Carbon Contribution of the dark moon samples: Quenched solids of the lunar materials

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The extraterrestrial bodies without the atmosphere (including the Moon) can usually be seen wholly blackish dark color. The lunar black and white surface is explained simply by the differences of colored minerals the albedo by smooth and irregular topographic surface. This explanation can be generally understood by descriptive terminology and formation, but is clearly main reason that it cannot be developed further study and challenges in future. Recently author has analyzed comparatively that based on terrestrial rocks and artificial analyses with carbon contents and micro-textures, the lunar samples of the Apollo (USA) and lunar meteorites (including present analyzed samples) show significant carbon contents and carbon-bearing textures, which indicate large contribution of blackish carbon on the Moon surface.
Difference of rock minerals on the Moon surface, has been explained generally by colored dark minerals of pyroxene, olivine and metallic mineral on the Mare basalt (Earth volcanic type) and the Highland gabbro-to-anorthosite (Earth plutonic type). However, the lunar minerals reveal blackish dark color by limited rock-composition range, which cannot be compared with whitish minerals of silica quartz and various feldspars on the water-planet Earth evolved widely.
The moon minerals which are also observed in two lunar meteorites (NWA4483 and Y-86032) , show comparatively low crystallization, very few kinds of minerals and rocks caused by poor fluids, hydrous mineral, silica-feldspar variety on the Moon surface, which might be lower activity in the Moon.
In the present study, it is resolved finally big differences of carbon contents obtained not only at mineral-rocks on the Mare and the Highlands, but also on regolith soils and breccias.
Earth's rocks are obtained in this study that carbon contents and textures by bulk analyses and SEM observation, are increased on colored minerals and volcanic rocks. It indicates in this study that carbon contents are changed directly by cooling process, which is not simply caused by a depth of unknown Earth's interior explained by descriptive explanation.
It is experimentally confirmed in author's study that a carbon-bearing solids and textures are formed newly by artificial laser experiments reacted as quenching sputtering.
The present results of Moon's color study are summarized as follows.
1) The colors of the Earth's rocks are classified with the silica contents (and feldspar), whereas the lunar rocks can be classified with carbon contents by the different cooling process not mainly by mineral variety.
2) Lunar quenched rocks of regolith soil and breccias have much content of lunar carbon. On the other hand, terrestrial carbon can be obtained relatively in volcanic rocks quenched rapidly.
3) Carbon increases formed by carbon-bearing solids have been obtained by the laser irradiation experiment, which can be confirmed strongly by formation of carbon-bearing materials and textures on the Moon rocks studied in this study..
4) From comparative study of the Moon and water-planet Earth, the isolated Moon body surface shows finally blackish dark color including carbon-bearing local solids and micro-textures formed by quenched processes of brecciated reaction.

Keywords: Blackish dark color of lunar sampes, Carbon content effect, Quenched solids formation

Stratigraphy of mare basalts and topographic features in the central region of the Procellarum KREEP Terrane of the Moon

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Reconstructing the volcanic history of the Moon is essential to understand the solidification process and subsequent thermal evolution of lunar mantle. Lunar mare basalts provide insights into compositions and thermal history of lunar mantle. According to previous crater counting analysis with remote sensing data, magma activity has a second peak at the end of mare volcanism (~2 Ga), and the latest eruptions were limited in the Procellarum KREEP Terrane (PKT), which has high abundances of heat-producing elements. To understand the mechanism for causing the second peak and its magma source is important to constrain models of lunar thermal evolution. We have examined the correlation between the titanium contents and eruption ages of mare basalt units using compositional and chronological data updated by SELENE/Kaguya. As a result, we found that a rapid increase in mean titanium (Ti) content occurred at 2.3 Ga in the PKT, suggesting that the magma source of mare basalts changed at that time. The high-Ti basaltic eruption, which occurred at the late stage of mare volcanism, can be correlated with the second peak of volcanic activity at ~2 Ga. The latest volcanic activity can be explained by a high-Ti hot plume originated from the core-mantle boundary. If the hot plume was occurred, the topographic features formed by the hot plume may be remained. We calculated the difference between topography and selenoid and found the circular feature like a plateau in the center of the PKT, which scale is ~1000 km horizontal and ~500 m vertical. We investigated the stratigraphic relationship between mare basalts and mare ridges in the PKT by using Kaguya TC and MI data. We found that the mare ridges were formed before and after the high-Ti basaltic eruptions and seem to be along with the plateau. Considering that ridges were formed during formation and relaxation of the plateau, the timing of the plateau formation is consistent with the timing of ridge formation.

