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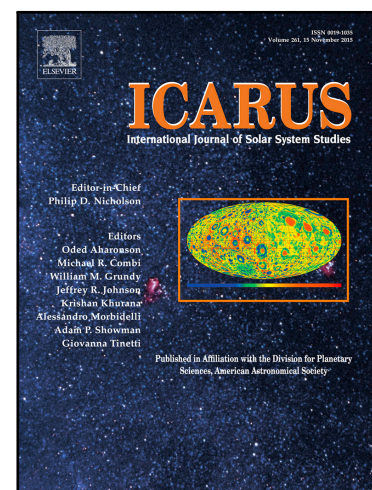
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Iron Distribution of the Moon Observed by the Kaguya Gamma-ray Spectrometer: Geological Implications for the South Pole-Aitken Basin, the Orientale Basin, and the Tycho Crater.

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Abstract

In this study we describe the distribution of iron on the Moon as obtained by the Kaguya high energy resolution gamma-ray spectrometer (KGRS). We achieved for the first time the identification of iron based on the fast neutron flux obtained by the KGRS. The iron distribution obtained by KGRS is compared to that of the Lunar Prospector Gamma-Ray Spectrometer (LP GRS), showing that the FeO distributions observed by KGRS and LP GRS, in general, are in good agreement. Furthermore, we compare the iron content data obtained by KGRS and LP GRS to spectral reflectance measurements of the Clementine, Kaguya and Chandrayaan-1 spacecraft as well as those inferred from returned samples. We found differences in FeO concentration and distribution in areas of moderate abundance (6-15 wt%) of the South Pole-Aitken basin, Mare Orientale, and around the crater Tycho crater. It implies that high concentrations of FeO at Mare Ingenii in the South Pole-Aitken basin and Mare Orientale are due to the presence of mare basalts, whereas the enriched FeO content in the central depression of the South Pole-Aitken basin and the Tycho crater indicates the presence of mafic materials such as impact melt breccia.

Keywords: Kaguya gamma-ray spectrometer (KGRS), gamma-ray, neutron,

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15 moon, iron.

1. Introduction

The elemental composition of a planetary surface is of essential importance in planetary science, and it provides important clues to solve questions related to planetary formation and evolution. In particular, iron is one of the most important major elements in solar system bodies such as planets, meteorites, and asteroids (e.g. [1, 2]). For the Moon, the determination of the iron content is also important for the development of the magma ocean theory [3]. The iron abundance of the lunar surface has already been studied using Clementine multispectral data (e.g. [4]) and Lunar Prospector Gamma Ray Spectrometer (LP GRS) data [5, 6]. Minerals such as olivine ($(\text{Fe, Mg})_2\text{SiO}_4$) and pyroxene ($(\text{Ca, Mg, Fe})_2\text{Si}_2\text{O}_6$) forming the lunar mare basalt have a high iron content while plagioclase (mainly $\text{CaAl}_2\text{Si}_2\text{O}_8$) forming anorthosite in the highlands contains a very low abundance of iron. Samples returned by the Apollo and Luna missions as well as lunar meteorites have provided local information about the source regions, and remote sensing techniques, such as spectral reflectance measurements by Clementine [4] and gamma-ray spectroscopy by Lunar Prospector [5, 6] have provided insights into the global iron distribution. The spatial resolution of spectral reflectance measurements represents a great advantage compared to gamma-ray spectroscopy. However, high resolution elemental maps cannot be obtained for the lunar polar regions due to the low quality of the reflectance spectra under oblique illumination conditions. On the other hand, gamma-ray spectroscopy directly obtains information about the major elements over the whole lunar surface by measuring gamma-rays emitted by nuclear reactions between neutrons and atomic nuclei of the material. The elemental abundance data obtained by spectral reflectance measurements and gamma-ray spectroscopy are complementary to each other. Moreover, the simultaneous analysis of spectral reflectance measurements and low resolution elemental maps obtained using gamma-ray spectrometry is able to create high resolution maps of elemental

abundances [7, 8]. Therefore, it is interesting to compare the iron distribution
 45 obtained by spectral reflectance data with the results of gamma-ray spectroscopy
 measurements.

Gamma-ray spectrometers have been employed on several planetary orbiters
 such as Lunar Prospector [9], Mars Odyssey [10], Kaguya (SELENE) [11],
 Chang'E-2 [12], and MESSENGER [13] and have performed successful observa-
 50 tions of the elemental composition of the examined planetary surfaces. *Lawrence*
et al. [5] and *Prettyman et al.* [6] analyzed data from a bismuth germanate
 (BGO) scintillator, the main detector of the LP GRS, having a high detection
 efficiency and low energy resolution. They obtained the global distribution of lu-
 nar iron from the neutron capture gamma-ray flux and the thermal neutron flux
 55 obtained by the neutron spectrometer. The Kaguya Gamma-Ray Spectrometer
 (KGRS) employed a High-Purity germanium (HPGe) crystal as a main detector
 and a BGO scintillator for anticoincidence [11]. The characteristic feature of
 the HPGe detector is its excellent energy resolution, which enables the accurate
 identification of individual gamma-ray lines in a complex-shaped peak such as
 60 an iron gamma-ray line at 846 keV.

Inelastic scattering and capture of neutrons emit gamma-rays from the plan-
 etary surface. Generally, fast neutrons induce inelastic scattering while thermal
 neutrons induce neutron capture. These neutrons are produced by galactic cos-
 mic ray particles which vary depending on the level of solar activity. Therefore,
 65 it is preferable to correct the gamma-ray count rate by the neutron fluxes that
 were measured simultaneously, whereas the Kaguya spacecraft was not equipped
 with a neutron spectrometer. For this reason, the neutron correction of the
 KGRS has been made so far by the neutron fluxes obtained nearly 10 years
 before by the Lunar Prospector neutron spectrometer. Recently, *Hareyama et*
 70 *al.* [14] inferred the fast neutron flux from gamma-ray spectra of the KGRS. The
 neutron correction of inelastic scattering gamma-ray count rates by the fast neu-
 tron flux obtained by the KGRS is the best way to derive elemental abundance
 precisely because we can avoid problems arising due to changes of the neutron
 flux over time. On the other hand, according to *Hareyama et al.* [14], the rel-

75 ative changes of the fast neutron flux obtained by the KGRS and LP neutron
 observations show a high correlation, with differences of $\sim 3\%$. The similarity
 of the fast neutron flux might be caused by a similar level of solar activity dur-
 ing the observation periods of Kaguya and LP as both were performed during
 a solar minimum phase [15]. Hence, there are apparently no major problems
 80 to correct KGRS count rates of inelastic gamma-ray scattering by the LP fast
 neutron fluxes. However, in this study it is important that the iron concentra-
 tion was derived using the gamma-ray and neutron count rates obtained by the
 HPGe detector. Anyway, gamma-ray and neutron fluxes should always be mea-
 sured simultaneously when neutron observations of the target have never been
 85 conducted or the observation period of the Moon is during the solar maximum
 phase.

In this work, iron gamma-rays due to inelastic scattering at 846 keV are
 analyzed for the first time to construct a lunar iron distribution map without
 using Lunar Prospector neutron spectrometer data. We will show that the use
 90 of KGRS neutron data improves the accuracy of the iron abundance map. The
 results of peak fitting and neutron correction will be confirmed to be consis-
 tent with those of 7.63-7.65 MeV neutron capture gamma-rays corrected by the
 Lunar Prospector neutron flux. The KGRS iron map will be compared with
 those of LP GRS and spectral reflectance measurements of the Clementine UV-
 95 VIS and NIR cameras [16], Kaguya Multiband Imager [17], and Chandrayaan-1
 Moon Mineralogy Mapper (M^3) [18].

2. Methods

2.1. The KGRS observation and peak analysis of the KGRS data

100 The Kaguya spacecraft was launched on September 14, 2007. It took a
 circular polar orbit with a nominal altitude of 100 km and an inclination of
 90 degrees [19]. The orbital period of the Kaguya was ~ 2 hours. The KGRS
 instrument acquired a spectrum every 17 seconds. It observed the lunar surface
 for a period of ~ 180 days between December 2007 and May 2009. Fig. 1(a)

shows KGRS gamma-ray spectra in the energy range of 580-1,100 keV, including
 105 the inelastic scattering gamma-ray line of iron $^{56}\text{Fe}(\text{n}, \text{n}\gamma)$ at 846 keV. Gamma-ray lines derived from a variety of elements such as aluminum, iron, thorium series, and uranium series were observed. The total observation period of KGRS is divided into periods 1–3 defined by different spacecraft altitude and KGRS spectral energy resolution, respectively [20]. In this work, we conducted peak
 110 analyses of spectra during the period 3 since the energy and spatial resolution of period 3 (7.1 keV at 1.46 MeV and 67 km², respectively) is superior to those of periods 1–2. Gamma-ray counts were accumulated in areas of 5 by 5 degrees in latitude and longitude to construct a global map, and the count rates were smoothed by the nearest neighbor method with a radius of 300 km,
 115 corresponding to two pixels in equatorial region. In this analysis, one point has at most $\sim 40\%$ of its information in one pixel.

Iron gamma-ray peaks due to inelastic scattering $^{56}\text{Fe}(\text{n}, \text{n}\gamma)$ at 846 keV and due to neutron capture $^{56}\text{Fe}(\text{n}, \gamma)$ at 7.63–7.65 MeV were analyzed to obtain iron gamma-ray count rates. Energy spectra and results of peak analysis around
 120 these gamma-ray lines are shown in Figs. 1 and 2. Figure 1 shows gamma-ray spectra with an energy bin of 1.2 keV around the energy of 846 keV of inelastic scattering, whereas in Fig. 2 the energy bin corresponds to 4.4 keV at neutron capture energies of around 7.63–7.65 MeV. There are two types of energy peaks in Fig. 1(a), a gamma-ray line peak for monoenergetic gamma-rays
 125 and a sawtooth peak resulting from inelastic scattering of fast neutrons and Ge nuclei, $\text{Ge}(\text{n}, \text{n}\gamma)$, in the detector crystal [21]. The sawtooth peak has a high energy tail which corresponds to the sum of the Ge excitation energy and the Ge recoil energy due to the incident neutron. The low-energy tail of the gamma-ray spectra originates from the radiation damage of the HPGe crystal. Applying a
 130 peak-fitting algorithm to the energy spectra yields the count rates of the gamma-ray peaks. The peak functions of the gamma-ray line peaks and sawtooth peaks are shown in the work of *Hareyama et al.* [14]. In the following, the sum count rates of the 7.63 MeV and 7.65 MeV iron gamma-ray lines are treated as the count rates of neutron capture gamma-rays to obtain a statistically sufficient

135 number of counts.

