Timing and duration of mare volcanism in the central region of the northern farside of the Moon

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Age determinations of lunar mare basalts are essential for understanding the thermal evolution of the Moon. In this study, we performed new crater size-frequency measurements in mare deposits in the central region of the northern farside, consisting of Lacus Luxuriae, Buys-Ballot, Campbell, and Kohlschütter, using high-resolution images obtained by SELENE (Kaguya) Terrain Camera. The estimated model ages of the mare deposits range from 2.7 to 3.5 Ga. On the basis of model ages for all investigated mare deposits in the central part of the northern farside, considering the results of previous studies, we concluded that mare volcanism in this region began at least as early as 3.9 Ga and continued until ~ 2.6 Ga. From a comparison of model ages in the region and the South Pole-Aitken basin, we found that mare volcanism in these regions ended at the same time, suggesting that the South Pole-Aitken basin formation impact had a minor effect on mare volcanism in the region.

Key words: Moon, mare volcanism, lunar farside, Feldspathic Highland Terrane, the South Pole-Aitken basin, crater size-frequency measurement.

1. Introduction

Unraveling the volcanic history of the Moon is essential for understanding its origin and thermal evolution. Lunar mare basalts, which are the most common volcanic features on the Moon, cover 17% of its total surface area and occur preferentially in topographic lows on the nearside (e.g., Head, 1975; Head and Wilson, 1992). On the farside, limited numbers of maria occur in some basins and craters. The asymmetrical distribution of exposed mare basalts has evoked many questions concerning the generation and emplacement mechanisms of mare basalts (e.g., Solomon, 1975; Wasson and Warren, 1980; Head and Wilson, 1992; Zhong *et al.*, 2000; Werner and Loper, 2002). To reconstruct and understand the mechanisms, it is critical to determine the ages, volumes, and compositions of mare basalts.

A considerable number of nearside maria have been dated by using image data from Lunar Orbiters and Apollo missions (e.g., Wilhelms and McCauley, 1971; Boyce, 1976; Wilhelms, 1987; Hiesinger *et al.*, 2000, 2003, 2006, 2008; Bugiolacchi and Guest, 2008). These studies revealed that the largest number of mare basalts formed in the Late Imbrian Epoch at 3.2 to 3.8 Ga, indicating good

agreement with radiometric ages for returned basaltic rocks, and that mare volcanism lasted until the Eratosthenian Period (e.g., Boyce, 1976) or even until the Copernican Period (Wilhelms, 1987; Hiesinger *et al.*, 2003, 2008), suggesting that the total duration of lunar volcanism was 1.5 to 3.0 Ga.

Prior to the SELENE (Kaguya) mission (Kato *et al.*, 2008), accurate age determinations of most maria on the farside had not been performed because of the lack of high spatial resolution images. Therefore, a systematic, high-resolution mapping of the entire lunar surface, particularly the farside, is a primary objective of the SELENE mission. The Terrain Camera (TC) onboard SELENE is a panchromatic push-broom imager with two optical heads that acquire stereo data for the entire surface of the Moon with an average resolution of 10 m/pixel (Haruyama *et al.*, 2008). The TC has obtained high-resolution images of most areas of the lunar farside at solar elevation angles lower than 10° . Using the high-resolution images, Haruyama *et al.* (2009) carried out crater size-frequency measurements in farside mare deposits within the South Pole-Aitken (SPA) basin and Mare Moscoviense, and found that mare volcanism on the lunar farside lasted ~ 2.5 Ga, longer than was previously considered.

Here we performed new crater size-frequency measurements in mare deposits in the central region of the northern farside, which had been previously undated, using new high-resolution images obtained by TC. The mare deposits

Fig. 1. Clementine 750 nm basemap indicating the location of the investigated mare deposits, Lacus Luxuriae, Buys-Ballot, Campbell, and Kohlschütter. Sinusoidal map projection.

include Lacus Luxuriae (19°N , 176°E), and mare deposits in Buys-Ballot (21°N , 175°E), Campbell (45°N , 152°E), and Kohlschütter (15°N , 154°E) (Fig. 1). The farside northern hemisphere corresponds to the highest parts of the topography and the thickest parts of the crust of the Moon. This region is also characterized by a central anorthositic region that constitutes the remnant of an anorthositic craton resulting from early lunar differentiation and is known as “Feldspathic Highland Terrane (FHT)” (Jolliff *et al.*, 2000). Although mare deposits cover less than 1% of this region, these deposits provide insight into the crustal evolution and volcanic history of the FHT. Based on our new crater size-frequency measurements, we will discuss how long mare volcanism in the central region of the northern farside was active and whether a difference existed in the durations of mare volcanisms in the region and the SPA basin.