Keywords: Moon, Volcanism, Lunar mare, Topography, Mare ridge, Stratigraphy

Broadband noise and associated electron heating observed by Kaguya around the Moon in the solar wind

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Broadband electromagnetic noise in the frequency range up to ~10 Hz has been detected around the Moon at ~100 km altitude [Halekas et al., 2008; Nakagawa et al., 2011; Tsugawa et al., 2012]. Halekas et al. [2008] suggested that the waves are associated with electron energizations and are basically generated through the interaction between the solar wind plasma and crustal magnetic field. Nakagawa et al. [2011] studied the characteristics of the broadband waves by considering properties of whistler-mode waves propagating in the solar wind frame of reference. Tsugawa et al. [2012] showed that the statistical distributions of the intense noise are clearly located at the magnetic anomalies. While they discussed the possible generation process of the waves through resonant or non-resonant instability by ions reflected from the lunar surface, details of the generation process of the waves have not been clarified yet.
We analyzed the broadband noise observed by Kaguya statistically, and suggest that the absolute condition to observe the noise at altitudes ~100 km are 1) the spacecraft is connected to the Moon through the magnetic field, and 2) the solar wind ions are reflected considerably in the connected region on the Moon. The fluxes of reflected ions depend on the solar wind parameters and the magnetisms of the lunar crusts. In a usual solar wind condition (roughly the dynamic pressure < 2 nPa), the second condition is mostly satisfied above the magnetic anomalies. In the solar wind with larger density and faster speed than usual (roughly the dynamic pressure > 2 nPa), the second condition can be satisfied above not only magnetic anomalies but also unmagnetized surface. Electrons are often energized perpendicular to the ambient magnetic field or isotropically in association with the noise and reflected ions. The electron heating above the lunar magnetic anomalies are also associated with the broadband electrostatic noise in the frequency range up to ~10 kHz [Kasahara et al., 2011]. Their correlation is suggested in analogous to the transverse ion acceleration due to broadband extremely low frequency noise in the Earth's auroral region [e.g., Andre et al., 1998].

Formation process of linear gravity anomalies of the Moon

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Gravity data obtained from the Gravity Recovery and Interior Laboratory (GRAIL) have revealed linear gravity anomalies (LGAs), which might be formed by the early global expansion of the Moon and subsequent magma intrusion. If the formation process of the LGAs is true, the surface exposure of mafic rock originated from ancient dykes is expected around large craters, which excavated deep material in the crust. We carried out a compositional investigation to examine existences of intrusion associated with the LGAs using SELENE (Kaguya) high-resolution spectral datasets obtained by Multiband Imager (MI) and Spectral Profiler (SP). Here we investigated LGA2 because the LGA2 is one of the largest LGAs and is superposed by the 150 km-diameter crater Roche, which might excavate intrusion. Clustered small-scale basaltic exposures in the highland are found in the northern outer region of Roche crater across the LGA2. The basaltic exposures exist not at topographic lows but at fresh crater rays and slopes. This indicates that the clustered basaltic exposures originate from the intrusion in the crust and/or ancient maria.

Keywords: Moon, volcanism, linear gravity anomaly, intrusion

Evaluation of chronological measurement method of geological units by collapsed crater on the Moon

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The age of the moon is an important clue in understanding the former state of igneous activity of the moon. To explore the time course of the scale and the eruption of the magma leads to pursue the internal evolution of the moon. Generally, exploring crater size frequency distribution is used to determine the model ages of lunar geological units. However, this age determination is susceptible to the influence of secondary craters, and an error is likely to occur in the measured age. Therefore, by using another age determination, it is necessary to confirm whether the measurement age by the age determination that is free from influence of the secondary crater should be investigated. The way based on the status of crater collapse is another expected method for age determination of lunar geological units. In order to establish this method, it is needed to investigate the correlation between the age of the geological units and a parameter value expressed by F which is corresponding to the total amount of impacted objects disrupting the craters. Since the F value is a numerical value determined by the most collapsed crater in a geological unit, it does not include the effects of secondary craters probably occurring after the formation of the oldest most collapsed craters. Here, we explore the correlation relationship between the F values and the model ages based on crater size frequency distribution for several lunar geological units, and discuss the possibility of the way based on crater collapse as an age determination of lunar geological units.

