Journal of Earth Science, *Vol. 22*, *No. 5*, *p. 601–609*, *October 2011* *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-011-0211-8

Geological Characteristics and Model Ages of Marius Hills on the Moon

Jun Huang (黄俊), **Long Xiao*** (肖龙), **Xinxing He** (贺新星), **Le Qiao** (乔乐),
Jiannan Zhao (赵健楠), **Hui Li** (李卉)
Planetary Science Institute, *China University of Geosciences*, *Wuhan* 430074, *China*

ABSTRACT: Marius Hills is a volcanic plateau on the nearside of the Moon. It is of great interest for its high concentration of volcanic features, including domes, cones, ridges, and rilles. However, the morphological and chronological characteristics of this plateau were not well studied due to the low resolution of early mission data. This study describes the detailed morphology of the volcanic features using the latest high spatial resolution images of the Terrain Camera (TC) onboard Selene-1 (10 m/pix) and Narrow Angle Camera (NAC) onboard the Lunar Reconnaissance Orbiter (LRO) (0.5 m/pix). We report here some new structures such as skylights and remnants of lava tubes. We have divided spectrally homogenous areas with Clementine UVVIS data and did crater size frequency distribution (CSFD) measurements with Lunar Orbiter (LO) IV and TC images in every spectral unit. We first report absolute model ages of 1.10 Ga for Marius basalt 1, 1.49 Ga for Flamsteed basalt, and 1.46 Ga for Schiaparelli Basalt. In addition, we have identified several younger lava events: they are Marius basalt 2 (814 Ma), medium to low titanium basalt (949 Ma), and undifferentiated medium titanium basalt (687 Ma). Finally, we propose a mantle plume scenario for the formation of Marius Hills, which could solve the inconsistency of previous models.

KEY WORDS: the Moon, Marius Hills, absolute model age, volcanic feature, mantle plume.

INTRODUCTION

Marius Hills plateau with an area of ~35 000 km^2 (Greeley, 1971) lies in Oceanus Procellarum (Fig. 1a), rising several hundred meters to 2 km above its surrounding area (Ping et al., 2009). This plateau contains large amounts of low domes, steep-sided dome cones (Head and Gifford, 1980; McCauley, 1967), and rilles and ridges (Greeley, 1971) (Figs. 1b and 1c). By analyzing the variations in dome morphology, McCauley (1969) suggested that igneous differentiations are present in this region. Using Clementine UVVIS data, Weitz and Head (1999) and Heather et al. (2003) identified six spectral units, analyzed the compositional variation, and proposed a magmatic evolution model. However, the time sequence of the magmatic evolution has not been well constrained. Although Boyce and Jonnson (1978) derived model ages by studying crater degradation, the results are believed to have large errors (Burgess and Turner, 1998).

This study was supported by the National Natural Science Foundation of China (Nos. 41072045, 41102209), the Research Fund for the Doctoral Program of Higher Education (No. 20090145110001), Nondestructive Analysis Technique and Best Analysis Scheme of Lunar Sample (No. TY3Q20110029) and China University of Geosciences (Wuhan) GF Special Research Fund (No. CUGXGF0901).
*Corresponding author: longxiao@cug.edu.cn

Manuscript received December 16, 2010.
Manuscript accepted March 10, 2011.