The SPA basin is the largest impact feature on the Moon. It is more than 8 km deep and extends ~ 2500 km from the South Pole to the crater Aitken (e.g., Wilhelms, 1987; Spudis *et al.*, 1994; Smith *et al.*, 1997), which is located 15° south of the equator. According to lunar crustal thickness models (e.g., Neumann *et al.*, 1996; Wieczorek and Phillips, 1998), the mean crustal thickness within the SPA basin is less than a half of that in the central region of the northern farside. We will discuss the effects of the large impact on mare formation from the viewpoint of the duration of mare volcanism by comparing the model ages for mare basalts in the FHT and SPA basin.

2. Technique of Age Determination

Crater counting is a well-established technique for deriving the relative and absolute ages of planetary surfaces. Based on the simple idea that older surfaces accumulate more craters, we can infer the relative and absolute ages by measuring the crater size-frequency distribution (CSFD)

with image data. This technique has been described in detail in a number of papers (e.g., Arvidson *et al.*, 1979; Neukum and Ivanov, 1994; Hiesinger *et al.*, 2000, 2003; Hartmann and Neukum, 2001; Neukum *et al.*, 2001; Wagner *et al.*, 2002). Therefore we will just briefly present the procedure.

Determining the ages of photogeologic units with crater size-frequency measurements requires two procedures: (1) measuring the surface area of the unit and (2) measuring primary crater diameters within the unit (Hiesinger *et al.*, 2000). In this study, we manually performed crater counts on the computer. We used images that are converted to stereographic projection with a resolution of 10 m/pixel at the projection center because the projection introduces little distortion in a narrow area. The diameters of small craters were calculated by multiplying a crater diameter in units of image pixels and the pixel resolution (10 m/pixel).

Age estimates from crater size-frequency measurements are sensitive to any contamination by secondary craters. It has been discussed in previous studies of lunar and Martian crater densities that the majority of small craters, not only those in clusters or rays, are secondary in origin, and that some of these secondary craters may not be obvious (e.g., Namiki and Honda, 2003; McEwen *et al.*, 2005; Hirata and Nakamura, 2006; McEwen and Bierhaus, 2006; Dundas and McEwen, 2007). However, this argument has been challenged by various observations. The encounter rates of bolides with Earth’s atmosphere determined from satellite records and the small crater production function on the Moon appear to be in good agreement (e.g., Ivanov, 2006). Also, the size-frequency distributions of lunar and Martian craters appear invariant over long time scales (e.g., Neukum and Ivanov, 1994; Werner *et al.*, 2009). Therefore, we believe that craters over a wide diameter range are primary, although the contribution of secondary craters to the population of small craters must continue to be studied. In this

study, we eliminated obvious secondary craters based on their morphological characteristics (e.g., chain craters, elliptical craters, and clusters) (Melosh, 1989).

We used the cumulative crater size-frequency diagram (e.g., Arvidson *et al.*, 1979) because the cumulative presentation has the advantage of lower variability with statistical noise. We assume that a lunar CSFD can be expressed by the following crater production function polynomial proposed by Neukum and co-workers (Neukum, 1983; Neukum and Ivanov, 1994),

$$\log_{10} N(D) = a_0 + \sum_{n=1}^{11} a_n (\log_{10} D)^n \quad (1)$$

where D is the crater diameter in kilometers and $N(D)$ is the cumulative number of craters larger than D per km². We assigned commonly accepted values for the coefficients of a_1 to a_{11} (Neukum, 1983; Neukum and Ivanov, 1994). By fitting the observed CSFD to Eq. (1), we derived the crater frequency (cumulative crater density for $D \geq 1$ km, i.e., $N(1)$). More recently, the polynomial coefficients were updated (Neukum *et al.*, 2001). However, in the diameter range (<1 km) used in this study, the differences between the polynomials are insignificant (Neukum *et al.*, 2001) and hardly produce differences in the estimated ages.