Keywords: chronology, lunar craters, status of crater collapse

Water-rich lunar upper mantle as recorded in lunar meteorites

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Bulk water analyses of the Apollo samples have revealed almost scant water (<1 ppb), which has resulted in the post-Apollo view of a dry Moon. However, with the discoveries of OH species in lunar secondary minerals by mass spectrometry, questions concerning water in the mantle have been revived. Some recent studies of lunar samples proposed a water-rich mantle (9–585 ppm) based on carefully considered assumptions. However, the wet mantle hypothesis has remained inconclusive because the inferences made must be taken with caution as the result of the unreliability of the tentative assumptions used. Recent isotopic analyses of chlorine and oxygen in lunar second minerals predict the dry lunar mantle (<10 ppb), but this hypothesis was build up based on the indirect evidences (not in the direct way using hydrogen mass spectrometry). In this study, we measured water in gabbroic clinopyroxene and olivine of the gabbro lithic lunar meteorites using *in-situ* transmission FTIR heating absorption spectroscopy to determine the actual water content of the upper mantle beneath the Procellarum basin without the unreliable assumptions.
In-situ FTIR heating measurements at 120 °C represent water bands at ~3750, ~3600 and ~3500 cm^{-1} for clinopyroxene and at ~3550, ~3500 and ~3250 cm^{-1} for olivine in the gabbroic lithologies. The *in-situ* FTIR spectra of clinopyroxene and olivine entrained on the shock veins and fusion crusts include similar water bands but with obviously lower absorbances. This behaviour appears to be the result of the dehydration of intrinsic water due to the post-shock annealing in an impact event for the shock vein, and due to aerodynamic heating during the atmospheric entry for fusion crust. Therefore, the abundant water in the gabbroic minerals appears to be derived from the Moon and not the Earth. The *in-situ* FTIR heating measurements of the gabbroic clinopyroxene and olivine at 200–550 °C demonstrated that the absorbances show almost no change up to 300 °C but drastically decrease in temperature from 300 to 550 °C. This result can be attributed to the dehydration of tightly bound molecular water. The other water bands remained after heating to 550 °C, and exhibit anisotropies of the absorbance during rotation of the polarizer. Therefore, the remaining bands can be assigned to structurally oriented OH species.
A conversion using the Beer-Lambert law of the integral absorbance into the water contents revealed that the gabbroic clinopyroxene and olivine contain >339–1363 and >199–1152 ppm water, respectively. Based on these water contents, a mode composition of the constituent minerals determines the mantle water content without the previously proposed assumptions. As a result of our findings, we conclude that there is a water-rich part of the upper mantle that spreads >631 ±498 ppm at depth of >30 to >400 km beneath the Procellarum basin; such water concentrations are as plentiful as that found in the Earth’s mantle. Notably, however, the wet mantle hypothesis requires further consideration because there are some evidence concerning water depletion in the lunar

mantle as reported in the previous studies. A tentative theory that explains this discrepancy proposes that the indigenous water is heterogeneously distributed and partly included in the lunar mantle. The heterogeneously and partly water-rich lunar upper mantle proposed here supports recent lunar evolutionary models; accretion and cooling processes of the primary materials in the aftermath of the Giant Impact, differentiation in the lunar magma ocean, the cause of a deep moonquake, and a share of common water sources between proto-Earth and Moon. Our findings also promises new insights into future lunar missions and, particularly into landings on and sample returns from the mantle-originated olivine-bearing sites found by the SELENE mission on the Procellarum basin and South Pole Aitken.

Keywords: Moon, Lunar mantle, Lunar meteorite, Mantle water content, Infrared absorption spectroscopy, Procellarum basin

A spatio-temporal change of the density structure beneath impact basins of the Moon