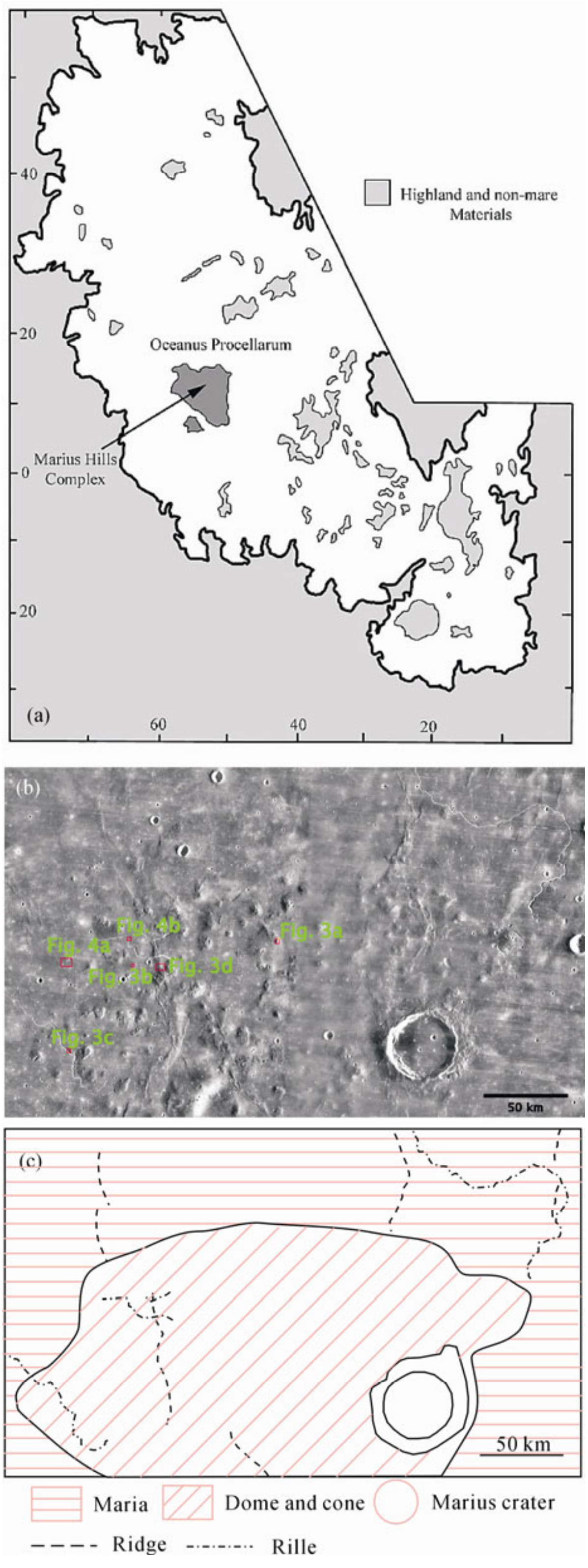

Figure 1. (a) Geological setting of Marius Hills plateau (adapted from Whitford-Stark and Head, 1980); (b) LO IV mosaic of Marius Hills plateau (12.53°N, 308.12°E). Boxes are locations of Figs. 3 and 4; (c) brief geological map of Fig. 1b.

In the new era of lunar explorations, Japan, China, India, and the United States have successfully launched lunar orbiters and gained numerous high-resolution remote sensing images. Imagery acquired by the Terrain Camera (TC) (10 m/pix) onboard Selene-1 and Narrow Angle Camera (NAC) (0.5 m/pix) onboard Lunar Reconnaissance Orbiter (LRO) have provided the opportunity to study the morphology of Marius Hills in detail (Lawrence et al., 2010); Moon Mineralogy Mapper (M^3) onboard Chandrayyan-1 gained both high spatial and high spectral resolution imaging spectrometer data and is very useful for the compositional analysis of the plateau (Besse et al., 2011).

The high concentration of volcanic features and complex magmatic evolution in Marius Hills plateau are significant for understanding the geological history and thermal evolution of the Moon. Hence, it could be a candidate site for sample return and lunar base constructions.

We first describe the volcanic features on the Marius Hills plateau using NAC and TC images. Then, we introduce the crater size frequency distribution (CSFD) measurement for deriving the absolute model ages of planetary surface. After that we apply the CSFD measurements using Clementine UVVIS data and the Lunar Orbiter (LO) IV and TC data to calculate the absolute model ages of the plateau. We propose a possible evolution scenario for this region and suggest its significance for understanding lunar thermal history.

VOLCANIC FEATURES

Marius Hills plateau contains 262 low domes and steep-sided domes, 59 cones (Head and Gifford, 1980; McCauley, 1967), and 20 rilles and extensive ridges (Greeley, 1971). By using Lucey et al.'s (2000) algorithm on Clementine UVVIS data, we have found variations for both FeO and TiO_2 concentrations. Although rocks in this region are basaltic, their FeO and TiO_2 abundances have large variation, both ranging from 0 to 20 wt.% (Fig. 2).

According to Whitford-Stark and Head (1977), the height of the 135 low domes ranges from 50 to 200 m with a maximum diameter of 25 km; the height of the 127 steep-sided domes ranges from 200 to 500