2.2. Neutron correction

To derive the elemental composition of the lunar surface from gamma-ray counts, the correction for neutron flux is essential since gamma-ray emission is proportional to the product of the numbers of target nuclei and neutrons, respectively. Moreover, the correction for neutron flux is especially important in iron gamma-ray analysis since the number of neutrons produced by galactic cosmic ray particles in a certain area increases with the average atomic number in the area. Additionally, thermal neutron flux varies by a factor of 3 across the surface of the Moon while the variation of fast neutron flux is at most $\sim$ 30 % [26]. Accordingly, the use of gamma-rays due to inelastic scattering is advantageous since the gamma-ray flux of neutron capture is largely affected by variations of the thermal neutron flux. In this work, the accuracy of measurements of the lunar iron content is improved by using gamma-ray and neutron data directly inferred from KGRS observations. This is the first derivation of the lunar iron abundance from gamma-ray count rates by inelastic scattering and the fast neutron flux, which were obtained by KGRS.

2.3. Error estimation

The statistical error in the gamma-ray counts, N , is obtained by

$$\begin{aligned} N_n &= N_g - N_b \pm \sqrt{\sigma_{N_g}^2 + \sigma_{N_b}^2} \\ &= N_g - N_b \pm \sqrt{\sigma_{N_n}^2 + 2\sigma_{N_b}^2} \end{aligned} \quad (1)$$

$$\sigma_{N_b}^2 = \sum_i \sigma_{N_{b_i}}^2 \quad (2)$$

where g , n , and b in the subscript represent gross, net, and background of gamma-ray count. The gross is sum of net and background. The value of $\sigma_{N_b}^2$ is obtained by the squared sum of background components as in Eq. (2). In our peak analysis, N_n corresponds to the iron gamma-ray counts. N_{b_i} corresponds to gamma-ray counts of baseline, sawtooth, Mn, and Al for inelastic scattering, and those of the baseline for neutron capture in the FWTM energy range of

iron gamma-rays. The FWTM energy ranges of iron gamma-rays were 839.0–
 849.2 keV for inelastic scattering and 7.562–7.646 MeV for neutron capture,
 which are shown in Figs. 1 and 2. In the analysis of inelastic scattering gamma-
 rays, the proportions of sawtooth, Mn and Al peaks included in the FWTM were
 determined by fitting of whole spectra, yielding values of 18 % for sawtooth, 38
 % for Mn, and 81 % for Al, respectively.

3. Results

3.1. Gamma-ray count rates due to inelastic scattering and neutron capture

The gamma-rays due to inelastic scattering have larger count rates than the
 neutron capture gamma-rays. The count rate of gamma-rays due to inelastic
 scattering (0.021–0.27 counts per second) was up to ~ 9 times larger than that of
 neutron capture gamma-rays (0.0080–0.032 counts per second), while *Reedy* [22]
 estimated the emission rates of the gamma-rays for both inelastic scattering and
 the sum of the neutron capture gamma-rays to be comparable. Simple Monte
 Carlo simulation injecting monoenergetic pencil gamma-rays perpendicularly
 towards the center of the detector showed ~ 5 times larger detection efficiency
 of 846 keV gamma-rays than that of 7.63–7.65 MeV gamma-rays in the KGRS
 instrument. It is considered that the variations of the neutron flux and the
 detection efficiency cause these large differences in count rates since in general
 the thermal and fast neutrons are inversely correlated. Statistical errors in the
 maximum count rates of inelastic scattering and neutron capture were calculated
 based on Eq. (1) as ~ 8.5 % and 23 %, respectively. Therefore, it is found that
 the 846 keV Fe gamma-ray peak is statistically superior to the 7.63–7.65 MeV Fe
 peaks. The scatter plot of the gamma-ray count rates of inelastic scattering and
 neutron capture is shown in Fig. 3. We note that the count rates of inelastic
 scattering are corrected by the fast neutron flux derived from the sawtooth
 peak [14] and those of neutron capture are corrected by the thermal neutron
 flux obtained by the Lunar Prospector neutron spectrometer [26]. These two

count rates are roughly in agreement with a linear correlation coefficient of $R = 0.893$.

190 3.2. Calibration

The count rates of iron gamma-rays are calibrated to the iron concentration by using ground truth of the Apollo-Luna returned samples and meteorites from lunar feldspathic highland terrain (FHT). Although the returned samples hold some local information of the landing site, they are not always representative for the average composition of different types of lunar rocks in the area corresponding to the spatial resolution of KGRS. Hence, we conducted the calibration with these samples carefully. The difference in spatial resolution is partially improved by using the regolith and soil samples, which are made of mixed samples around the sampling sites. Therefore, the soil and regolith samples of the Apollo and Luna missions are selected as ground truth since these samples are more suitable to calibrate the gamma-ray count rates than the rock samples. However, the landing sites of Luna 16 and 24 were excluded from calibration since it is considered that these samples do not have a composition that is representative of the respective landing sites [27, 28]. The regolith samples of Apollo 15 and 17 were also excluded from calibration because the variation of the iron concentration among these samples was large due to the location of the landing sites at the boundary between mare and highland [29, 30]. The FeO and Al₂O₃ abundances of the ground truth are shown in Table 1 [30, 31, 32, 33, 34]. The iron gamma-ray count rates corresponding to each point are also shown in Table 1. The gamma-ray count rate of FHT is obtained by averaging over the northern farside quarter of the Moon.

Figure 4 shows plots between iron gamma-ray count rates, x , and FeO or Al₂O₃ abundances, y , of the ground truth in Table 1. As shown in this figure, there is an anti-correlation between iron and aluminum. This means that the influence of aluminum background for the iron gamma-ray peak of inelastic scattering is large when the iron content is low. By least squares fitting, we obtained linear relationships of $y = 107x - 3.72$ with a linear correlation coef-

ficient $R = 0.950$ for inelastic scattering (Fig. 4(a)), and $y = 419x - 2.59$ with
 $R = 0.723$ for neutron capture (Fig. 4(b)). Hereafter, the abundance of iron rep-
 220 resented as FeO weight percent is determined by this relationship. However, the
 count rates of iron gamma-rays are below the detection limits (N_d with 1σ) in
 some low-FeO areas. The detection limits were determined by iron gamma-ray
 counts and background counts in each pixel. The KGRS lower limits of detec-
 tion are ~ 3 – 4 wt% for inelastic scattering and ~ 6 wt% for neutron capture;
 225 i.e., gamma-ray counts of neutron capture correspond to FeO values below the
 detection limits at some ground truth sites. Thus, these areas are interpreted
 to contain very low abundances of FeO. The FeO abundances in such areas are
 represented as black pixels in the iron distribution map. Because of the statisti-
 cal accuracy, which is shown as error bars in Fig. 4, we will use in the following
 230 the count rate of the 846 keV iron gamma-ray line corrected by the fast neutron
 flux to derive the iron concentration. The statistical error in the lower limits is
 ~ 35 %; i.e. the FeO abundance varies by 1.0–1.4 wt% at the lower limits.

To confirm that the removal of aluminum background during the gamma-
 ray line of inelastic scattering is correct, the concentration of Al obtained by
 235 LP GRS [6] and FeO, obtained by both KGRS and LP GRS [6], on the northern
 lunar farside are compared in Fig. 5. The KGRS data were rebinned to $150 \text{ km} \times 150 \text{ km}$
 equal area pixels, which corresponds to the spatial resolution of the
 LP GRS data sets, to construct Fig. 5. The LP GRS Al_2O_3 and FeO values show
 a strong anti-correlation, although the lower limit of ~ 4.2 wt% is apparent. On
 240 the other hand, the anti-correlation between LP GRS Al_2O_3 and KGRS FeO
 is weak. The weaker anti-correlation of KGRS compared to LP GRS is caused
 by the influence of the aluminum peak near the 846 keV iron gamma-ray line.
 However, the influence is not strong enough for the anti-correlation between
 iron and aluminum to disappear. This implies that the subtraction of peaks
 245 surrounding the 846 keV iron gamma-ray line is acceptably correct.

Table 1: FeO and Al₂O₃ abundances of the returned samples [30, 31, 32, 34] and FHT [33] and iron gamma-ray count rates. Errors of sample data and KGRS count rates represent standard deviations and statistical errors, respectively.

	Sample data (wt%)		KGRS count rate (counts per sec)	
	FeO	Al ₂ O ₃	(n, n γ)	(n, γ)
A11 [32]	15.8 $\pm$ 0.15	13.6 $\pm$ 0.18	0.161 $\pm$ 0.021	0.033 $\pm$ 0.011
A12 [34]	16.5 $\pm$ 0.17	12.5 $\pm$ 0.40	0.185 $\pm$ 0.021	0.035 $\pm$ 0.013
A14 [34]	10.5 $\pm$ —	17.3 $\pm$ —	0.149 $\pm$ 0.021	0.036 $\pm$ 0.013
A16 [31]	5.51 $\pm$ 0.06	27.8 $\pm$ 0.30	0.075 $\pm$ 0.021	0.015 $\pm$ 0.007
L20 [30]	7.46 $\pm$ 0.47	22.75 $\pm$ 0.69	0.114 $\pm$ 0.026	0.035 $\pm$ 0.010
FHT [33]	4.4 $\pm$ 0.5	28.2 $\pm$ 1.0	0.076 $\pm$ 0.001	0.017 $\pm$ 0.001

3.3. FeO abundance map

The lunar FeO distribution map obtained by the KGRS instrument is shown in Fig. 6. The FeO abundance has a general trend that it is high in mare regions and low in the highlands. Its maximum is in the western mare region on the nearside. In some highland regions, the count rate of iron gamma-rays was below the detection limit. The South Pole-Aitken (SPA) basin and some lava-filled impact basins such as Mare Orientale and Mare Crisium also show relatively high FeO abundances. This general trend is consistent with previous works based on Clementine and LP GRS data [4, 5, 6]. The error map of Fig. 6 calculated based on Eq. (1) is shown in Fig. 7.