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Impact basin, a large-scale structure on the surface of the Moon, is formed by a giant impact in the past and is considered to affect the evolution of not only the surface but also the internal structure of the Moon. Recent analyses of GRAIL data of the all mission phases provide the gravity field model with the spherical harmonics up to degree and order of 900 [Lemoine et al. 2014; Konopliv et al., 2014]. We can, therefore, expect to obtain detailed information of the interior of the Moon from this gravity model. In this study, from the latest selenodetic data, we estimate the density structure (i.e., Moho) beneath the impact basins and discuss differences of the density structure.We use the topographic model of LRO_LTM01_PA_1080 with the spherical harmonics of degree and order of 1080 [Neumann, 2013]. Bouguer anomaly is calculated from the topographic data and the gravity potential data of GRGM900C [Lemoine et al., 2014] with the Bouguer correction density of 2560 kg/m3 and is expanded by the spherical harmonics of degree and order of 600 (wavelength ~9km). We estimate the depth of the lunar Moho using the gravity inversion method of Wieczorek and Phillips (1998). In the estimation of the Moho depth, considering the values of crustal density reported by Han et al. (2014), we set the crustal density of 2750 kg/m3 and the mantle density of 3360 kg/m3 [Ishihara et al., 2009], respectively, so that our estimation coincides with seismological estimations of the crustal thickness at Apollo 12/14 sites and the average crustal thickness reported by previous works. We apply a downward continuation filter with the half-power degree of 100. The crustal structure is expanded by the spherical harmonics of degree and order of 600. We call the density structure calculated by this method as global model.We estimate the local Moho relief using the gravity inversion method of Rama Rao et al. (1999) for each impact basin. The crustal density and mantle density are the same as the case of the global model and we set a spatial resolution to 10 km. We set the initial boundary depth to the deepest point of the global model and the shallowest point of the density structure to the deepest point of the topography for each impact basin. We call the density structure obtained by this method prism model.To evaluate the prism model structures quantitatively, we take following four steps.(1) We make the azimuthally averaged cross section of the prism model within 1.5 times of the positive Bouguer anomaly area [Neumann et al., 2015] for each impact basin.(2) We define the area within the radius of the positive Bouguer anomaly as the inner region and the outside area as the outer region.(3) We define the distance from the center to the farthest point within top 15% of the depth width as D_upper and that from the center to the intersection between the linear fitting line of the outer region data points and the cross section profile as D_lower.(4) We calculate D_upper/D_lower.We found that the distribution of the value of D_upper/D_lower showed positive correlation with the size of the impact basins and have regional characteristic. We suggest that the latter is controlled by the difference of the internal temperature structure, because it is consistent with the distribution of radioactive elements [Jolliff et al., 2000] and the thermal state at the time of basin formation estimated based on viscoelastic deformation calculation [Kamata et al., 2013]. In the presentation, we discuss the major control on subsurface structure, together with calculation results of viscoelastic deformation.

Keywords: impact basin, inversion, viscoelastic deformation

Paleomagnetic poles of the early Moon estimated from small isolated magnetic anomalies

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Paleomagnetic measurements and satellite observations indicate that the global magnetic field existed in the early Moon, in probable, a core dynamo field. Using the Kaguya and Lunar Prospector observations at 20-40 km altitudes, Takahashi et al. (2014) estimated magnetization directions for 24 lunar magnetic anomalies, suggesting the polar wandering of the early Moon. Although they applied a dipole approximation, the observations at high altitudes are generally affected by the crustal field at relatively wide area. Thus their estimation includes some ambiguity of the dipole approximation. In the present study, we use the global maps of the lunar magnetic anomalies on the surface with the Surface Vector Mapping (SVM) method [Tsunakawa., et al. 2015]. The SVM data with high spatial resolution are useful for finding small isolated anomalies like a single dipole. As a result, we have selected several tens of magnetic anomalies to be approximated with a single dipole source. The magnetic poles in the present analysis show two main clusters: one is near the selenographic north pole and the other is on the eastern hemisphere.

Keywords: Moon, magnetic anomaly, paleomagnetic pole

Kaguya observation of oxygen ion precipitation from the Earth to the Moon

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It is widely believed that the Moon was formed due to the impact between the Earth and a planet-sized body, which we have called Theia. In order to confirm that the impact had taken place, many studies was done by numerical modeling and measuring the ratios between the isotopes. Theoretical models proposed that the Moon would form mostly from Theia, and thus would be expected to be compositionally different from Earth. However measured isotope ratios are similar between the Earth and Moon. Measured isotope ratios and theoretical models had conflicted with each other. Recent isotope measurements used lunar samples from the Apollo 11, 12 and 16 missions and found significantly higher levels of 17O/16O than Earth's counterparts.
One of the reasons of the similarity of the isotope ratio is isotope exchange with water from the Earth especially in lunar samples arrived via meteorites. We propose the other reason, oxygen ion transport from the Earth to the Moon, because many satellites such as GEOTAIL and STEREO observed the oxygen ion escape from the Earth in the Earth's magnetotail.
KAGUYA, a Japanese lunar orbiter, conducted scientific observation in 100 km altitude in 2008. An ion mass analyzer on KAGUYA detected oxygen ions coming from the Earth to the Moon in the Earth's magnetosphere. Here we show the amount of the oxygen ion transport estimated by using KAGUYA data and discuss the effect to measuring the isotope ratios.