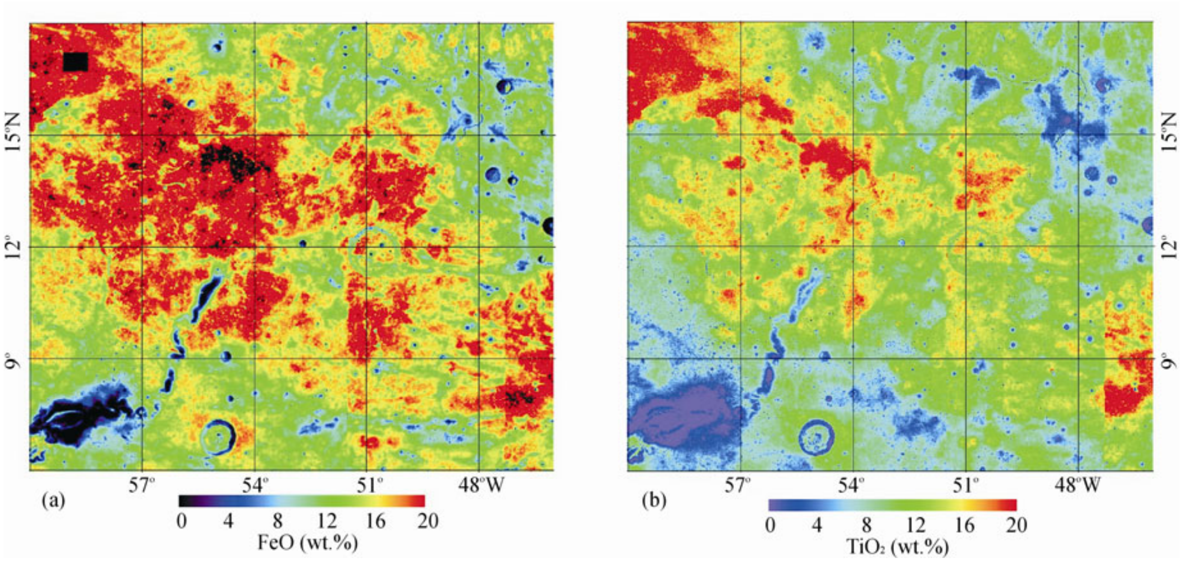

Figure 2. (a) FeO content derived using the algorithms of Lucey et al. (2000); (b) TiO_2 derived using the algorithms of Lucey et al. (2000).

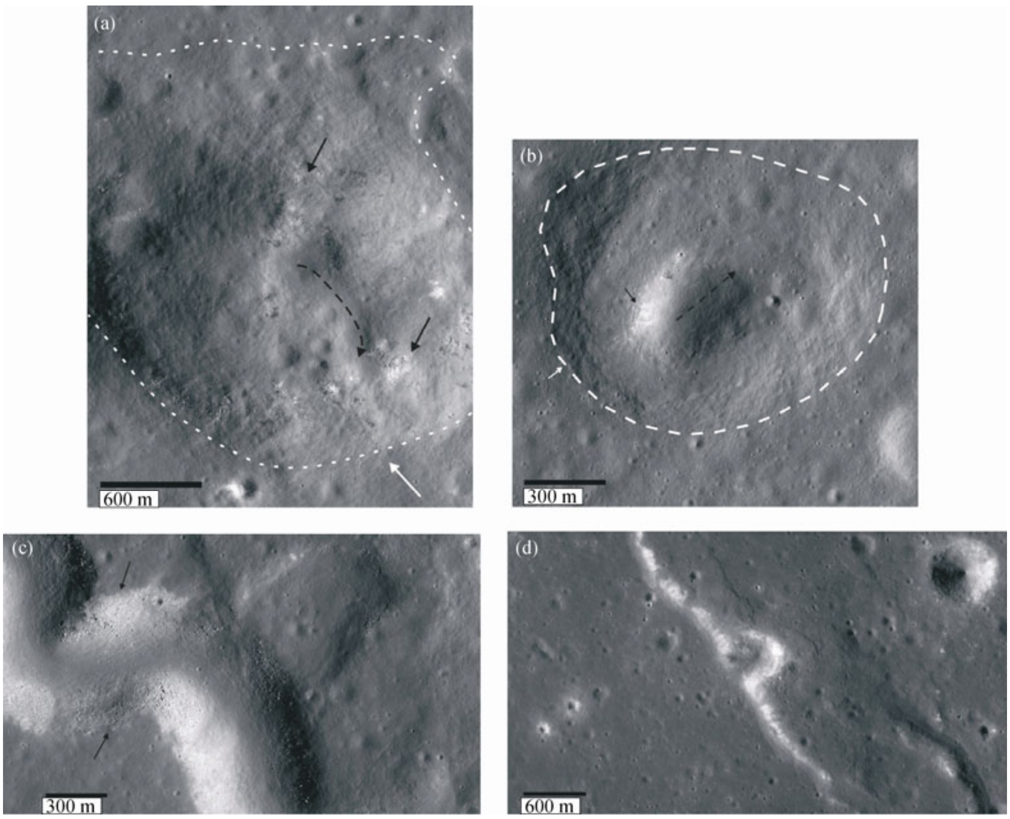

Figure 3. (a) a low dome (14.04°N, 306.22°E), the white arrow and dash lines indicate the contact between the dome and younger lava, the black arrows show the random distribution of boulders, the black arrow with dash line suggests the lava flow path. Illuminated from right. LRO NAC: M114308099LC; (b) a cone (13.56°N, 303.27°E), the white arrow and dash line indicate the contact between the cone and younger lava, the black arrow shows the random distribution of boulders, the black arrow with dash line suggests the lava flow path. Illuminated from right. LRO NAC: M114328462LC; (c) a rille (11.82°N, 301.98°E), the black arrows indicate the possible bedrock outcrop. Illuminated from right. LRO NAC: M114335284RC; (d) a ridge (13.54°N, 303.85°E). Illuminated from left. LRO NAC: M104877210LC.

m with a 2 to 15 km diameter range. Therefore, the slopes of all the domes are less than 15°.

A closer view of a dome is shown in Fig. 3a. It can be seen that this dome is truncated by adjacent mare plains (the white arrow and dashed lines in Fig. 3a), suggesting that it formed earlier and then younger lava flows covered parts of its apron. There is a depression on its summit which is a possible volcanic vent because it lacks an uplifted rim. The dashed arrow in Fig. 3a shows a downward depression, which was the path of the lava flow. Meters to tens of meters boulders sit randomly on the summit and the apron (black arrows in Fig. 3a); they might be volcanic bombs or shattered rocks.