The FeO abundances obtained by KGRS and LP GRS were also compared, see histogram in Fig. 8. The data set of *Prettyman et al.* [6] was used as the LP GRS data since the FeO abundance values obtained by the calibration method of *Lawrence et al.* [5] are affected by Al, especially in the highlands. The KGRS data were rebinned to 150 km $\times$ 150 km equal area pixels as in the case of Fig. 5. The pixels with FeO values below the detection limit are excluded in Fig. 8. The iron distribution obtained by KGRS and LP GRS generally shows a good correlation, especially in areas with FeO abundances exceeding 6 wt%. On

the other hand, the iron concentration at around (50° W, 20° N) becomes lower than that of the surrounding area (~ 15 wt%, shown as green dots in Fig. 6). This “hole” is absent in earlier maps [5, 6]. The position of the hole seems to correspond to that of Aristarchus Plateau. Some previous studies of reflectance spectra (e.g., [35]) reported an anorthositic signature at the crater Aristarchus. The apparent depletion of iron in this region might be caused by the averaging of the iron concentration due to the limited spatial resolution and the applied smoothing. However, considering the statistical error of $\sim 10\%$ in this region, we cannot clearly infer the presence of an anorthostic signature. Additionally, some differences are found in the regions with low to moderate FeO abundances (< 15 wt%).

The FeO histogram of the northern farside is also presented by dots in Fig. 8. The average of FeO on the northern farside is ~ 4.6 wt%. This value is consistent with the FeO concentration of FHT [33]. However, there are a lot of points where the FeO concentration is below the detection limits, and these points are not included to calculate this average value. In these areas, large gamma-ray counts of aluminum increase the detection limits, such that the iron gamma-ray counts become lower than the detection limits. Actually, the inverse correlation of iron and aluminum on the northern farside causes a large statistical error of up to $\sim 90\%$, and the detection limit was calculated as ~ 5.0 wt%. Considering this fact, the expanse of regions below the detection limit is acceptable although the FeO concentrations in these regions are ambiguous.

4. Discussion

4.1. Comparison between the KGRS and LP GRS iron maps

One difference between the KGRS and the LP GRS maps is the applied calibration method. Numerical calculations were used in order to derive absolute abundances of FeO from the gamma-ray count rates of LP GRS [5, 6], while we derived it with a calibration using sample ground truth. In spite of the differences between the calibration methods, a reasonable agreement of the

FeO distribution between KGRS and LP GRS was obtained. We thus conclude that our ground truth based calibration has been conducted successfully. On the other hand, in many areas where the FeO abundances are below the detection limits of KGRS, the LP GRS data show ~ 4 wt% FeO [6]. This value is comparably high since the KGRS detection limits are ~ 3 –4 wt%. Although the minimum FeO concentration of the LP GRS map is ~ 3.4 wt%, pixels with values below 4 wt% are rare. We should thus consider the lower limit of the LP GRS FeO concentration as ~ 4 wt%. Hence, the lower limit of KGRS is improved in comparison to LP GRS (see also Fig 8).

The important difference between KGRS and LP GRS is the main detector; the HPGe detector of the KGRS instrument is better in energy resolution and worse in detection efficiency than the BGO scintillator of the LP GRS instrument. The differences in energy resolution directly affect the identification capability of the detector. Moreover, 846 keV inelastic scattering gamma-rays were used to construct the KGRS iron map, while for the LP GRS map 7.63–7.65 MeV neutron capture gamma-rays were used. Although low energy gamma-rays are detected with high efficiency, the detection efficiency of KGRS at 846 keV and that of LP GRS at 7.63–7.65 MeV are almost comparable. Therefore, the discrepancy in the region of low to moderate FeO abundance is considered to be caused by the differences in the gamma-ray emission process, i.e., inelastic scattering vs. neutron capture. On planetary surfaces with zero or very low hydrogen content such as the Moon, the flux of fast neutrons inducing inelastic scattering is, in general, ~ 5 times larger than that of thermal neutrons inducing neutron capture [36]. The low thermal neutron flux causes its large variation over the lunar surface as mentioned in Sec. 2.2. In the low-FeO areas, the thermal neutron flux is high, i.e., the neutron correction decreases the FeO abundances derived from the gamma-ray count rates. The low-FeO areas in the LP GRS maps shown in the following sections seem to correspond to the detection limit (~ 4 wt%). We believe that in these regions the variation of thermal neutron flux affects the gamma-ray count rates obtained by LP GRS and the strong reduction of the FeO concentration by the neutron correction led

to a lower limit of the LP GRS calibration. The strong variations of the thermal
 325 neutron flux resulted in differences between the KGRS map and the LP GRS
 map in areas with low to moderate FeO content.

In the following discussion, we will pay special attention to areas of low
 to moderate FeO abundance such as the SPA basin, Mare Orientale, and the
 crater Tycho, which exhibit distinct differences between the KGRS map and
 330 the LP GRS map. FeO abundance maps of the SPA, Mare Orientale, and the
 Tycho area are shown in Figs. 9, 10, and 11, respectively.

4.2. Local differences in FeO distribution

4.2.1. The South Pole-Aitken Basin

The SPA basin is the largest lunar impact structure with a diameter of
 335 $\sim 2,600$ km. It is located near the lunar south pole. The SPA basin is an
 attractive research target since it is believed that the large impact excavated the
 deep crust or mantle (e.g. [37, 38]). Although various previous works have been
 devoted to geological studies of the SPA basin (e.g. [39, 40]), the mineralogical
 and geological understanding of the basin structure and interior still remains
 340 limited.

Figure 9 shows elemental maps rebinned to equal area pixels of $150 \text{ km} \times 150 \text{ km}$ of the region surrounding the SPA, where equal latitude $\times$ equal
 longitude pixels are too small in the polar regions. The LP GRS map (Fig. 9(b))
 was constructed using the data set of *Lawrence et al.* since it has a higher spatial
 345 resolution than the data set of *Prettyman et al.*. The FeO content in this region is
 relatively high, such that the influence of Al can be neglected. There are distinct
 differences between the KGRS map and the LP GRS map. The maximum FeO
 concentration of the KGRS map is up to 13.5 wt%, whereas that of the LP GRS
 map is up to 11.5 wt% in the same area. The KGRS map (Fig. 9(a)) shows two
 350 high-FeO areas in the SPA, the central depression (163°W , 54°S [40]) and Mare
 Ingenii (164°E , 34°S) represented as orange and blue dots, respectively, while
 the LP GRS map (Fig. 9(b)) shows only one area of high FeO abundance in the
 central depression. The highest FeO region in the SPA is slightly offset from

the central depression to the northeast in the KGRS map. This offset becomes
 355 apparent in comparison with the location of the Apollo basin represented by red
 dots in Fig. 9. It may be due to the relatively low spatial resolution of KGRS,
 leading to a “smoothed” representation of the FeO distribution. The Apollo
 basin is considered to be composed of mare materials, and the FeO distribution
 obtained by the Kaguya multiband imager shows the highest concentration of
 360 FeO (~ 16 wt%) in the central part of that basin [40]. The Kaguya multiband
 imager also shows high concentrations near the central depression and in Mare
 Ingenii (~ 13 -15 wt% and 16 wt%, respectively) [40].

Ohtake et al. [40] interpreted the Mare Ingenii region as mare according to
 its high concentration of FeO and TiO₂. The FeO abundance of ~ 11.3 wt% at
 365 Mare Ingenii region observed by KGRS is smaller than typical mare values ($>$
 13 wt% [41]). However, this value is also interpreted as the effect of averaging
 due to the relatively low spatial resolution. On the other hand, they present
 two possible scenarios as the origin of the SPA central depression: impact melt
 dominated by high-Ca pyroxene and old mare covered by ejecta of later impacts,
 370 suggesting that the impact melt origin is more likely [40]. The Th and CaO dis-
 tributions obtained by LP GRS [6] and KGRS [42], respectively, are compared
 in Fig. 9(c) and (d) to discuss the origin of the central depression. The highest
 Th concentration in SPA of up to 3.2 ppm is observed between Mare Ingenii
 and the central depression, while the Th concentration at the central depression
 375 (~ 1.4 ppm on the average) is lower than that of its surroundings [6]. The area
 of maximal Th content is considered to be dominated by high-Ca pyroxene [40],
 while no particular elevation of the Ca content is apparent there. However, the
 Th distribution around the central depression suggests that the central depres-
 sion and the Th maximum area were formed by different processes. The CaO
 380 distribution shows similar values in the central depression, Mare Ingenii, and
 the Apollo basin (~ 14 wt%). Both the mare and nonmare contain some high-
 Ca pyroxene, and they exhibit almost the same range in Ca concentration. This
 fact might explain the absence of elevated Ca content at the area of maximal
 Th content. Considering the FeO enhancement in the central depression of the

385 Apollo basin, the FeO concentration in the central depression is considered to
be ~ 13 wt% or less. This value is accepted to be a result of mafic impact melt
breccia returned from the nearside (< 13 wt%) [43, 44] rather than mare basalt
(> 13 wt%) [41]. Therefore, the eruption of mare basalts apparently occurred
as a result of the Ingenii basin impact, possibly favored by the thinning of the
390 crust by the previous SPA impact.