Keywords: Isotope of the Moon, Kaguya spacecraft, Mass analyses

Instrumental performance and present status of development of Active X-ray Spectrometer for future lunar landing mission

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Recent Chinese lunar landing mission (Chang’E 3) was successful in landing on the surface of the Moon after their twice successful remote observations. The landing mission investigated the elemental compositions of landing sites in more detail, and obtained new “ground truth” by using alpha particle X-ray spectrometer, which could have not been provided by any returned samples.
The compositions of major elements as Mg, Al, Si, K, Ca, Ti, Fe of landing site help us to understand its petrogenesis and evolution. In Japan, the global investigation of Kaguya promoted our knowledge and understanding of the origin and evolution of the Moon. The landing and/or sample-returned missions in the future will be followed in order to investigate the geology in more details, in the next.
We have been developing the active X-ray spectrometer (AXS) as elemental analyzer on site, in order to prepare for future lunar landing mission. Present AXS consists of active X-ray generators with pyroelectric crystal ($LiTaO_3$), and a silicon drift detector (SDD). Here, the present status of development is reported, and the instrumental performance of AXS and the observation targets of AXS will be discussed.

Keywords: Active X-ray spectrometer, landing mission

One-dimensional crater chronology: A method of estimating the termination age of faulting

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The timing of the tectonic deformation will be a clue to distinguish the origins of geological structures among global cooling (Solomon and Chaiken, 1976), orbital evolution of the Earth-Moon system (Melosh, 1980) and subsidence by the loads of mare basalts (e.g., Solomon and Head, 1980). There are a number of deformed and undeformed craters on a fault on the lunar surface. Undeformed craters mean that they were formed after the fault ceased its tectonic activity. In order to estimate the termination age of faulting, we propose a new method named one-dimensional crater chronology. The method converts the linear density of the undeformed craters on a fault into the termination age. By means of numerical experiments we estimate the relationship between one-dimensional crater size-frequency distribution and the termination age.

Keywords: Moon, Tectonic history, Crater chronology, Mare ridge

Enhancement of lunar topographic data with statistical voting algorithm

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In addition to terrestrial planets, grabens and ridges that are typical topographic features on the moon indicate stress activity of the lunar surface. The grabens, which show negative channel-like reliefs result from tensile stress in lunar subsurface. On the other hand, the ridges, which show positive riliefs, result from compressive stress in the lunar subsurface. Especially, grabens and ridges have been supposed to be indicators of thermal evolution of the moon, because these feature result from expansion and constriction of the moon.
In order to find grabens and ridges by visual inspection, images taken by exploration camera are usable. However, some of ridge have gentle slope and some of graben have shallow channel-like relief, so it is difficult to identify these degraded features by visual inspection. In addition to degraded features, visibility of these topographic features is affected by spatial resolution and sun-lighting condition. Therefore, we use the Digital Terrain Model (DTM) of the moon for production of enhanced topographic data. The DTM provides elevation data of the lunar surface and is not generally affected by sun-lighting condition. However, it is difficult to identify small grabens and ridges with DTM data. In previous research with a similar purpose, roughness parameter (Root Mean Square Slope, here after RMS) with DTM data was utilized to identify several topographic features such as craters, ridges, and lava flows. The RMS with DTM data depends on a parameter set of calculation window size and data sampling step size. Appropriate parameter combination of these two parameters was needed to adjust to every scale of topographic features. In this study, on the basis of topographic data, we developed new calculation algorithm based on statistics named as “statistical voting algorithm”. In this algorithm, we calculated an average and standard deviation in calculation window and it vote to each pixel which has a significant difference comparing with the average value. Continuously, we do same procedure along with moving calculation window. We expect that this algorithm is good at identifying small degraded or small-scale topographic feature.
As a result, and an availability of the statistical voting algorithm with DTM data to enhance the contrast of DTM data at the topographic features was confirmed. The appropriate parameter of this algorithm is window size 640 pixels in both case of grabens and ridges. This algorithm is useful to identify not only normal topographic features but also small and indistinct ones. However, small target superposed on large topographic feature could not be identified by visual inspection with our statistical voting algorithm data.