The cratering chronology formulated by relating crater frequencies to the radiometric ages of Apollo and Luna samples enables us to convert the crater frequencies into absolute model ages (e.g., Hartmann, 1970, 1972; Neukum *et al.*, 1975; Neukum, 1983; Neukum and Ivanov, 1994; Stöffler and Ryder, 2001). In this study, we translated the crater frequency into an absolute model age using the following cratering chronology model proposed by Neukum (1983) and Neukum and Ivanov (1994),

$$N(D \geq 1) = 5.44 \times 10^{-14} \{ \exp(6.93 \times t) - 1 \} + 8.38 \times 10^{-4} t \quad (2)$$

where $N(D \geq 1)$ is the cumulative number of craters ≥ 1 km in diameter per km² and t is the age in Gyr. More recently, a different chronology model was proposed (Stöffler and Ryder, 2001), indicating a steeper slope in the age range of >3.75 Ga, where the difference from the model we adopt becomes large. However, in the range of <3.6 Ga, the ages from their model differ from our results by less than 0.1 Ga.

Model ages from crater counts are principally limited by statistical errors (Neukum *et al.*, 2001). The statistical error of individual data points in our crater frequency measurements is mostly $<20\%$ (1σ); the errors of ages based on the chronology model are ± 0.02 Ga for >3.5 Ga, 0.01 to 0.03 Ga for between 3.2 and 3.0 Ga, and $<\pm 20\%$ for <3.0 Ga (Hiesinger *et al.*, 2000). It must be noted that these are uncertainties of each data point in CSFD, and the variation from point to point is not represented by these errors.

The synchronous rotation of the Moon generates an apex-antapex asymmetry in cratering production rate (Morota and Furumoto, 2003; Morota *et al.*, 2005; Le Feuvre and Wieczorek, 2008; Gallant *et al.*, 2009). However, in the region investigated by our study, the effect of the apex-antapex cratering asymmetry on age determination is estimated to be less than 7% (Gallant *et al.*, 2009), much

smaller than the error due to statistical fluctuation. Therefore, we excluded the effect in this study.

Lunar geologic history is subdivided into five chronologic periods defined by impact events that formed the Nectaris basin, the Imbrium basin, the crater Eratosthenes, and the crater Copernicus. Various authors defined lunar chronologic systems in different ways (e.g., Neukum, 1983; Wilhelms, 1987; Neukum and Ivanov, 1994; Stöffler and Ryder, 2001). Estimates of the beginning of the Eratosthenian Period agree well among Neukum (1983), Wilhelms (1987), and Neukum and Ivanov (1994) at 3.2 Gyr, and Stöffler and Ryder (2001) at 3.15 Gyr. However, there are differences in the definitions for the beginnings of the Nectarian, Imbrian, and Copernican given in detail by Hiesinger *et al.* (2000, 2003) and Wagner *et al.* (2002). The cratering model ages for the major impact basins fall within the range of radiometric ages published by several investigators (see Neukum, 1983; Neukum and Ivanov, 1994; Hiesinger *et al.*, 2000, 2003; Wagner *et al.*, 2002). In this study, therefore, we adopt the chronologic system of Neukum (1983) and Neukum and Ivanov (1994), with Nectaris being 4.1 ± 0.1 Gyr, the Imbrium basin being 3.91 ± 0.1 Gyr old, and the Copernican Period beginning 1.5 Gyr ago.

3. Results

3.1 Lacus Luxuriae

Mare deposit, Lacus Luxuriae is located at the center of the 600 km-diameter Freundlich-Sharonov basin (18.5°N , 175°E) and has a diameter of 50 km (Fig. 1). The mare deposit was previously mapped as Imbrian age (Stuart-Alexander, 1978).

Figure 2 presents a TC mosaic image of Lacus Luxuriae and the Buys-Ballot region, obtained with a low solar elevation angle of $\sim 7^\circ$. The northern part of Lacus Luxuriae exhibits relatively lower albedo than the southern part. This difference is probably not due to compositional differences in mare basalts, but to vertical and horizontal impact mixing with low-iron and low-titanium highland materials in the southern unit.