4.2.2. The Orientale Basin

The Orientale basin is a multi-ring impact basin centered at (93° W, 19° S).
The diameter of the Orientale basin is ~ 900 km, and large mare deposits
are located in the central part of 300 km diameter. This large impact basin has
395 been studied extensively to understand mechanisms of basin formation and lunar
volcanism (e.g. [45, 46]) since the Orientale basin is the youngest lunar multi-
ring impact basin (~ 3.7 Ga [47, 48]). Some studies indicate that the impact
event of the Orientale basin has sampled the upper boundary of a magmatic
intrusion [49].

400 The FeO distribution in the Orientale basin and its surroundings obtained by
KGRS and LP GRS [6] are shown in Fig. 10. Both maps exhibit a concentration
of FeO at Mare Orientale which is higher (~ 8 wt%) than that in the outer,
multi-ringed part of the basin. The FeO concentration below the typical value
of mare basalts is thought to be caused by the spatial smoothing just like in
405 the case of Mare Ingenii. Very low FeO abundances below the detection limits
(< 3 wt%) are also observed outside Mare Orientale in the KGRS map. This
area corresponds to the multiple rings of the Orientale basin that is believed to
be dominated by anorthosite [50, 51]. Spectral data acquired from Earth [50]
and by the Clementine spacecraft [51] also reveal a high content of FeO in Mare
410 Orientale (~ 16 wt%) and a very low content (< 2 wt%) in the outer multi-ring
area. These previous studies suggest mare basalt in Mare Orientale. The CaO
distribution (Fig. 10(c) [42]) shows a lower abundance (~ 17 wt%) at Mare
Orientale and a higher abundance (~ 19 wt%) in the outer multi-ring area.
These results are consistent with those of previous studies [49, 50, 51].

415 The gamma-ray observations by the Chang'E-2 has proposed the existence
 of Orientale ejecta southwest of the Orientale basin ($120\text{--}90^\circ$ W, $30\text{--}50^\circ$ S) [52].
 These areas are shown as yellow dots in Fig. 10. They reported a basaltic com-
 position with a higher content of potassium than the environment as evidence
 of the Orientale ejecta. The basaltic composition is estimated to be high in
 420 FeO and low in CaO. On the other hand, anorthosite with its low FeO and high
 CaO concentration is considered to be dominant in the outer multi-ring areas
 as mentioned above. Thus, the signatures of FeO and CaO should be observed
 if Orientale ejecta were located in those regions. However, the KGRS maps in
 Fig. 10 show low FeO and low CaO concentrations in these regions. These con-
 425 centrations of FeO and CaO are not consistent with the presence of Orientale
 ejecta. Moreover, high concentrations of potassium are neither indicated by
 the KGRS observations [53] nor by the LP GRS data [6]. This discrepancy is
 thought to be due to the 1.436 MeV gamma-rays from naturally radioactive La
 in Chang'E-2 GRS and not from the 1.461 MeV emission of potassium. The use
 430 of a $\text{LaBr}_3(\text{Ce})$ detector in the Chang'E-2 GRS causes high background counts
 around 1.46 MeV, i.e., near the potassium gamma-ray line. The statistical ac-
 curacy of the Chang'E-2 GRS map becomes low due to these high background
 gamma-ray counts. Based on the discussion provided above, we conclude that
 there are no evident signatures of the presence of impact ejecta in the region of
 435 the Orientale basin.

4.2.3. The crater Tycho

440 The crater Tycho located at 12° W, 43° S with a diameter of ~ 85 km has
 been studied because of its relatively young age of ~ 110 Ma [54] and its pe-
 culiar spectral features [55]. According to spectral reflectance measurements
 from the Earth [56] and orbiters such as Clementine [57], Kaguya [58], and
 Chandrayaan-1 [59], the crater Tycho is considered to be composed of mafic
 materials dominated by high-Ca pyroxene. These spectral studies indicate FeO
 abundances of $\sim 7\text{--}8$ wt% on the floor of crater Tycho and ~ 14 wt% at the cen-
 tral peak of Tycho crater [60]. However, gamma-ray spectroscopy by LP GRS [6]

445 indicates very low FeO abundances of ~ 5 wt% inside Tycho (Fig. 11(b)). On the other hand, the KGRS data show ~ 8 – 9 wt% FeO in that region (Fig 11(a)). There is a little difference between the location of Tycho and the high-FeO area, where the smoothing of the KGRS map may have caused an extension of the high-FeO area at Tycho towards northwest.

450 Some of the returned samples of Apollo 16 ascribed to the Tycho impact ejecta have a FeO content of 6.9–9.7 wt% [31]. The FeO concentrations of these samples are consistent with those in Tycho observed by the KGRS. Similar to the LP GRS data, in the Diviner Christiansen frequency (CF) map in *Greenhagen et al.* [61] based on thermal infrared multispectral image data of the Diviner
455 instrument on the Lunar Reconnaissance Orbiter (LRO), the crater Tycho seems to be composed of feldspathic (thus low-Fe) material. An explanation of this difference between the results of visible and near infrared data analyses [57, 58, 59] may be a possible sensitivity of the CF data to soil maturity, which is very low for the crater Tycho, since in the CF map of *Lucey et al.* [62] the crater
460 Tycho does not appear any more as a negative anomaly after applying their correction for soil maturity. These results support the interpretation that the spectral observations indicate a basaltic or gabbroic pluton excavated by the Tycho impactor.

In the future, we plan to apply methods previously developed for the joint
465 analysis of M³ and LP GRS data to the analysis of KGRS FeO data [8]. It will allow us to create a high-resolution iron map of the vicinities of the crater Tycho and to study geological processes in this region with very high spatial resolution.

5. Conclusion

470 We have conducted a spectral analysis of iron gamma-rays obtained by the KGRS instrument. Gamma-ray spectra with high energy resolution and saw-tooth peak gamma-ray spectra observed by the HPGe detector enabled an elemental analysis of high accuracy. The count rates of iron gamma-rays and

fast neutrons were obtained to construct a global FeO map. With the fast
 475 neutron count rates obtained by KGRS, the iron abundance was for the first
 time obtained without data acquired by another neutron spectrometer. The
 comparison of the KGRS and LP GRS [6] FeO maps, in general showed a good
 agreement, especially in the area of > 6 wt% FeO despite the different cali-
 bration methods. However, some differences between the KGRS and LP GRS
 480 maps are apparent in high-FeO areas within the SPA, Mare Orientale and the
 crater Tycho. It is considered that the inelastic scattering gamma-rays ($^{56}\text{Fe}(n, n\gamma)$ at 846 keV) analyzed by KGRS were more useful than the neutron capture
 gamma-rays ($^{56}\text{Fe}(n, \gamma)$ at 7.36–7.38 MeV) measured by LP GRS to construct
 the iron map. Variations over the lunar surface of the fast neutron flux yielding
 485 inelastic scattering gamma-rays are smaller than those of the thermal neutron
 flux inducing neutron capture gamma-rays. The effect of the thermal neutron
 variations might be relevant in low-FeO areas of the LP GRS map. A low vari-
 ation of the fast neutron flux allows for the construction of an accurate FeO
 map. Considering previous studies based on near-infrared reflectance spectra
 490 and gamma-ray measurements, the origin of the high FeO content in the above
 regions has been discussed. The FeO abundance at Mare Ingenii (~ 12 wt%)
 in the SPA is consistent with that of mare basalt (> 13 wt% [41]). This is a
 plausible result since the smoothing of the KGRS map due to its relatively low
 spatial resolution decreases the apparent FeO concentration. Although the FeO
 495 abundance at the central depression is ~ 14 wt%, it is interpreted as impact
 melt dominated by high-Ca pyroxene. The highest FeO concentration at the
 central depression is considered to be increased by mare material in the Apollo
 basin because of the limited spatial resolution. The distributions of Th and
 CaO in these regions [6, 42] are consistent with this origin.

500 A high FeO content of presumably basaltic origin has been observed at Mare
 Orientale. A very low FeO abundance below the detection limit is also observed
 in the KGRS map in the area occupied by the Orientale basin rings. This result
 supports the fact that the materials in this region are dominated by anorthosite
 having a low FeO content. This interpretation is also supported by the distribu-

tion of CaO. However, the characteristic features of the Orientale impact ejecta as proposed by the Chang'E-2 gamma-ray spectrometer measurements [52] are not present in our FeO map at the locations found by the Chang'E-2 team [52].

The KGRS FeO map shows a high FeO content of 8–9 wt% at the crater Tycho, which was not observed by LP GRS. This FeO concentration is consistent with spectral reflectance measurements. The high FeO content at the crater Tycho implies that this region is composed of mafic materials. The agreement in FeO content between the KGRS map and the Apollo 16 returned samples ascribed to the Tycho impact ejecta also supports this assumption.