Keywords: Topographic feature, Digital Terrain Model, Statistical voting algorithm

Scientific observation plan for Smart Lander for Investigating Moon mission

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Main objective of Smart Lander for Investigating Moon (SLIM) mission is to develop and demonstrate technology of high-precision landing on the Moon, which enables us to explore not only the Moon but the other planetary body with gravity. This mission is planned to land on the lunar surface within a hundred meters from the pre-fixed destination, and it is extremely attractive for landing site dependent study themes. Therefore, although weight and other resource budgets are very limited for this mission because the mission aims to develop a challenging light weight and small lander, possibility of a payload have been discussed recently within that strict resource budgets for adding extra result to the mission. Around 20 instruments were proposed for the mission as the results of efforts of instrument team members and candidate instruments and candidate objectives were identified. In this presentation, the candidate instruments and their objectives will be discussed with the information of current status the mission.

Keywords: Moon, SLIM, high-precision landing

Linear mass anomalies going through three volocano complex areas in the Oceanus Procellarum

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In western part of the Oceanus Procellarum of the lunar nearside, there are several large-scale volcanic complexes, in which volcanic geographycal features are highly concentrated. In this study, Gravity Recovery and Interior Laboratory (GRAIL)-derived lunar gravity field data is used to investigate the geophysical relevance of the major volcanic complexes in the region. One of our concerns is whether the volcanisms of these complexes are caused by common factors or not. We estimated Bouguer gravity anomaly in the region and investigated the directions of the linear structure of the anomalies. The result shows that there are linear mass anomalies, which connect the mass anomalies at the volocano complexes of Aristarchus Plateau, Marius Hills and Flamstead Basin. The observed linear structures lie inward of the large quasi-rectangular pattern revealed by Andrews-Hanna et al., and much shallower than the pattern. Considering that, the observed linear structures should have been created later than the quasi-rectangular outer structure. After the quasi-rectangular pattern was created, magma rose to the surface through the cracks. The observed linear structure is supposed to be created through cooling of the overflowed magma. The geological units, which the linear structures go through, are younger than that of the outer quasi-rectangular pattern. The linear cracks created by cooling are weaker than other locations. Therefore, magma probably rose easier than in other area. That may be why the three currently observed volcano complexes lie on the same linear structure.

Keywords: lunar gravity field, GRAIL, volcanic activity

Where did the oldest lunar mare sample come from?

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Introduction: Kalahari 009 is a lunar meteorite classified as a very-low-titanium (VLT) mare basalt breccia and known as one of the oldest mare basalts with the U-Pb age of 4.35 ±0.15 Gyr (Terada et al., 2007). This meteorite provides the information of the lunar oldest mare magmatism prior to the Late Heavy Bombardment around 3.8-4.1 Gyr ago and potentially facilitates understanding of the origin of lunar mare magma activity. Here we report search for the source crater of the Kalahari 009 meteorite and shock products in the meteorite.
Analytical Methods: The source crater of Kalahari 009 was searched in a region from northern latitude of 60 degree to southern latitude of 60 degree using data of the Multiband Imager (MI) and Gamma Ray Spectrometer (GRS) obtained by the lunar explorer SELENE (KAGUYA). We selected candidates of the source crater, of which FeO, TiO2 and Th concentrations are comparable to those in Kalahari 009 (16 wt% of FeO, 0.45 wt% of TiO2 and 0.09 ppm of Th) (Sokol et al., 2008). To estimate the compositions of FeO and TiO2 we used the algorithms for deriving the abundances of FeO and TiO2 based on MI image data (Otake et al., 2012). At the same time, optical maturity parameter (OMAT), which is an index of relative surface age of craters, was also calculated to search for the source crater of Kalahari 009 using the method in Lucey et al. (2000).
To reveal the impact history of Kalahari 009, we observed the thin section of the meteorite using the field emission scanning electron microscope (JEOL 7001F) and Raman spectrometer (JASCO NRS-2000).
Result and Discussion: 254 craters with concentrations of FeO (14-17 wt%), TiO2 (≤ 1 wt%) and Th (≤ 1 ppm) were identified. It was suggested that Kalahari 009 was ejected together with the Kalahari 008 highland breccia (Sokol et al., 2008), and therefore the source crater may be located in a region of cryptomare. 92 out of 254 craters are located in cryptomare. The cosmic exposure age of Kalahari 009 is from 220 ±40 yr to ~0.3 Myr (Nishiizumi et al., 2005), which means that the craters with relatively high OMAT are candidates of the source crater. Thus, the source crater of Kalahari 009 is probably one of 92 craters in cryptomare having relatively high OMAT.
In the thin section of Kalahari 009, shock products such as coesite, ringwoodite, partly mosaicism and planar fracturing in plagioclase and olivine were observed. According to the shock classification in Stöffler et al. (1991), the shock pressure is estimated as 30-35 GPa. The presence of ringwoodite suggests the shock pressure of ~ 7-14 GPa based on the Fe2SiO4 phase diagram (Ohtani, 1979). Thus, it is inferred that Kalahari 009 experienced the shock pressure of ~ 7-35 GPa. The Ar-Ar dating of Kalahari 009 showed that the meteorite experienced significant loss of radiogenic Ar at 1.7 Gyr (Fernandes et al., 2007). Thus, Kalahari 009 has experienced at least one impact which caused loss of radiogenic Ar and/or produced shock-induced minerals.
In summary, we describe a possible ejection scenario of Kalahari 009 based on the results of the present and previous studies. An impact event occurred at 1.7 Gyr, but the ancient basalt clast remained in the impact crater as a breccia. Then, the 2nd impact produced a small crater inside the large crater between ~0.3 Myr and 220 ±40 yr and ejected the meteorite from the small crater.
In the presentation, we will discuss the source crater of Kalahari 009 in conjunction with the impact history of the meteorite.