We performed crater counts in the northern unit (area N) and in the southern unit (area S) (Fig. 2). The results are presented in Fig. 3 as cumulative size-frequency plots (e.g., Arvidson *et al.*, 1979). The model age of the southern unit is estimated to be 3.4–3.5 Ga from the CSFD for $D < 400$ m (Table 1); thus, it is classified as an Upper Imbrian Epoch. However, the CSFD for $D > 500$ m gives a model age of ~ 3.7 Ga. The deflection of the CSFD, generating two distinct model ages, can be associated with a possible resurfacing event (e.g., Neukum and Horn, 1976; Greeley *et al.*, 1993; Hiesinger *et al.*, 2002; Wagner *et al.*, 2002; Michael and Neukum, 2007). In our interpretation, the southern unit has been resurfaced by a basaltic eruption at 3.4–3.5 Ga, where the erupted lava flow did not completely obliterate pre-existing craters on a deposit formed at ~ 3.7 Ga. The data suggest the diameters of obliterated craters are less than 500 m. Thus, based on the experiential relationship between the diameter and rim height for fresh lunar craters (Pike, 1977), the thickness of the younger flow can be estimated as 15–22 m.

Table 1. Model ages of mare deposits.

Mare deposit		Count area [km ²]	$N(1)^a$ [km ⁻²]	Model age [Ga]	Stuart-Alexander (1978)	Wilhelms (1987)
Lacus Luxuriae (19°N, 176°E)	N	213.9	0.00316	3.28 (+0.06/−0.08)	Im ^b	
			0.00958	3.68 (+0.07/−0.12)		
	S	75.7	0.00430	3.46 (+0.03/−0.04)	Im ^b	
			0.00898	3.67 (+0.06/−0.10)		
Buys-Ballot (21°N, 175°E)		86.3	0.00295	3.22 (+0.10/−0.18)	Im ^b	
Campbell (45°N, 151°E)		481.0	0.00229	2.72 (+0.24/−0.29)	Im ^b	Im ^b
Kohlschütter (15°N, 154°E)		183.0	0.00261	3.03 (+0.24/−0.56)	Im ^b	

^aNumber of craters with a diameter larger than or equal to 1 km per km², derived by fitting the crater production function polynomial (Neukum, 1983; Neukum and Ivanov, 1994) to the observed CSFD. ^bIm = Imbrian mare material.

Fig. 2. (a) TC mosaic image of Lacus Luxuriae and Buys-Ballot. Mean solar elevation angle of the original images is ~ 7 degree. Counting areas are indicated by white lines. The bizarre shape of the count area for Buys-Ballot is due to excluding an area occupied by numerous secondary craters. (b and c) Close-up images of the northern unit and the southern unit in Lacus Luxuriae, respectively. The locations of these areas are shown as dashed boxes in (a). Stereographic projection centered at 20°N latitude and 175°E longitude.

The CSFD for the northern unit also exhibits evidence of resurfacing events. For the lava flow exposed in the northern unit, the CSFD for $D < 450$ m gives a model age of ~ 3.3 Ga, younger than that of the southern unit (Table 1). The result supports the interpretation that the higher albedo of the southern part is mainly due to impact mixing with highland materials. From the CSFD for $D > 650$ m, the model age of the underlaid flow is estimated to be ~ 3.7 Ga, which is equivalent to that of the flow under the southern unit. Therefore, we consider the lava flow under the northern unit to be the same as that under the southern unit. Furthermore, we note that the CSFD for $0.45 \text{ km} < D < 0.6 \text{ km}$ lies on the polynomial of 3.46 Ga, although the errors are significantly large. This result implies that the lava flow of 3.4–3.5 Ga exposed in the southern unit would

spread under the northern unit. From the crater diameter-rim height relation (Pike, 1977), the thickness of the lava flow of ~ 3.3 Ga is estimated to be 13–19 m, and that of 3.4–3.5 Ga is estimated to be 19–28 m.

Our results indicate that mare volcanism in Lacus Luxuriae began at least ~ 3.7 Gyr ago and continued through the Late Imbrian Epoch, that is consistent with the previous mapping as Imbrian age (Stuart-Alexander, 1978).