References

- [1] E. Anders, N. Grevesse, Abundances of the elements: Meteoritic and solar, *Geochim. Cosmochim. Ac.* 53 (1989) 197–214. doi:10.1016/0016-7037(89)90286-X.
- [2] N. Yamashita, T. H. Prettyman, D. W. Mittlefehldt, M. J. Toplis, T. J. McCoy, A. W. Beck, R. C. Reedy, W. C. Feldman, D. J. Lawrence, P. N. Peplowski, O. Forni, H. Mizzon, C. A. Raymond, C. T. Russell, Distribution of iron on Vesta, *Meteorit. Planet. Sci.* 48 (2013) 2237–2251. doi:10.1111/maps.12139.
- [3] P. H. Warren, The magma ocean concept and lunar evolution, *Annual Rev. Earth Planet. Sci.* 13 (1985) 201–240. doi:10.1146/annurev.ea.13.050185.001221.
- [4] P. G. Lucey, G. J. Taylor, E. Malaret, Abundance and Distribution of Iron on the Moon, *Science* 268 (1995) 1150–1153. doi:10.1126/science.268.5214.1150.
- [5] D. J. Lawrence, W. C. Feldman, R. C. Elphic, R. C. Little, T. H. Prettyman, S. Maurice, P. G. Lucey, A. B. Binder, Iron abundances on the lunar surface as measured by the Lunar Prospector gamma-ray and neu-

- tron spectrometers, *J. Geophys. Res.* 107 (2002) E125130. doi:10.1029/2001JE001530.
- [6] T. H. Prettyman, J. J. Hagerty, R. C. Elphic, W. C. Feldman, D. J. Lawrence, G. W. McKinney, D. T. Vaniman, Elemental composition of the lunar surface: Analysis of gamma ray spectroscopy data from Lunar Prospector, *Journal of Geophysical Research: Planets* 111 (2006) E12007. doi:10.1029/2005JE002656.
- [7] C. Wöhler, A. Berezhnoy, R. Evans, Estimation of elemental abundances of the lunar regolith using clementine UVVIS+NIR data, *Planetary and Space Science* 59 (1) (2011) 92–110. doi:10.1016/j.pss.2010.10.017.
- [8] C. Wöhler, A. Grumpe, A. Berezhnoy, M. U. Bhatt, U. Mall, Integrated topographic, photometric and spectral analysis of the lunar surface: Application to impact melt flows and ponds, *Icarus* 235 (2014) 86–122. doi:10.1016/j.icarus.2014.03.010.
- [9] W. C. Feldman, B. L. Barraclough, K. R. Fuller, D. J. Lawrence, S. Maurice, M. C. Miller, T. H. Prettyman, A. B. Binder, The Lunar Prospector gamma-ray and neutron spectrometers, *Nucl. Inst. Meth. A.* 422 (1999) 562–566. doi:10.1016/S0168-9002(98)00934-6.
- [10] W. V. Boynton, W. C. Feldman, I. G. Mitrofanov, L. G. Evans, R. C. Reedy, S. W. Squyres, R. Starr, J. I. Trombka, C. D’uston, J. R. Arnold, P. A. J. Englert, A. E. Metzger, H. Wänke, J. Brückner, D. M. Drake, C. Shinohara, C. Fellows, D. K. Hamara, K. Harshman, K. Kerry, C. Turner, M. Ward, H. Barthe, K. R. Fuller, S. A. Storms, G. W. Thornton, J. L. Longmire, M. L. Litvak, A. K. Ton’chev, The Mars Odyssey Gamma-Ray Spectrometer Instrument Suite, *Space Sci. Rev.* 110 (2004) 37–83. doi:10.1007/978-0-306-48600-5_2.
- [11] N. Hasebe, E. Shibamura, T. Miyachi, T. Takashima, M. Kobayashi, O. Okudaira, N. Yamashita, S. Kobayashi, T. Ishizaki, K. Sakurai,

- 560 M. Miyajima, M. Fujii, K. Narasaki, S. Takai, K. Tsurumi, H. Kaneko,
M. Nakazawa, K. Mori, O. Gasnault, S. Maurice, C. D'Uston, R. C.
Reedy, M. Grande, Gamma-ray spectrometer (GRS) for lunar polar or-
biter SELENE, *Earth, Planets and Space* 60 (2008) 299–312. doi:10.
1186/BF03352795.
- 565 [12] T. Ma, J. Chang, N. Zhang, W. Jian, M. S. Cai, Y. Z. Gong, H. S. Tang,
R. J. Zhang, N. S. Wang, M. Yu, J. P. Mao, Y. M. Hu, A. A. Xu, M. H.
Zhu, Gamma-ray spectrometer onboard Chang'E-2, *Nucl. Inst. Meth. A.*
726 (2013) 113–115. doi:10.1016/j.nima.2013.05.162.
- [13] J. O. Goldsten, E. A. Rhodes, W. V. Boynton, W. C. Feldman, D. J.
570 Lawrence, J. I. Trombka, D. M. Smith, L. G. Evans, J. White, N. W.
Madden, P. C. Berg, G. A. Murphy, R. S. Gurnee, K. Strohhahn, B. D.
Williams, E. D. Schaefer, C. A. Monaco, C. P. Cork, J. Del Eckels, W. O.
Miller, M. T. Burks, L. B. Hagler, S. J. DeTeresa, M. C. Witte, The MES-
SENGER Gamma-Ray and Neutron Spectrometer, *Space Sci. Rev.* 131
575 (2007) 339–391. doi:10.1007/s11214-007-9262-7.
- [14] M. Hareyama, Y. Fujibayashi, Y. Yamashita, Y. Karouji, H. Nagaoka,
S. Kobayashi, R. C. Reedy, O. Gasnault, O. Forni, C. D'Uston, K. J.
Kim, N. Hasebe, Estimation method of planetary fast neutron flux by a
Ge gamma-ray spectrometer, *Nucl. Inst. Meth. A.* 828 (2016) 145–155.
580 doi:10.1016/j.nima.2016.05.045.
- [15] I. G. Usoskin, G. A. Bazilevskaya, G. A. Kovaltsov, Solar modulation pa-
rameter for cosmic rays since 1936 reconstructed from ground-based neu-
tron monitors and ionization chambers, *Journal of Geophysical Research:*
Space Physics 116 (2011) A02104. doi:10.1029/2010JA016105.
- 585 [16] S. Nozette, P. Rustan, L. P. Pleasance, J. F. Kordas, I. T. Lewis, H. S.
Park, R. E. Priest, D. M. Horan, P. Regeon, C. L. Lichtenberg, E. M.
Shoemaker, E. M. Eliason, A. S. McEwen, M. S. Robinson, P. D. Spudis,
C. H. Acton, B. J. Buratti, T. C. Duxbury, D. N. Baker, B. M. Jakosky,

- J. E. Blamont, M. P. Corson, J. H. Resnick, C. J. Rollins, M. E. Davies,
 590 P. G. Lucey, E. Malaret, M. A. Massie, C. M. Pieters, R. A. Reisse, D. E.
 Smith, T. C. Sorenson, R. W. V. Breugge, M. T. Zuber, The Clementine
 Mission to the Moon: Scientific Overview, *Science* 266 (1994) 1835–1839.
 doi:10.1126/science.266.5192.1835.
- [17] M. Ohtake, J. Haruyama, T. Matsunaga, Y. Yokota, T. Morota, C. Honda,
 595 Performance and scientific objectives of the SELENE (KAGUYA) Multi-
 band Imager, *Earth, Planets and Space* 60 (2008) 257–264. doi:10.1186/
 BF03352789.
- [18] C. M. Pieters, J. Boardman, B. Buratti, A. Chatterjee, R. Clark,
 T. Glavich, R. Green, J. Head III, P. Isaacson, E. Malaret, T. McCord,
 600 J. Mustard, N. Petro, C. Runyon, M. Staid, J. Sunshine, L. Taylor,
 S. Tompkins, P. Varanasi, M. White, The Moon Mineralogy Mapper (M₃)
 on Chandrayaan-1, *Curr. Sci.* 96 (2009) 500–505.
- [19] M. Kato, S. Sasaki, Y. Takizawa, The Kaguya Mission Overview, *Space
 Sci. Rev.* 154 (2010) 3–19. doi:10.1007/s11214-010-9678-3.
- 605 [20] M. Kobayashi, N. Hasebe, T. Miyachi, M. Fujii, E. Shibamura, O. Oku-
 daire, Y. Karouji, M. Hareyama, T. Takashima, S. Kobayashi, C. D’Uston,
 S. Maurice, N. Yamashita, R. C. Reedy, The Kaguya gamma-ray spec-
 trometer: instrumentation and in-flight performances, *J. Instrumentation*
 8 (2013) P04010. doi:10.1088/1748-0221/8/04/P04010.
- 610 [21] J. Brückner, H. Wänke, R. C. Reedy, Neutron-induced gamma ray spec-
 troscopy: Simulations for chemical mapping of planetary surfaces, *J. Geo-
 phys. Res.* 92 (B4) (1987) E603–E616. doi:10.1029/JB092iB04p0E603.
- [22] R. C. Reedy, Planetary gamma-ray spectroscopy, *Proc. Lunar Planet. Sci.
 Conf.* 9 (1978) 2961–2984.
- 615 [23] L. G. Evans, R. C. Reedy, R. D. Starr, K. E. Kerry, W. V. Boynton,

Analysis of gamma ray spectra measured by Mars Odyssey, *J. Geophys. Res.* 112 (2006) E03S04. doi:10.1029/2005JE002657.

[24] E. A. McCutchan, T. Johnson, Evaluated Nuclear Structure Data File (ENSDF) (2016).

620 [25] R. B. Firestone, V. S. Shirley, C. M. Baglin, S. Y. F. Chu, J. Zipkin (Eds.), Table of Isotopes, eighth edi Edition, John Wiley & Sons, Inc., New York, 1996.

[26] S. Maurice, Reduction of neutron data from Lunar Prospector, *J. Geophys. Res.* 109 (2004) E07S04. doi:10.1029/2003JE002208.

625 [27] P. G. Lucey, D. T. Blewett, B. L. Jolliff, Lunar iron and titanium abundance algorithms based on final processing of Clementine ultraviolet-visible images, *J. Geophys. Res.* 105 (E8) (2000) 20297–20305. doi:10.1029/1999JE001117.

630 [28] M. S. Robinson, J. B. Plescia, B. L. Jolliff, S. J. Lawrence, Soviet lunar sample return missions: Landing site identification and geologic context, *Planet. and Space Sci.* 69 (2012) 76–88. doi:10.1016/j.pss.2012.03.013.

635 [29] J. J. Gillis, B. L. Jolliff, R. L. Korotev, Lunar surface geochemistry: Global concentrations of Th, K, and FeO as derived from lunar prospector and Clementine data, *Geochimica et Cosmochimica Acta* 68 (18) (2004) 3791–3805. doi:10.1016/j.gca.2004.03.024.

[30] L. Haskin, P. Warren, Lunar Source Book, Cambridge University Press, New York, 1991.

