of continuous spectra obtained by SP/SELENE (Kaguya). From these, we find that HCP is distributed rather widely on the highlands in mafic silicates.

[23] We proposed that HCP is widely distributed near the surface of the lunar highlands. We presented several potential interpretations of the origin of the observed HCP. Further studies and assessments are necessary to constrain or support each of these possibilities. HCP could be a key to understanding the process of the fractional crystallization of plagioclase and the solidification of LMO [e.g., Longhi, 2003; Warren, 1986].

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References

- Araki, H., *et al.* (2009), Lunar global shape and polar topography derived from Kaguya-LALT Laser Altimetry, *Science*, 323, doi:10.1126/science.1164146.
- Bussey, D. B. J., and P. D. Spudis (2000), Compositional studies of the Orientale, Humorum, Nectaris, and Crisium lunar basins, *J. Geophys. Res.*, 105, 4235–4243, doi:10.1029/1999JE001130.
- Cintala, M. J., and R. F. Grieve (1998), Scaling impact melting and crater dimensions: Implications for the lunar cratering record, *Meteorit. Planet. Sci.*, 33, 889–912, doi:10.1111/j.1945-5100.1998.tb01695.x.
- Denevi, B. W., P. G. Lucey, E. J. Hochberg, and D. Steutel (2007), Near-infrared optical constants of pyroxene as a function of iron and calcium content, *J. Geophys. Res.*, 112, E05009, doi:10.1029/2006JE002802.
- Hawke, B. R., C. A. Peterson, D. T. Blewett, D. B. J. Bussey, P. G. Lucey, G. J. Taylor, and P. D. Spudis (2003), Distribution and modes of occurrence of lunar anorthosite, *J. Geophys. Res.*, 108(E6), 5050, doi:10.1029/2002JE001890.
- Hess, P. C. (2000), On the source regions for mare picrite glasses, *J. Geophys. Res.*, 105, 4347–4360, doi:10.1029/1999JE001067.
- Klima, R. L., and C. M. Pieters (2005), Pyroxene spectroscopy: Effects of major element composition on near-, mid-, and far-infrared spectra, *Lunar Planet. Sci.*, XXXVI, Abstract 1462.
- Longhi, J. (2003), A new view of lunar ferroan anorthosites: Postmagma ocean petrogenesis, *J. Geophys. Res.*, 108(E8), 5083, doi:10.1029/2002JE001941.
- Lucey, P. G. and B. R. Hawke (1988), A remote mineralogical perspective on gabbroic units in the lunar highlands, *Proc. Lunar Planet. Sci. Conf.*, 18th, 16–20.
- Matsunaga, T., *et al.* (2008), Discoveries on the lithology of lunar crater central peaks by SELENE Spectral Profiler, *Geophys. Res. Lett.*, 35, L23201, doi:10.1029/2008GL035868.
- Noble, S. K., C. M. Pieters, T. Hiroi, and L. A. Taylor (2006), Using the modified Gaussian model to extract quantitative data from lunar soils, *J. Geophys. Res.*, 111, E11009, doi:10.1029/2006JE002721.
- Nyquist, L., *et al.* (2006), Feldspathic clasts in Yamato-86032: Remnants of the lunar crust with implications for its formation and impact history, *Geochim. Cosmochim. Acta*, 70, 5990–6015, doi:10.1016/j.gca.2006.07.042.
- Ohtake, M., *et al.* (2009), The global distribution of pure anorthosite on the Moon, *Nature*, 461, 236–240, doi:10.1038/nature08317.

- Papike, J., L. Taylor, and S. Simon (1991), Lunar minerals, in *Lunar Sourcebook: A User's Guide to the Moon*, edited by G. Heiken, D. Vaniman, and B. French, pp. 121–181, Cambridge Univ. Press, New York.
- Petro, N. E., and C. M. Pieters (2008), The lunar-wide effects of basin ejecta distribution on the early megaregolith, *Meteorit. Planet. Sci.*, *43*, 1517–1529, doi:10.1111/j.1945-5100.2008.tb01025.x.
- Pieters, C. (1986), Composition of the lunar highland crust from near-infrared spectroscopy, *Rev. Geophys.*, *24*, 557–578, doi:10.1029/RG024i003p00557.
- Snyder, G. A., L. A. Taylor, and C. R. Neal (1992), A chemical model for generating the sources of mare basalts: Combined equilibrium and fractional crystallization of the lunar magmasphere, *Geochim. Cosmochim. Acta*, *56*, 3809–3823, doi:10.1016/0016-7037(92)90172-F.
- Spudis, P. D., B. R. Hawke, and P. Lucey (1988), Materials and formation of the Imbrium Basin, *Proc. Lunar Planet. Sci. Conf.*, *18th*, 155–168.
- Sunshine, J. M., C. M. Pieters, and S. F. Pratt (1990), Deconvolution of mineral absorption bands: an improved approach, *J. Geophys. Res.*, *95*, 6955–6966, doi:10.1029/JB095iB05p06955.
- Takeda, H., et al. (2006), Magnesian anorthosites and a deep crustal rock from the farside crust of the moon, *Earth Planet. Sci. Lett.*, *247*, 171–184, doi:10.1016/j.epsl.2006.04.004.
- Tompkins, S., and C. M. Pieters (1999), Mineralogy of the lunar crust: Results from Clementine, *Meteorit. Planet. Sci.*, *34*, 25–41, doi:10.1111/j.1945-5100.1999.tb01729.x.
- Warren, P. H. (1986), Anorthosite assimilation and the origin of the Mg/Fe-related bimodality of pristine moon rocks: Support for the magmasphere hypothesis, *J. Geophys. Res.*, *91*, D331–D343, doi:10.1029/JB091iB04p0D331.
- Wilhelms, D. E. (1987), The geologic history of the Moon, *U.S. Geol. Surv. Prof. Pap.*, *1348*.
- Yamaguchi, A., et al. (2010), The variety of lithologies in the Yamato-86032 lunar meteorite: Implications for formation processes of the lunar crust, *Geochim. Cosmochim. Acta*, *74*, 4507–4530, doi:10.1016/j.gca.2010.04.015.
- Yamamoto, S., et al. (2011), Preflight and in-flight calibration of the spectral profiler on board SELENE (Kaguya), *IEEE Trans. Geosci. Remote Sens.*, doi:10.1109/TGRS.2011.2144990, in press.
- Yokota, Y., et al. (2010), Refinement of lunar VIS/NEAR phase curve acquired by SELENE spectral profiler, *Lunar Planet. Sci.*, *XLI*, Abstract 2532.
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