3.2 Buys-Ballot

Buys-Ballot, which lies just northwest of Lacus Luxuriae, is a 55 km-diameter Imbrian crater (Stuart-Alexander, 1978) or Nectarian crater (Wilhelms, 1987). The odd shape exhibits the distinctive signatures of a very low-angle impact: elongated pear-shaped plan (90×60 km), crater widening transverse to the inferred trajectory,

Fig. 3. Cumulative crater size-frequency distributions of Lacus Luxuriae. Solid curves indicate the crater production function polynomial fitted to the observed CSFDs (Neukum, 1983; Neukum and Ivanov, 1994). Error bars are calculated by $\log(N \pm N^{1/2})/A$, where N is the cumulative number of craters and A is the counted area.

Fig. 4. Cumulative crater size-frequency distribution of the mare deposit in Buys-Ballot. Solid curve indicates the crater production function polynomial fitted to the observed CSFDs (Neukum, 1983; Neukum and Ivanov, 1994). Error bars are calculated by $\log(N \pm N^{1/2})/A$, where N is the cumulative number of craters and A is the counted area.

and central peak ridge (Schultz *et al.*, 1998) (Fig. 2). The floor of this crater is filled by mare basalt with iron content estimated to be 8–15 wt% and titanium content estimated to be 0–2 wt% from Clementine spectral data (Gillis and Spudis, 1998).

We performed crater size-frequency measurement in the

eastern part of the floor (Fig. 2). Figure 4 plots the result as cumulative size-frequency distribution. The mare deposit exhibits no evidence of any resurfacing events in the CSFD; the observed CSFD can be well-fitted by one polynomial function for the investigated diameter range (>250 m). The model age is estimated to be 3.2–3.3 Ga, which is equivalent to that of the exposed lava flow in the northern unit of Lacus Luxuriae (~ 3.3 Ga) within the uncertainties, suggesting that the lava flows might have formed from the same magma (Table 1).

3.3 Campbell

Campbell is a 220 km-diameter pre-Nectarian crater (Stuart-Alexander, 1978; Wilhelms, 1987). Mare basalt covers an area of 2400 km² within the central western portion of the crater and was previously mapped as Imbrian age (Stuart-Alexander, 1978; Wilhelms, 1987). The basalt has low iron (10–14 wt% FeO) and low titanium (0.5–1.5 wt% TiO₂) contents. Furthermore, the concentration of mafic material is constant and does not vary across the expanse of the mare (Gillis and Spudis, 1996, 1998).

Figure 5 presents a TC mosaic image of the mare deposit within Campbell, obtained with a low solar elevation angle of $\sim 5^\circ$. We carried out crater counts in the central area of this mare. To the northeast of the area there is a fresh rayed crater with a diameter of 3.2 km, which may be accompanied by numbers of secondary craters. However, most expected secondaries are estimated to be smaller than 160 m in diameter, i.e. below the minimum size of our study (250 m), according to the relationship between primary crater diameter and mean maximum secondary crater diameter for lunar craters (Allen, 1979). In any case, we eliminated obvious secondary craters based on their morphological characteristics, such as chain craters, elliptical craters, and clusters.

Figure 6 plots the cumulative size-frequency distribu-

Fig. 5. TC mosaic image of the mare deposit in Campbell. Mean solar elevation angle of the original images is $\sim 5^\circ$. Counting area is indicated by white lines. Stereographic projection centered at 45.5° N latitude and 151° E longitude.

Fig. 6. Cumulative crater size-frequency distribution of the mare deposit in Campbell. Solid curve indicates the crater production function polynomial fitted to the observed CSFDs (Neukum, 1983; Neukum and Ivanov, 1994). Error bars are calculated by $\log(N \pm N^{1/2})/A$, where N is the cumulative number of craters and A is the counted area.

tion of counted craters. The observed CSFD can be fitted to one production function polynomial for the investigated diameter range (>250 m). The derived model age of this deposit is estimated to be ~ 2.7 Ga; hence, it is substantially younger than the Imbrian-Eratosthenian boundary (3.2 Ga). Haruyama *et al.* (2009) also found that several farside maria (e.g., Apollo, Antoniadi, and the eastern part of Mare Moscoviense) formed in the Eratosthenian Period. Our result indicates that the mare basalt in Campbell is one of the mare deposits formed in the latest phase of farside volcanism.