640 [31] R. L. Korotev, Some things we can infer about the Moon from the composition of the Apollo 16 regolith, *Meteorit. Planet. Sci.* 32 (1997) 447–478. doi:10.1111/j.1945-5100.1997.tb01291.x.

- [32] R. L. Korotev, J. J. Gillis, A new look at the Apollo 11 regolith and KREEP, *J. Geophys. Res.* 106 (E6) (2001) 12339–12353. doi:10.1029/2000JE001336.
- 645 [33] R. L. Korotev, B. L. Jolliff, R. A. Zeigler, J. J. Gillis, L. A. Haskin, Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust, *Geochim. Cosmochim. Ac.* 67 (2003) 4895–4923. doi:10.1016/j.gca.2003.08.001.
- 650 [34] R. L. Korotev, B. L. Jolliff, R. A. Zeigler, S. M. Seddio, L. A. Haskin, Apollo 12 revisited, *Geochim. Cosmochim. Ac.* 75 (2011) 1540–1573. doi:10.1016/j.gca.2010.12.018.
- [35] C. M. Weitz, J. W. Head, C. M. Pieters, Lunar regional dark mantle deposits: Geologic, multispectral, and modeling studies, *Journal of Geophysical Research* 103 (E10) (1998) 22725. doi:10.1029/98JE02027.
- 655 [36] M. Naito, N. Hasebe, K. Yoshida, J. Ishii, D. Aoki, H. Nagaoka, H. Kusano, E. Shibamura, Neutron Fluxes from Martian Satellites as a Function of Chemical Composition and Hydrogen Content, *JPS Conf. Proc.* 11 (2016) 050003. doi:10.7566/JPSCP.11.050003.
- 660 [37] P. D. Spudis, J. J. Gillis, R. A. Reisse, Ancient Multiring Basins on the Moon Revealed by Clementine Laser Altimetry, *Science* 266 (1994) 1848–1851. doi:10.1126/science.266.5192.1848.
- [38] C. M. Pieters, J. W. Head, L. Gaddis, B. Jolliff, M. Duke, Rock types of South Pole-Aitken basin and extent of basaltic volcanism, *J. Geophys. Res.* 106 (E11) (2001) 28001–28022. doi:10.1029/2000JE001414.
- 665 [39] P. G. Lucey, G. J. Taylor, B. R. Hawke, P. D. Spudis, FeO and TiO₂ concentrations in the South Pole-Aitken basin: Implications for mantle composition and basin formation, *J. Geophys. Res.* 103 (E2) (1998) 3701–3708. doi:10.1029/97JE03146.

- [40] M. Ohtake, K. Uemoto, Y. Yokota, T. Morota, S. Yamamoto, R. Nakamura, J. Haruyama, T. Iwata, T. Matsunaga, Y. Ishihara, Geologic structure generated by large-impact basin formation observed at the South Pole-Aitken basin on the Moon, *Geophysical Research Letters* 41 (2014) 2738–2745. doi:10.1002/2014GL059478.
- [41] B. L. Jolliff, J. J. Gillis, L. A. Haskin, R. L. Korotev, M. A. Wieczorek, Major lunar crustal terranes: Surface expressions and crust-mantle origins, *J. Geophys. Res.* 105 (E2) (2000) 4197–4216. doi:10.1029/1999JE001103.
- [42] N. Yamashita, O. Gasnault, O. Forni, C. D’Uston, R. C. Reedy, Y. Karouji, S. Kobayashi, M. Hareyama, H. Nagaoka, N. Hasebe, K. J. Kim, The global distribution of calcium on the Moon: Implications for high-Ca pyroxene in the eastern mare region, *Earth Planet. Sci. Lett.* 353–354 (2012) 93–98. doi:10.1016/j.epsl.2012.08.010.
- [43] R. L. Korotev, Compositional variation in Apollo 16 impact-melt breccias and inferences for the geology and bombardment history of the Central Highlands of the Moon, *Geochim. Cosmochim. Ac.* 58 (1994) 3931–3969. doi:10.1016/0016-7037(94)90372-7.
- [44] R. L. Korotev, The great lunar hot spot and the composition and origin of the Apollo mafic (“LKFM”) impact-melt breccias, *J. Geophys. Res.* 105 (E2) (2000) 4317–4345. doi:10.1029/1999JE001063.
- [45] W. M. Vaughan, J. W. Head, L. Wilson, P. C. Hess, Geology and petrology of enormous volumes of impact melt on the Moon: A case study of the Orientale basin impact melt sea, *Icarus* 223 (2013) 749–765. doi:10.1016/j.icarus.2013.01.017.
- [46] Y. Cho, T. Morota, J. Haruyama, M. Yasui, N. Hirata, S. Sugita, Young mare volcanism in the Orientale region contemporary with the Procellarum KREEP Terrane (PKT) volcanism peak period ~ 2 billion years ago, *Geophysical Research Letters* 39 (2012) L11203. doi:10.1029/2012GL051838.

- [47] R. Greeley, S. D. Kadel, D. A. Williams, L. R. Gaddis, J. W. Head, A. S. McEwen, S. L. Murchie, E. Nagel, G. Neukum, C. M. Pieters, J. M. Sunshine, R. Wagner, M. J. S. Belton, Galileo imaging observations of lunar maria and related deposits, *J. Geophys. Res.* 98 (E9) (1993) 17183. doi:10.1029/93JE01000.
- [48] J. Whitten, J. W. Head, M. Staid, C. M. Pieters, J. Mustard, R. Clark, J. Nettles, R. L. Klima, L. Taylor, Lunar mare deposits associated with the Orientale impact basin: New insights into mineralogy, history, mode of emplacement, and relation to Orientale Basin evolution from Moon Mineralogy Mapper (M³) data from Chandrayaan-1, *J. Geophys. Res.* 116 (2011) E00G09. doi:10.1029/2010JE003736.
- [49] J. W. Head, S. Murchie, J. F. Mustard, C. M. Pieters, G. Neukum, A. McEwen, R. Greeley, E. Nagel, M. J. S. Belton, Lunar impact basins: New data for the western limb and far side (Orientale and South Pole-Aitken Basins) from the first Galileo flyby, *J. Geophys. Res.* 98 (E9) (1993) 17149–17181. doi:10.1029/93JE01278.
- [50] P. D. Spudis, B. R. Hawke, P. Lucey, Composition of orientale basin deposits and implications for the lunar basin-forming process, *J. Geophys. Res.* 89 (S01) (1984) C197. doi:10.1029/JB089iS01p0C197.
- [51] D. B. J. Bussey, P. D. Spudis, Compositional studies of the Orientale, Humorum, Nectaris, and Crisium lunar basins, *J. Geophys. Res.* 105 (E2) (2000) 4235–4243. doi:10.1029/1999JE001130.
- [52] M.-H. Zhu, J. Chang, T. Ma, W.-H. Ip, W. Fa, J. Wu, M. Cai, Y. Gong, Y. Hu, A. Xu, Z. Tang, Potassium map from Chang'E-2 constraints the impact of crisium and orientale basin on the moon, *Scientific Reports* 3 (2013) 2–7. doi:10.1038/srep01611.
- [53] S. Kobayashi, N. Hasebe, E. Shibamura, O. Okudaira, M. Kobayashi, N. Yamashita, Y. Karouji, M. Hareyama, K. Hayatsu, C. D'Uston, S. Mau-

- rice, O. Gasnault, O. Forni, B. Diez, R. C. Reedy, K. J. Kim, Determining the Absolute Abundances of Natural Radioactive Elements on the Lunar Surface by the Kaguya Gamma-ray Spectrometer, *Space Sci. Rev.* 154 (2010) 193–218. doi:10.1007/s11214-010-9650-2.
- [54] R. Arvidson, R. Drozd, E. Guinness, C. Hohenberg, C. Morgan, R. Morison, V. Oberbeck, Cosmic ray exposure ages of Apollo 17 samples and the age of Tycho, *Proc. Lunar Planet. Sci. Conf.* 7 (1976) 2817–2832.
- [55] C. M. Pieters, P. A. J. Englert (Eds.), Compositional diversity and stratigraphy of the Lunar crust derived from reflectance spectroscopy, in Remote Geochemical Analysis: Elemental and Mineralogical Composition, Cambridge University Press, Cambridge, 1993.
- [56] B. R. Hawke, P. G. Lucey, J. F. Bell, R. Jaumann, G. Neukum, Spectral reflectance studies of Tycho Crater: Preliminary results, *Lunar Planet. Sci. Conf. Abst.* 17 (1986) 999–1000.
- [57] S. Tompkins, B. R. Hawke, Distribution of materials as Tycho Crater, *Lunar Planet. Sci. Conf. Abst.* 32 (2001) 1206.
- [58] T. Matsunaga, M. Ohtake, J. Haruyama, Y. Ogawa, R. Nakamura, Y. Yokota, T. Morota, C. Honda, M. Torii, M. Abe, T. Nimura, T. Hiroi, T. Arai, K. Saiki, H. Takeda, N. Hirata, S. Kodama, T. Sugihara, H. Demura, N. Asada, J. Terazono, H. Otake, Discoveries on the lithology of lunar crater central peaks by SELENE Spectral Profiler, *Geophysical Research Letters* 35 (2008) L23201. doi:10.1029/2008GL035868.
- [59] P. Chauhan, P. Kaur, N. Srivastava, S. Bhattacharya, Ajai, A. S. Kiran Kumar, J. N. Goswami, Compositional and morphological analysis of high resolution remote sensing data over central peak of Tycho crater on the Moon: Implications for understanding lunar interior, *Curr. Sci.* 102 (2012) 1041–1046.