These cones are broader and lower than the cones on the Earth because of lower gravity and absence of atmosphere on the Moon (Wilson and Head, 1981). The maximum diameter of cones is 3 km, and the highest is 300 m (Whitford-Stark and Head, 1977). They are usually located on domes or inter-dome plains. The most obvious morphological difference between domes and cones is the larger slope of cones. The cones are also truncated by the younger lava plain, and some of their aprons were eroded by the lava flowing out from the vent (Fig. 3b).

Twenty rilles on Marius Hills plateau have been identified (Whitford-Stark and Head, 1977) and one of them extends over 250 km (Fig. 1b). Boulders with sizes of tens of meters are located on both sides of the rille and the boulders are not related to the surrounding impact craters (Fig. 3c). However, the distribution of the boulders is controlled by the path of the rille, so we suggest that the boulders are the bedrock outcrop. As we know, most of the lunar surface is covered by regolith and these rilles are good candidates for bedrock study.

Extensive ridges are located in this region and the most dominant directions for them are NNE and NNW (Fig. 1b). Using a digital elevation model (DEM) derived from the TC data, we know these ridges are tens of meters high and several hundred meters wide (Fig. 3d).

A possible relatively well-preserved lava tube has been identified, with its southwest and northeast roof crust collapsed (Fig. 4a). A skylight was first reported by Haruyama et al. (2009) using TC data; here, we confirm this observation using LRO NAC data (Fig. 4b). This skylight infers a possible lava tube beneath the surface. This kind of structures could shield an astronaut from radiation from the sun and the deep space, so they are a good candidate site for long-term lunar surface human exploration and lunar base construction.

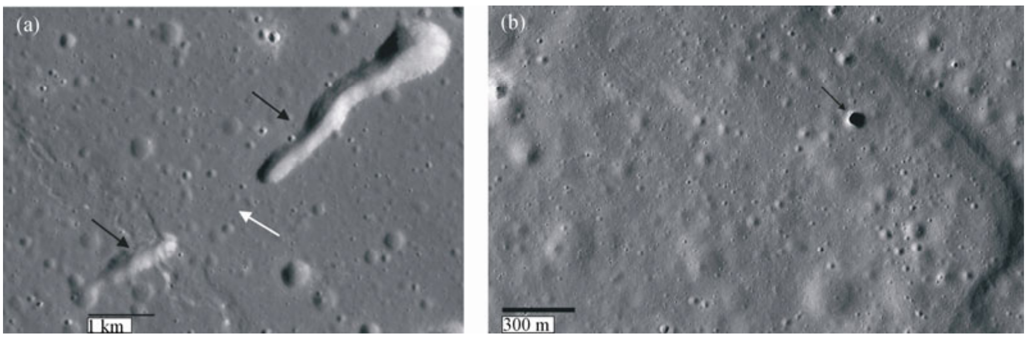

Figure 4. (a) Remnant lava tube (13.06°N, 301.93°E), black arrows indicate roof collapsed part, and the white arrow suggests the intact part. Illuminated from left. Selene-1 TC: TC_EVE_02_N15E300N12E303SC; (b) A skylight in a rille (14.10°N, 303.23°E). Illuminated from right. LRO NAC: M114328462RC.

CSFD MEASUREMENTS

It is well known that impact craters are widely present on solid surfaces in the solar system and older surfaces tend to have denser impact craters. CSFD measurement is a powerful tool for deriving the relative and absolute model ages for planetary surfaces (e.g., Hiesinger et al., 2000). We briefly outline the method as follows (Hartmann and Neukum, 2001; Ivanov, 2001; Neukum et al., 2001; Stöffler and Ryder, 2001; Hiesinger et al., 2000; Neukum and

Ivanov, 1994) and then use this method to calculate absolute model ages of selected regions.

This method is based on three assumptions (Hiesinger et al., 2000): (1) the crater distribution on lunar surface is random, (2) the formation process of craters is much faster than the deconstruction process, and (3) rocks within the same spectrally homogenous unit are formed in a very short range of time. A color ratio image has been produced using Clementine UVVIS data to identify various geological units (Fig. 5). In this study, we adopted the color scheme as described in Weitz and Head (1999), which uses the 750/415 nm ratio as red, 750/950 nm ratio as green, and 415/750 nm ratio as blue. The CSFD measurements were done in two steps: first, the surface area of the spectrally homogenous unit was measured; then, the diameter of every primary crater within this area was measured.

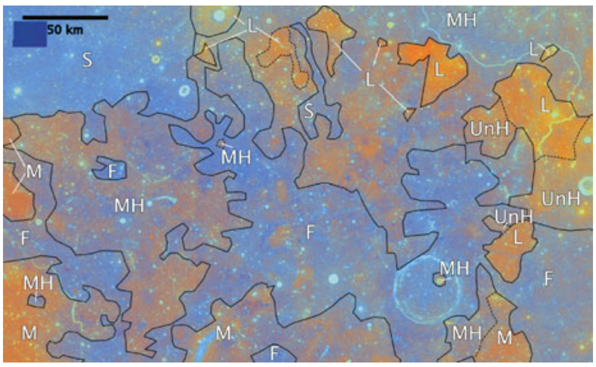

Figure 5. Spectral units in Marius Hills plateau (R=750/415 nm, G=750/950 nm, B=415/750 nm, centered at 12.53°N, 308.12°E). Flamsteed basalt (F), Schiaparelli basalt (S), medium to low titanium basalt (L), undifferentiated medium titanium basalt (UnH) in Sharp Formation, and Marius basalt 1 (M) and Marius basalt 2 (MH) in Hermann Formation.