3.4 Kohlschütter

Kohlschütter, which is located to the southeast of the Mare Moscoviense (Fig. 1), is a 53 km-diameter Nectarian crater (Stuart-Alexander, 1978; Wilhelms, 1987). The floor of the crater is partially covered by mare basalt. The mare deposit was previously classified as Imbrian in age (Stuart-Alexander, 1978).

Figure 7 presents a TC mosaic image of the mare deposit within Kohlschütter, obtained with a low solar elevation angle of $\sim 6^\circ$. In the central western part of the floor, which corresponds to the highly cratered area, highland material remains uncovered by mare basalt. The northern part of the floor is also occupied by clusters of secondary craters from the 20-km-diameter rayed crater that lies northwest of Kohlschütter (Fig. 1). Therefore, we chose the southeastern part of the floor as the count area (Fig. 7). We also excluded a mare ridge, possibly formed by a vertical displacement of mare lava (e.g., Lucchitta, 1976), from the count area because it makes shades particularly in the northeastern part of the count area, inhibiting identification of small craters in particular.

Figure 8 plots the result as a cumulative size-frequency distribution. The observed CSFD can be fitted to one pro-

Fig. 7. TC mosaic image of the crater Kohlschütter. Mean solar elevation angle of the original images is ~ 6 degree. Counting area is indicated by white lines. The mare ridge area indicated by a white box was excluded from the count area because it inhibits identification of small craters (see the text). Stereographic projection centered at 14°N latitude and 154°E longitude.

Fig. 8. Cumulative crater size-frequency distributions of the mare deposit in Kohlschütter. Solid curve indicates the crater production function polynomial fitted to the observed CSFDs (Neukum, 1983; Neukum and Ivanov, 1994). Error bars are calculated by $\log(N \pm N^{1/2})/A$, where N is the cumulative number of craters and A is the counted area.

duction function polynomial for the investigated diameter range (>250 m). The model age is estimated to be ~ 3.0 Ga, younger than the Imbrian-Eratosthenian boundary. However, it must be noted that the error of the model age estimated in our study is close to $\pm 20\%$ (1σ). If we adopt the upper limit of the error range, the mare basalt should be classified as Upper Imbrian.

4. Discussion

4.1 Duration of mare volcanism in the FHT

The model ages of mare basalts investigated in our study range from 3.7 to 2.7 Gyr ago (i.e., from the Late Imbrian Epoch to the Eratosthenian Period). The oldest basalt was found in Lacus Luxuriae as a layer buried by later flows. In contrast, the youngest basalt occurs in Campbell. No evident correlations exist between the model ages and the topography, the gravity anomaly, and the sizes and ages of the craters or the basins filled by the mare basalts.

Mare Moscoviense, which is one of the most outstanding mare deposits on the lunar farside, is also located in the FHT on which our study focused (Fig. 1). Previous dating of four mare units in Mare Moscoviense using TC image data (Haruyama *et al.*, 2009; Morota *et al.*, 2009) revealed that

the lava flows were formed from 3.9 to 2.6 Gyr ago. Figure 9(A) presents the frequency distribution of model ages for all investigated mare deposits in the FHT, indicating that most lava flows in the FHT formed in the Late Imbrian Epoch. However, three deposits (Campbell, Kohlschütter, and the eastern unit in Mare Moscoviense) indicate younger model ages. Thus, we conclude that mare volcanism in the FHT continued until ~ 2.6 Gyr ago.

Previous studies of dark haloed craters and light plains revealed the presence of cryptomaria (i.e., maria that were buried by ejecta from large craters or basins) and interpreted them as evidence for ancient mare volcanism (e.g., Schultz and Spudis, 1978, 1983; Hawke and Bell, 1981; Bell and Hawke, 1984; Antonenko *et al.*, 1995). Such ancient mare volcanism has been supported by radiometric analyses of rock samples returned from the lunar nearside (e.g., Taylor *et al.*, 1983; Dasch *et al.*, 1987; Nyquist *et al.*, 2001) and lunar meteorites (Terada *et al.*, 2007), which indicate ages of 4.2–4.35 Gyr for their basalt clasts. In the central northern region of the farside, the onset of mare volcanism is not well understood, even though our results indicate that mare volcanism began at least as early as 3.9 Gyr ago, for a total duration of ~ 1.3 Gyr. However, the total duration in the region might be expanded to ~ 1.7 Gyr, if the light plains that can be found as small patches in the FHT (Howard *et al.*, 1974) are associated with cryptomaria.