- [60] M. Bhatt, U. Mall, R. Bugiolacchi, S. McKenna-Lawlor, M. Banaszkiewicz,
A. Nathues, K. Ullaland, Lunar iron abundance determination using the
2- μ m absorption band parameters, *Icarus* 220 (2012) 51–64. doi:10.1016/
j.icarus.2012.04.010.
- [61] B. T. Greenhagen, P. G. Lucey, M. B. Wyatt, T. D. Glotch, C. C. Allen,
J. A. Arnold, J. L. Bandfield, N. E. Bowles, K. L. D. Hanna, P. O. Hayne,
E. Song, I. R. Thomas, D. A. Paige, Global Silicate Mineralogy of the
Moon from the Diviner Lunar Radiometer, *Science* 329 (2010) 1507–1509.
doi:10.1126/science.1192196.
- [62] P. G. Lucey, B. T. Greenhagen, E. Song, J. A. Arnold, M. Lemelin, K. D.
Hanna, N. E. Bowles, T. D. Glotch, D. A. Paige, Space weathering ef-
fects in Diviner Lunar Radiometer multispectral infrared measurements of
the lunar Christiansen Feature: Characteristics and mitigation, *Icarus* 283
(2017) 343–351. doi:10.1016/j.icarus.2016.05.010.

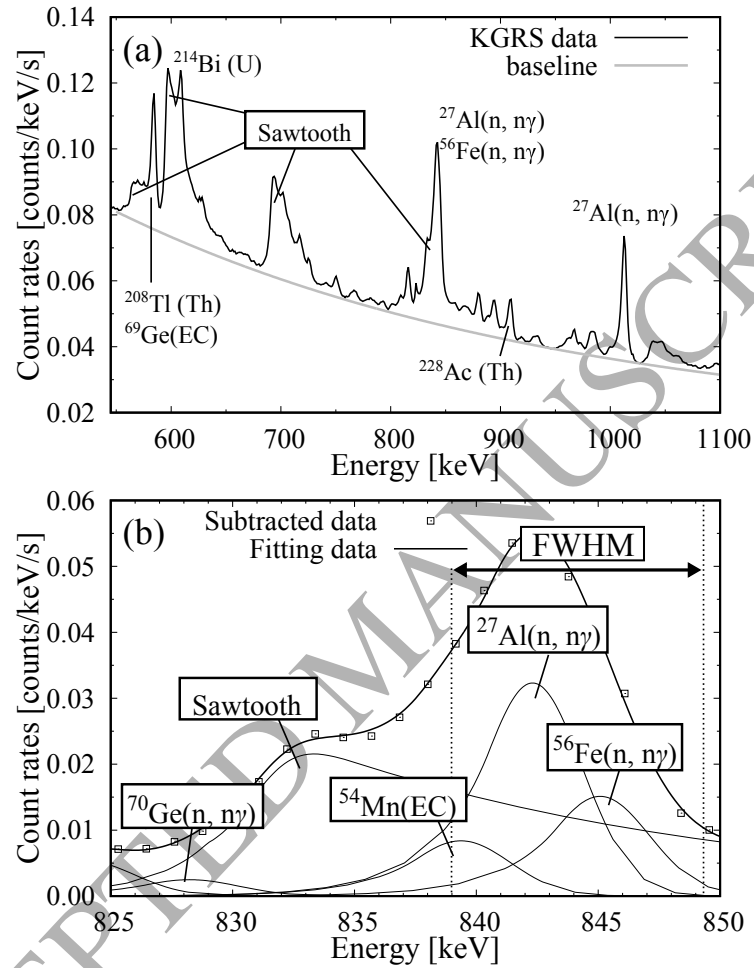


Figure 1: Energy spectra obtained by KGRS. Line gamma-ray peaks and some sawtooth peaks are observed in (a). The exponential baseline of the spectrum was determined using (a) to obtain (b). (b) Spectrum around the iron peak due to inelastic scattering at 846 keV, obtained by subtracting exponential baseline. Peak assignments of the spectra are also presented in the figure [22, 23, 24, 25]. Squares, thin lines, and the thick line in (b) represent the observed gamma-ray spectrum, the fitted gamma-ray peak, and the sum of the fitted peaks, respectively. Each plot was obtained by summing up three energy bins.

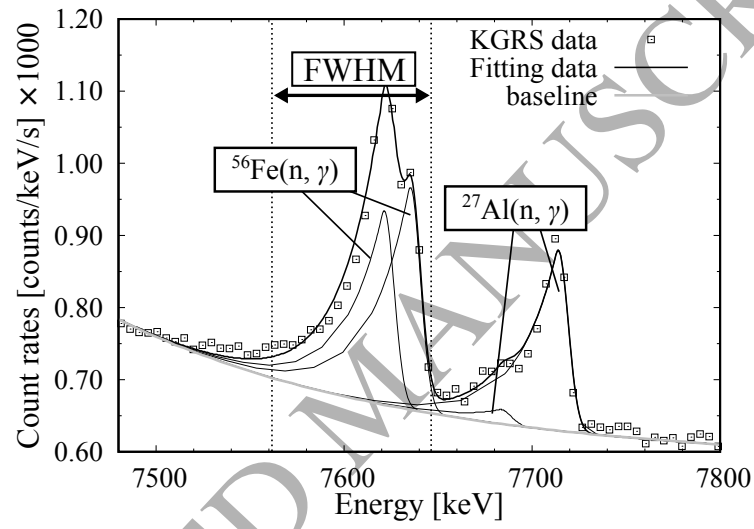


Figure 2: Energy spectra around the neutron capture gamma-ray line of iron at 7.6 MeV obtained by the KGRS instrument. Peak assignments are also shown in the figure[22, 23, 24, 25]. Squares, thin lines, and the thick line represent the observed gamma-ray spectrum, the fitted gamma-ray peak, and the sum of the fitted peaks, respectively. Each plot was obtained by summing up 3 energy bins.

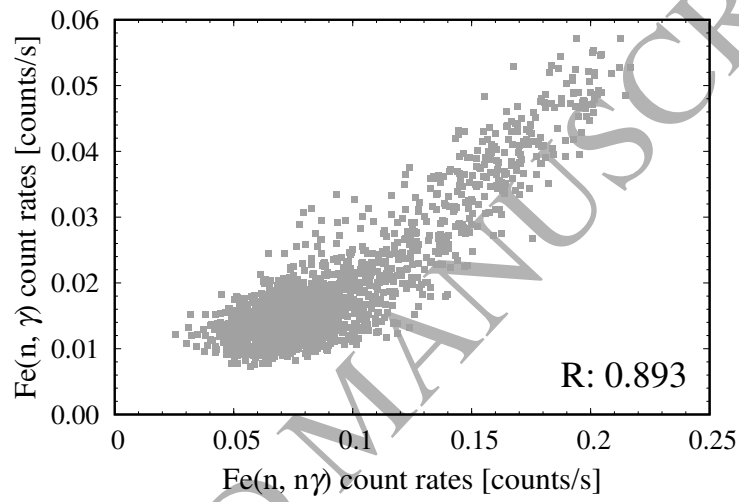


Figure 3: Scatter plot of the gamma-ray count rates of inelastic scattering and neutron capture. Each plotted gamma-ray count rate was obtained by rebinning to equal area pixels of $150 \text{ km} \times 150 \text{ km}$ to construct the scatter plot. The count rates of inelastic scattering and neutron capture were corrected by the relative change of fast neutrons and thermal neutrons, respectively. The count rate of inelastic scattering has larger values than that of neutron capture. It is considered that this difference in the count rates is caused by the difference in the detection efficiency and variation of neutron flux.

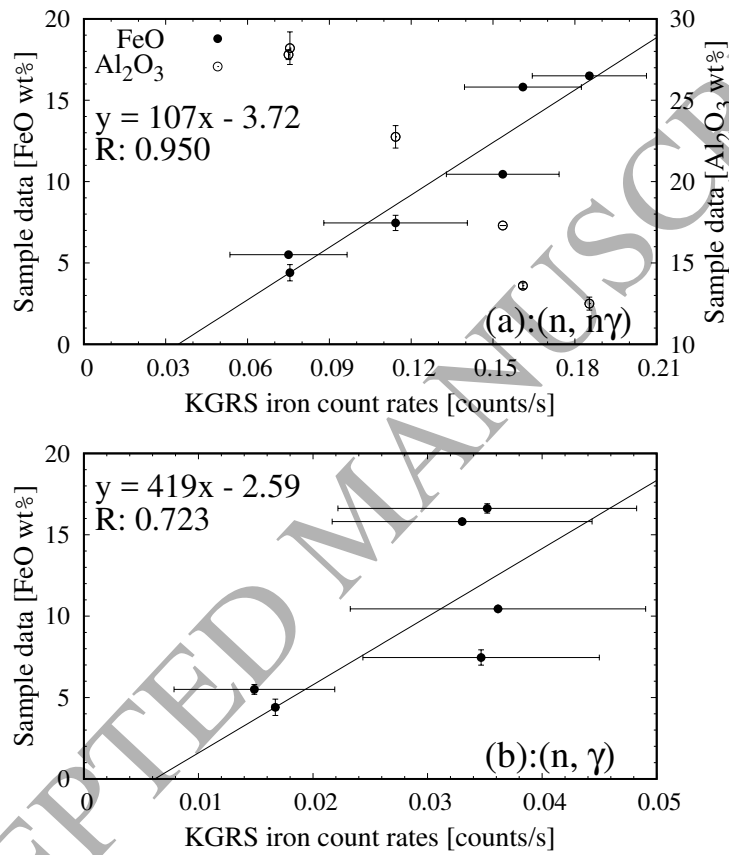


Figure 4: Relationship between the iron gamma-ray count rates ((a) inelastic scattering and (b) neutron capture) and FeO abundance in the returned samples taken as ground truth [30, 31, 32, 33, 34]. The Al₂O₃ abundance in the returned samples is also plotted in (a).