The empirically derived lunar impact chronology curve (Ivanov, 2001; Neukum et al., 2001) is given by

$$N(1)=5.44\cdot 10^{-14}[\exp(6.93T)-1]+8.38\cdot 10^{-4}T$$

where $N(1)$ is the number of craters with diameters larger than or equal to 1 km in unit area and T is the absolute model age of the surface unit.

We chose the LO high-resolution and TC data to apply the CSFD measurements in JMoon (http://jmars.asu.edu/), as these data have a large incidence angle and excellent contrast; thus, craters rims can be easily identified. Then, we introduced CSFD measurement results into Craterstats (http://hrscview.fu-berlin.de/craterstats.html) and calculated the absolute model ages.

ABSOLUTE MODEL AGES OF THE MARIUS HILLS PLATEAU

Figure 5 shows the six geological units as identified in previous work (Heather et al., 2003; Whitford-Stark and Head, 1980): Flamsteed basalt (F), Schiaparelli basalt (S), medium to low titanium basalt (L), and undifferentiated medium titanium basalt (UnH) in Sharp Formation and Marius basalt 1 (M) and Marius basalt 2 (MH) in Hermann Formation.

Marius basalt covers the largest area in Marius Hills plateau. Stratigraphy study showed that it might have erupted over a period of time (Whitford-Stark and Head, 1980). Significant variations in albedo and composition (Fig. 2) lead Marius basalt to be separated into two distinct groups: Marius basalt 1 has lower TiO_2, lower UV/VIS ratio, and medium 1 μm absorption (Heather et al., 2003). A large part of Marius basalt 1 was fed by the 210 km long rille on the southwestern edge of the plateau (Whitford-Stark and Head, 1980). Marius basalt 2 has medium TiO_2 content, higher UV/VIS ratio, and strong 1 μm absorption (Heather et al., 2003). Previous study showed that the age of Mariusb basalt 1 is 3.3±0.3 Ga (Boyce and Jonnson, 1978), but the age of Marius basalt 2 has not been reported. In this study, we find another magmatic event in Marius basalt 1 unit occurring at $1.10^{+0.15}_{-0.17}$ Ga (Fig. 6a), and the age of Marius basalt 2 is 814^{+120}_{-140} Ma (Fig. 6b).

Flamsteed basalt extends from east to west throughout the plateau and covers the second largest area with impact crater Marius. It has a relatively high TiO_2 abundance, high UV/VIS ratio, and strong 1 μm absorption (Heather et al., 2003). Previous study reported the age of Flamsteed basalt to be 2.5±0.5 Ga (Boyce and Jonnson, 1978). However, we have identified a younger lava event with an age of $1.49^{+0.30}_{-0.35}$ Ga (Fig. 6c).

Schiaparelli basalt lies in the northwest with a relatively flat topography and less volcanic features. This unit has a relatively high TiO_2 abundance, high