Keywords: Moon, Kaguya/SELENE, Cryptomare

The rheological structure of moon interior and the mechanism of deep moonquake.

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Apollo program installed some seismometers on the moon and the seismic data provided us the much information about the moon interior. Analysis of moonquake data supports the following: The moon interior is differentiated, and the crust and mantle are composed mainly of plagioclase and olivine, respectively (reviewed by Wieczorek et al., 2006). Although we have considered the moon interior based on moonquake data, the mechanism of moonquake is debatable problem. Moonquakes is categorized into shallow moonquake, deep moonquake, thermal moonquake, and moonquake by meteoroid impact. We discuss the mechanism of deep moonquakes, which occur at a depth of 800-1200 km, based on the rheological structure of moon interior. Unraveling the mechanism of deep moonquakes is key to understand the heterogeneity and evolution of moon interior.
We calculate the rheological structure of moon interior. In this calculation, thermal structure of moon interior is calculated using the equation suggested by Kuskov et al., (2002). Pressure was calculated using the crustal density of 3000 kg/m^3 and mantle density of 3300 kg/m^3. Moho depth is assumed to be 60 km depth (Hood and Zuber, 2000). Based on the above assumptions, Byerlee's law is applied to determine the rock strength in brittle deformation regions, and the flow laws are applied to calculate the rock strength in plastic deformation regions. Crustal deformation is calculated by flow laws of plagioclase (Rybacki and Dresen, 2000; Rybacki et al., 2006), mantle deformation is calculated by flow laws of olivine (Karato and Jung, 2003). Strain rate is assumed to be 10^{-14} or 10^{-19} (s^{-1}).
The calculated rheological structure suggests that the deep moonquakes occur in plastic deformation region, where the fracture and slip are generally not occurred. We verified the possibility that the thermal runaway instability causes the deep moonquakes in plastic deformation region (e.g., Karato et al., 2001). The key issues in thermal runaway instability are (1) the strain rate should be large and (2) the degree of thermal feedback must be large (Karato et al., 2001). We calculated the strain rate that produced by the tidal stress in lunar interior under dry and wet conditions, and the degree of thermal feedback (a degree of softening of material). We found it difficult that the thermal runaway instability causes the deep moonquakes under dry conditions because small tidal stress (~0.1 MPa) cannot produce the large strain rate under dry conditions. On the other hand, the large strain rate is produced and the thermal runaway instability can be occurred in moon interior under wet conditions (500-1000 ppm H/Si). It suggests that the water exists heterogeneously in moon interior, and this heterogeneity of water may cause that the deep moonquakes occur in localized regions (clusters).

Keywords: Moon, Deep moonquake, Rheological structure