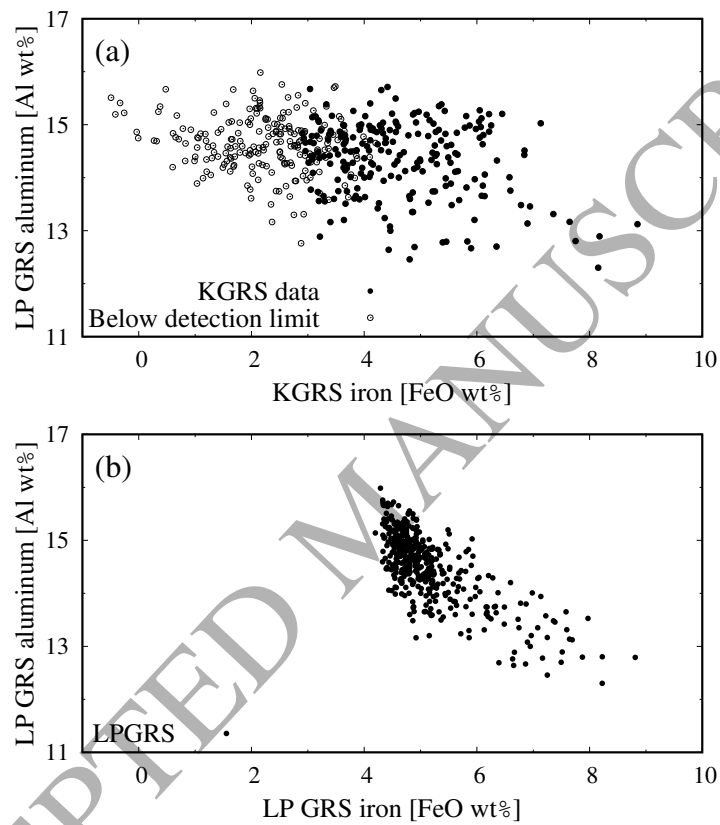


Figure 5: The scatter plots of LP GRS Al_2O_3 vs. (a) KGRS FeO and (b) LP GRS FeO on the northern lunar farside [6]. The KGRS data were rebinned to $150 \text{ km} \times 150 \text{ km}$. The anti-correlation between LP GRS Al_2O_3 and KGRS FeO is weaker than that between LP GRS Al_2O_3 and FeO due to the influence of the aluminum peak on the peak analysis.

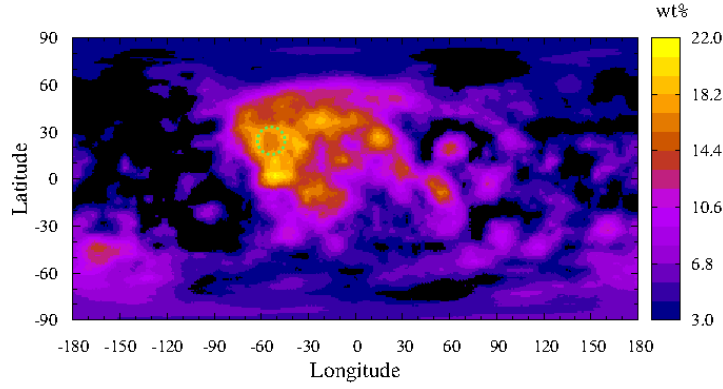


Figure 6: Lunar FeO wt% map obtained by KGRS. The abundances are determined by analyzing the 846 keV iron gamma-ray peak and ground truth based calibration. The pixels with values below the detection limit are filled in black. Green dots show the area with lower iron than the surrounding area.

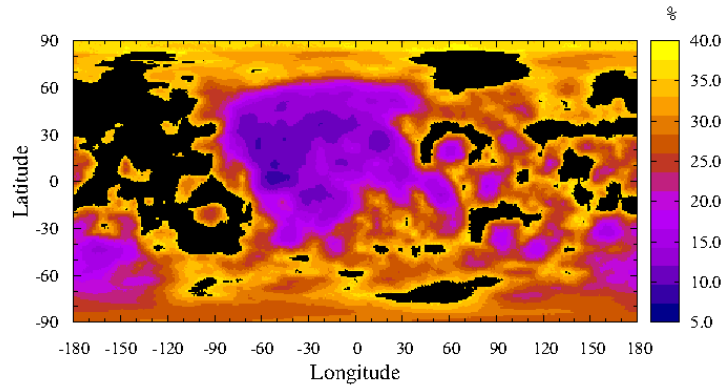


Figure 7: Error map of Fig. 6. The statistical error was calculated based on Eq. (1). The statistical error at the detection limit corresponds to $\sim 35\%$.

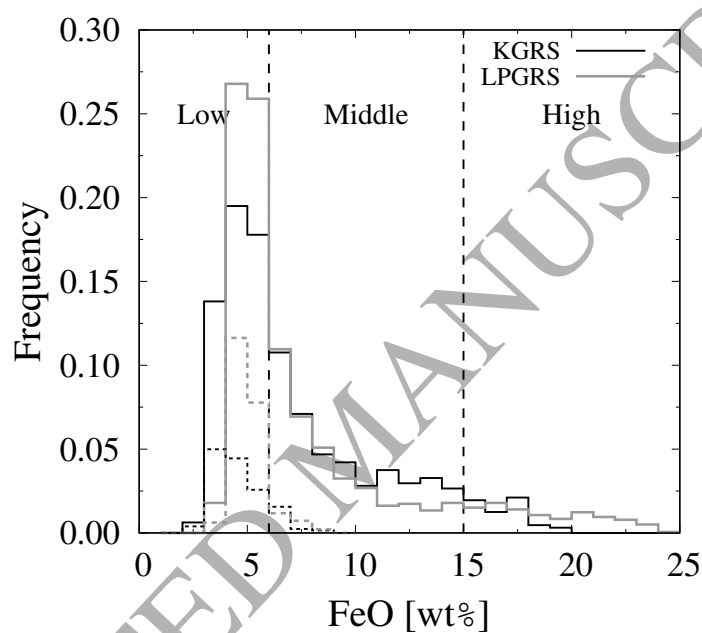


Figure 8: Histogram of the Fe distribution obtained by KGRS and LP GRS [6]. The data sets were rebinned to equal area pixels of $150 \text{ km} \times 150 \text{ km}$. Dots show the histogram on the northern farside. The two data set show a good correlation although there is a small difference in low-FeO areas. Pixels with gamma-ray count rates below the detection limit were neglected.

Figure 9: Maps of
(b) LP GRS [5]. The
respectively [6, 42].
cause of the small

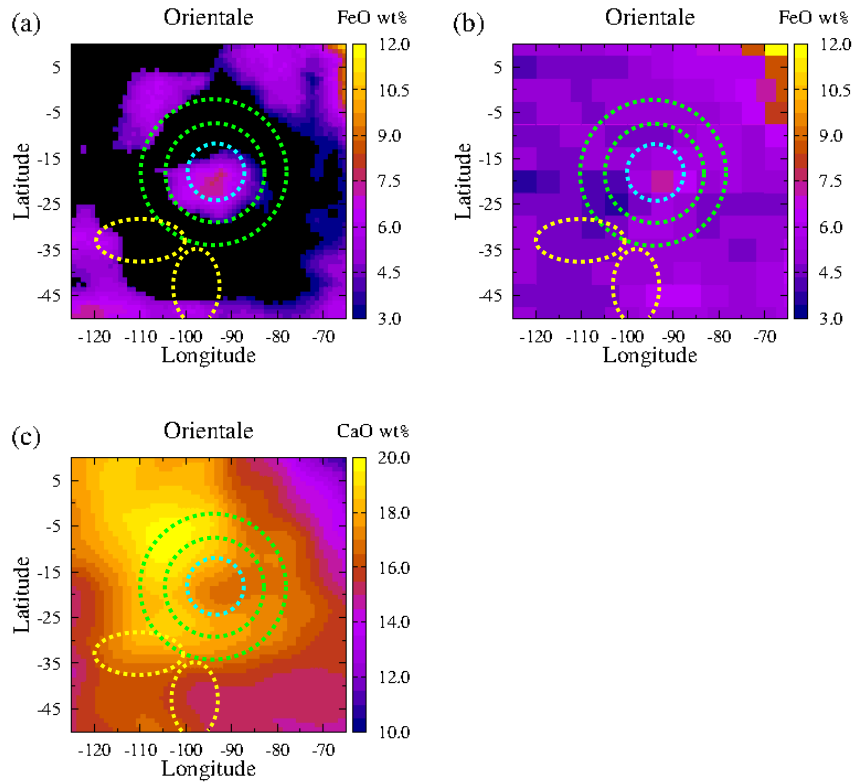


Figure 10: Maps of the FeO distribution of the Orientale basin obtained by (a) KGRS and (b) LP GRS [6]. (c) Ca distribution of the same region measured by KGRS [42]. Blue and green dots denote different rings of the Orientale basin. The mare region of Orientale basin is located inside the blue dots. Yellow dots show areas where Chang'E-2 has proposed the existence of Orientale ejecta.

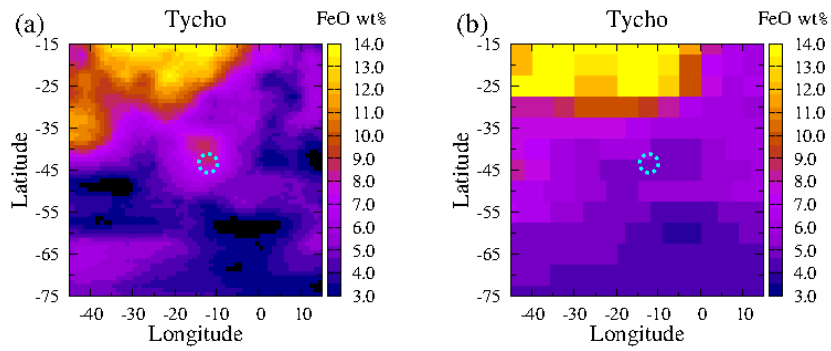


Figure 11: Maps of the FeO distribution around the crater Tycho ((a) and (b)). (a) and (b) were derived from KGRS data and LP GRS data [6], respectively. The blue dots denote the crater Tycho. At the location of crater Tycho, differences between the KGRS map and the LP GRS map are apparent.