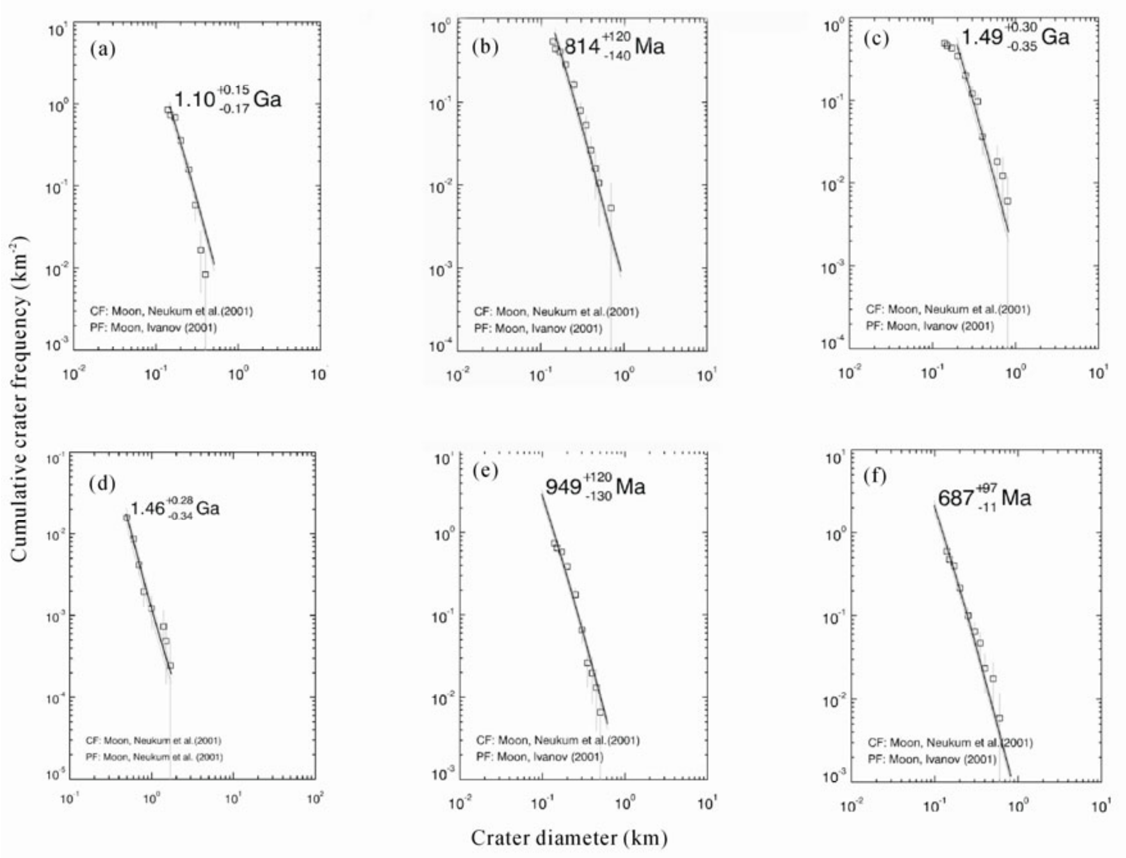

Figure 6. Absolute model ages. (a) Marius basalt 1; (b) Marius basalt 2; (c) Flamsteed basalt; (d) Schiaparelli basalt; (e) medium to low titanium basalt; (f) undifferentiated medium titanium basalt (UnH).

Table 1 Absolute model ages and CSFD measurement data of Marius Hills plateau

Geological units	Previous study (Ga)	This study	N(1) (km^{-2})	Area (km^2)	Crater number	Fit range (km)
M	3.3±0.3	$1.10^{+0.15}_{-0.17}$ Ga	9.22×10^{-4}	275	248	0.1–0.5
MH	-	814^{+120}_{-140} Ma	6.82×10^{-4}	266	133	0.2–1
F	2.5±0.5	$1.49^{+0.30}_{-0.35}$ Ga	1.25×10^{-3}	330	198	0.2–0.8
S	2.5±0.5	$1.46^{+0.28}_{-0.34}$ Ga	1.22×10^{-3}	4 093	64	0.5–1.7
L	-	949^{+120}_{-130} Ma	7.95×10^{-4}	149	119	0.1–0.7
UnH	-	687^{+97}_{-11} Ma	5.76×10^{-4}	208	125	0.1–0.8

Note: - means the age has not been reported in previous study.

UV/VIS ratio, and strong 1 μm absorption (Heather et al., 2003). The age of Schiaparelli basalt was reported to be 2.5±0.5 Ga (Boyce and Jonnson, 1978). We have shown a younger lava flow with an age of $1.46^{+0.28}_{-0.34}$ Ga (Fig. 6d).

Medium to low titanium basalt locates separately on the northeast plateau, with a uniform low TiO_2 content, low UV/VIS ratio, and weak 1 μm absorption (Heather et al., 2003). Undifferentiated medium titanium basalt lies in eastern part, which has a uniform medium TiO_2 content, high UV/VIS ratio, and strong 1 μm absorption (Heather et al., 2003). No age results of these two units were reported. Here, we show that they are relatively young: the absolute model age of medium to low titanium basalt is 949^{+120}_{-130} Ma (Fig. 6e) and that of undifferentiated medium titanium basalt is 687^{+97}_{-11} Ma (Fig. 6f). A summary of absolute model ages of Marius Hills plateau is listed in Table 1. However, we have not found obvious geological boundaries of younger lava events in M, F, and S units.

DISCUSSION

As presented above, some of the ages derived from CSFD measurements are very young, which are the Copernican. However, these results should be treated with caution. Although Neukum (1983) proposed craters in the diameter interval of 10 m to 300 km for obtaining the absolute model ages, van der Bogert et al. (2010) noted an effect of different target properties as using small craters (usually, the crater diameter is smaller than 100 m). In our study, we choose craters with diameters larger than 100 m as the lower fit range. Whether the same situation exists, it needs further investigation. In addition, we did not found sharp features such as flow front in current coverage of LROC NAC images for Marius Hills region. Further check is needed when new data are available.

The formation of volcanic domes on the Moon requires relatively low temperature magma or low volatile content and low eruption rate magma (Wilson and Head, 1981). The steep-sided domes in Marius Hills plateau indicate that the magma had very low eruption rate, low content of volatile, as well as relatively low temperature and high viscosity. It is well known that high viscosity is due to low temperature and high crystal content or high concentration of SiO_2. Previous study showed the magma could be evolved felsic magma (McCauley, 1969). However, the basaltic magma cannot be rich in SiO_2 (Rutherford et al., 1974). Therefore, we suggest that the magma had relatively low temperature and/or high crystal content.