4.2 Comparison with the SPA basin and the nearside

Figures 9(B) and 9(C) present histograms of model ages for mare deposits in the SPA basin (Haruyama *et al.*, 2009) and on the nearside (Hiesinger *et al.*, 2000, 2003, 2006) for comparison. We found that the shape of the frequency distribution of mare basalts in the FHT is very similar to that in the SPA basin; the histograms have a peak at ~ 3.5 Gyr, and expand to ~ 2.5 Gyr. However, it must be noted that some cryptomaria exist within the SPA basin (e.g., Pieters *et al.*, 2001), implying that mare volcanism in the SPA basin may have started prior to that in the FHT, though the volumes of the cryptomare deposits are not so large.

The effects of large impacts on the thermal evolution of the mantle have been proposed as one mechanism for the formation of lunar basalts (e.g., Arkani-Hamed, 1973, 1974; Elkins-Tanton *et al.*, 2004; Ghods and Arkani-Hamed, 2007). A recent version of the mechanism, related to the mantle convection triggered by impact-induced thermal perturbations (Ghods and Arkani-Hamed, 2004, 2007), requires that the SPA basin formation impact generates a substantial amount of melting in the mantle, which does not seem to be compatible with the minor amount of mare and cryptomare deposits filling this basin. Furthermore, the impact-induced convection model requires a long duration of mare volcanism for the SPA basin (Ghods and Arkani-Hamed, 2007). This is also incompatible with our result, which indicates no difference in the timing and the duration of mare volcanism within and outside the SPA basin. Thus, we concluded that the SPA basin formation impact had a minor effect on the formation of mare basalts in the region. It is probable that the basin simply provided a depression for magma generated by internal heating in early history to pond.

As presented by Haruyama *et al.* (2009), comparing

Fig. 9. Histograms of the model ages of mare deposits in the central region of the northern farside (A), including Lacus Luxuriae, Buys-Ballot, Campbell, Kohlschütter (this study), and those in Mare Moscoviense (Haruyama *et al.*, 2009; Morota *et al.*, 2009), within the SPA basin (B), including Poincaré, Ingenii, Antoniadi, Chrétien, Jules Verne, Aitken, Apollo, Von Karman, Von Karman M, Leibnitz, Rumford, Maksutov, and Nishina (Haruyama *et al.*, 2009), and on the nearside (C), including those in Mare Imbrium, Serenitatis, Humorum, Tranquillitatis, Humboldtium (Hiesinger *et al.*, 2000), Oceanus Procellarum, Mare Nubium, Cognitum, Insularum (Hiesinger *et al.*, 2003), and Mare Fecunditatis (Hiesinger *et al.*, 2006).

model ages of mare basalts on the farside and those on the nearside indicates that the timing of the termination of mare volcanism differed between the farside (~ 2.5 Ga) and the nearside (~ 1.2 Ga). This difference might be related to the thicker crust (e.g., Head and Wilson, 1992) and/or a deficiency of heat-producing radioactive elements on the farside (e.g., Jolliff *et al.*, 2000). However, a more solid interpretation of the causes for the nearside-farside dichotomy in mare volcanism requires a clearer understanding of the ages, volumes, compositions of mare basalts, and relation to crustal structure. Such clarification will be possible with SELENE multispectral (Matsunaga *et al.*, 2008; Ohtake *et al.*, 2009), topography (Araki *et al.*, 2009), and gravity (Namiki *et al.*, 2009) data sets.

5. Summary

The new high-resolution images obtained by SELENE TC enable us to perform accurate crater size-frequency measurements in the mare deposits in the central region of the northern farside, which were previously undated. Our results indicated that the mare deposits in the region formed from 3.7 to 2.7 Gyr ago. From model ages for all mare deposits in the region investigated by both our study and previous studies (Haruyama *et al.*, 2009; Morota *et al.*, 2009), we found that mare volcanism in this region began at least as early as 3.9 Gyr ago, and continued until ~ 2.6 Gyr ago. The comparison of model ages in the region and the SPA basin indicates the simultaneity of the mare volcanism in these regions. Therefore, we concluded that the SPA basin formation impact simply provided a depression for magma generated by internal heating in early history to pond rather than affecting the formation of mare basalts in the region.

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