There are no obvious compositional differences between the domes and the lava plains among domes (Heather et al., 2003; Weitz and Head, 1999). Both domes and lava plains show basaltic characters in Clementine multispectral analysis (Heather et al., 2003), but there are compositional variations in different domes (Fig. 2). The magmas that formed these domes either came from different source regions or the domes were the result of magmatic evolution. However, low temperature and high crystal content mentioned above can only happen at the late stage of magmatic evolution. The domes formed in the early stage on the plateau, so we prefer different source regions for the magma.

The cones on Marius Hills plateau are also truncated by younger lava plains, so their ages should be older than the younger lavas. As mentioned above, some cones are located on domes, so the cones and domes may share the same magmatic conduit. In addition, we cannot tell the compositional differences between the cones and the material around them.

The cones on the Moon are mainly made of fine tephra and coarse rock fragments (Wilson and Head, 1981). The magma forming the domes and cones on the Earth usually originates from a shallow magma chamber, which was not available on the Moon due to the low density of the crust (Head and Wilson, 1992, 1991). So most of the lava should come from a deep source region, but it was not able to form domes and cones. Therefore, Marius Hills might have some relatively shallow magma chambers providing lava for the formation of domes and cones. This indicates that the crust within the plateau had a larger density.

The rilles on the plateau extended very long distance. If these rilles were the eroded results by lavas, then the magmatic eruption rate should be very high (Ciesla and Keszthelyi, 2000; Fagents et al., 2000; Hulme, 1973). In addition, the rilles cut all the geological units on the plateau, so they should be the youngest volcanic features in this region. However, very high eruption rate indicates a deep source region, but it is against the shallow magma chambers discussed above.

Here, we propose a possible scenario to explain the inconsistency. Volcanic domes are the oldest features in this region, and they were controlled by different shallow magma chambers. Then, the magma ascended along the previous existed lava conduit, and cones formed on domes and plains between domes. After that, a mantle plume ascended and it raised the plateau (Ping et al., 2009). The magma in the mantle plume not only refilled the shallow magma chambers but also evolved the composition of the magma for the domes and cones. At the same time, the extensive magma provided by the mantle plume erupted at a very high rate and eroded all the previous geological units to form the rilles.

SUMMARY

(1) With latest high-resolution images and

altimeter data, we have described the detailed morphological characters of the volcanic features on the Marius Hills plateau including domes, cones, ridges, and rilles. In addition, we have confirmed a skylight located on the floor of a rille and found remnants of lava tubes.

(2) We first report CSFD absolute model ages for Marius basalt 2, medium to low titanium basalt, and undifferentiated medium titanium basalt, and the results are 814, 949, and 687 Ma, respectively. Besides that, we report several younger lava events; they occurred at 1.10 Ga in Marius basalt 1 unit, 1.49 Ga in Flamsteed basalt unit, and 1.46 Ga in Schiaparelli basalt unit. Further check of sharp features is needed when new data are available.

(3) A mantle plume scenario is proposed to explain the inconsistency of previous studies.

ACKNOWLEDGMENTS

We thank Jinsong Ping, Qian Huang, Ruiyan Yang, Yusen Dong, Qi He, Qing Liang, and Chiguang Peng for data processing discussion and Hao Zhang and Steve Ruff for help in manuscript writing. The constructive comments from an anonymous reviewer improved the quality of the manuscript. The LO data were obtained from USGS (http://astrogeology.usgs.gov/Projects/LunarOrbiterDigitization/). Selene-1 TC data are from JAXA (https://www.soac.selene.isas.jaxa.jp/archive/index.html.en). LRO NAC data are from PDS (http://pds.jpl.nasa.gov/). JMARS (http://jmars.asu.edu/) and Davinci (http://davinci.asu.edu/) are used in data processing.

REFERENCES CITED

Besse, S., Sunshine, J. M., Staid, M. I., et al., 2011. Compositional Variability of the Marius Hills Volcanic Complex from the Moon Mineralogy Mapper (M^3). *J. Geophys. Res*., 116: E00G13

Boyce, J. M., Jonnson, D. A., 1978. Ages of Flow Units in the Far Eastern Maria and Implications for Basin-Filling History. In: Lunar and Planetary Science Conference Proceedings. 3275–3283

Burgess, R., Turner, G., 1998. Laser ^{40}Ar-^{39}Ar Age Determinations of Luna 24 Mare Basalt. *Meteoritics and Planetary Science*, 33: 921–935

Ciesla, F. J., Keszthelyi, L., 2000. A Simple Model for Lava Flow Quarrying: Mechanical Erosion of the Substrate. In: Proceedings of the 31st Lunar and Planetary Science Conference. Houston, TX, United States. 1647

Fagents, S. A., Williams, D. A., Greeley, R., 2000. Thermal Erosion by Laminar Lava Flows: New Inferences. In: Proceedings of the 31st Lunar and Planetary Science Conference. Houston, TX, United States. 1038

Greeley, R., 1971. Lava Tubes and Channels in the Lunar Marius Hills. *The Moon*, 3(3): 289–314

Hartmann, W. K., Neukum, G., 2001. Cratering Chronology and the Evolution of Mars. *Space Sci. Rev.*, 96(1–4): 165–194

Haruyama, J., Hioki, K., Shirao, M., et al., 2009. Possible Lunar Lava Tube Skylight Observed by SELENE Cameras. *Geophys. Res. Lett.*, 36(21): 21206

Head, J. W., Gifford, A., 1980. Lunar Mare Domes: Classification and Modes of Origin. *The Moon and the Planets*, 22(2): 235–258

Head, J. W., Wilson, L., 1991. Absence of Large Shield Volcanoes and Calderas on the Moon: Consequence of Magma Transport Phenomena? *Geophys. Res. Lett.*, 18: 2121–2124

Head, J. W., Wilson, L., 1992. Lunar Mare Volcanism: Stratigraphy, Eruption Conditions, and the Evolution of Secondary Crusts. *Geochimica et Cosmochimica Acta*, 56(6): 2155–2175

Heather, D. J., Dunkin, S. K., Wilson, L., 2003. Volcanism on the Marius Hills Plateau: Observational Analyses Using Clementine Multispectral Data. *J. Geophys. Res.*, 108: 5017

Hiesinger, H., Jaumann, R., Neukum, G., et al., 2000. Ages of Mare Basalts on the Lunar nearside. *J. Geophys. Res.*, 105(E12): 29239–29275

Hulme, G., 1973. Turbulent Lava Flow and the Formation of Lunar Sinuous Rilles. *Modern Geology*, 4(2): 107–117

Ivanov, B. A., 2001. Mars/Moon Cratering Rate Ratio Estimates. *Space Sci. Rev.*, 96(1–4): 87–104

Lawrence, S. J., Stopar, J. D., Hawke, B. R., et al., 2010. LROC Observations of the Marius Hills. In: Proceedings of the 41st Lunar and Planetary Science Conference. Houston, TX, United States. 1906

Lucey, P. G., Blewett, D. T., Jolliff, B. L., 2000. Lunar Iron and Titanium Abundance Algorithms Based on Final Processing of Clementine Ultraviolet-Visible Images. *J. Geophys. Res.*, 105(E8): 20297–20305

McCauley, J. F., 1967. Geologic Map of the Hevelius Region of the Moon. U.S. Geological Survey, Reston, VA, United States

McGauley, J. F., 1969. The Domes and Cones in the Marius Hill Region: Evidence for Lunar Differentiation? *Moon*, 1: 133–134

Neukum, G., 1983. Meteoritenbombardement und Datierung Planetarer Oberflächen, Habilitationsschrift: [Dissertation]. Univ. München, Munich, Germany (in German)

Neukum, G., Ivanov, B. A., 1994. Crater Size Distributions and Impact Probabilities on Earth from Lunar, Terrestrial-Planet, and Asteroid Cratering Data. In: Gehrels, T., ed., Hazards due to Comets and Asteroids. University of Arizona Press, Tucson, AZ, United States. 359–416

Neukum, G., Ivanov, B. A., Hartmann, W. K., 2001. Cratering Records in the Inner Solar System in Relation to the Lunar Reference System. *Space Sci. Rev.*, 96(1–4): 55–86

Ping, J. S., Huang, Q., Su, X. L., et al., 2009. Chang'E-1 Orbiter Discovers a Lunar Nearside Volcano: YUTU Mountain. *Chinese Science Bulletin*, 54(23): 4534–4536

Rutherford, M. J., Hess, P. C., Daniel, G. H., 1974. Liquid Lines of Descent and Liquid Immiscibility in High Ti Lunar Basalt. Lunar Sci. Inst., Houston, Texas, United States. 657–659

Stöffler, D., Ryder, G., 2001. Stratigraphy and Isotope Ages of Lunar Geologic Units: Chronological Standard for the Inner Solar System. *Space Sci. Rev.*, 96(1–4): 9–54

van der Bogert, C. H., Hiesinger, H., McEwen, A. S., et al., 2010. Discrepancies between Crater Size-Frequency Distributions on Ejecta and Impact Melt Pools at Lunar Craters: An Effect of Differing Target Properties? In: Proceedings of the 41st Lunar and Planetary Science Conference. Houston, Texas, United States. 2165

Weitz, C. M., Head, J. W., 1999. Spectral Properties of the Marius Hills Volcanic Complex and Implications for the Formation of Lunar Domes and Cones. *J. Geophys. Res.*, 104(E8): 18933–18956

Whitford-Stark, J. L., Head, J. W., 1977. The Procellarum Volcanic Complexes: Contrasting Styles of Volcanism. In: Proceedings of the 8th Lunar and Planetary Science Conference. Houston, TX, United States. 2705–2724

Whitford-Stark, J. L., Head, J. W., 1980. Stratigraphy of Oceanus Procellarum Basalts: Sources and Styles of Emplacement. *J. Geophys. Res.*, 85(B11): 6579–6609

Wilson, L., Head, J. W., 1981. Ascent and Eruption of Basaltic Magma on the Earth and Moon. *J. Geophys. Res.*, 86(B4): 2971–3001