Morphometric and rheological study of lunar domes of Marius Hills volcanic complex region using Chandrayaan-1 and recent datasets

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Marius Hills volcanic complex is one of the most important regions on the lunar surface having an abundant number of volcanic features like domes and cones. Systematic mapping of 106 domes/cones in the Marius Hills region was carried out in this study using high-resolution orthoimage and digital elevation models of Chandrayaan-1 and Kaguya missions. Various morphometric parameters like diameter, height, volume, flank slope, circularity index and form factor are derived for all the mapped domes. The rheological parameters, such as viscosity and eruption rate are estimated for isolated domes and cones superimposed over low domes. The morphometric and rheological properties of these domes are comparable to those located in the area near to Hortensius crater and other mare regions. Surface ages derived for a selected region in NW portion of the Marius Hills volcanic complex using crater size-frequency distribution technique yields ages of 2.98 and 1.91 Ga. It suggests that the domes in this region formed at about 2.98 Ga ago, and then, the younger mare basalts likely embayed this region about 1.98 Ga ago. Stratigraphic sequence of rilles, wrinkle ridge and domes shows that wrinkle ridges are the oldest, while the rilles are younger than the domes.

Keywords. Marius Hills region; lunar domes; Chandrayaan-1.

1. Introduction

Morphological mapping of volcanic features such as domes and cones on the lunar surface will be helpful in understanding the volcanic processes. Lunar volcanic domes are broad, convex, and circular to

oval landforms of modest positive relief (Smith 1973; Head and Gifford 1980; Wilhelms 1987; Wöhler *et al.* 2006; Lena *et al.* 2013). The majority of domes are located in the mare regions of the lunar nearside, for example, Marius Hills volcanic complex region of Oceanus Procellarum, Mare

Insularum, Mare Tranquillitatis, etc. (Guest and Murray 1976; Head and Gifford 1980; Whitford-Stark and Head 1980; Hiesinger *et al.* 2000, 2003; Wilson 2009; Lena *et al.* 2013; Arya *et al.* 2014). Domes are also reported in highland regions, i.e., Gruithuisen and Mairan domes (Head *et al.* 1978; Wilson and Head 2003; Kusuma *et al.* 2012; Lena *et al.* 2013; Ivanov *et al.* 2016). Earlier studies using Clementine and telescopic datasets (Hiesinger *et al.* 2000, 2003; Heather *et al.* 2003; Lena *et al.* 2013) enriched our understanding. Recent lunar missions: Chandrayaan-1, Kaguya and Lunar Reconnaissance Orbiter (LRO) provided the images and Digital elevation model (DEM) at a higher-resolution than those used in the previous studies. For example, Lawrence *et al.* (2013) had given emphasis to the study of the morphology of cones having diameters between 1 and 2 km using high-resolution LRO Narrow Angle Camera (NAC) datasets. They have also shown that domes are not rich in silica and are not significantly different from surrounding mare materials based on 8 μm feature of LRO-Diviner data.

Our study is focused on estimation of morphometric and rheological parameters of domes/cones using datasets of Chandrayaan-1's Terrain Mapping Camera (TMC) and Kaguya's Terrain Camera (TC). The spatial resolution of orthoimage and DEM datasets of Chandrayaan-1's TMC are 5 and 25 m, respectively, while it is both 10 m for Kaguya's TC, which are sufficient for morphological mapping and measurement of morphometric parameters of domes/cones having a diameter greater than few 100s of meter. The location of Marius Hills region of Moon is shown on near side image of Cartosat-2A (figure 1). By detailed analysis of topography of the domes/cones, various morphometric parameters like diameter, height, volume, flank slope, form factor and circularity index are estimated. Further rheological parameters of these domes, i.e., viscosity and eruption rate are estimated. The qualitative interpretation of regional trends of gravity anomalies and topography of Oceanus Procellarum region vis-à-vis correlation with Marius Hills region is also discussed.

2. Geology of the study area

Marius Hills region is very significant in Oceanus Procellarum regarding the concentrations of volcanic features. This region is dominated by low and steep domes, cones and sinuous rilles, suggesting

Figure 1. Cartosat-2A satellite's panchromatic image of nearside of the Moon showing the location of Marius Hills volcanic complex region (rectangular box), Oceanus Procellarum on the western nearside and also the prominent Tycho.

variable eruption rates. The concentration of the volcanic features (domes, cones sinuous rilles) per unit area in Marius Hills is approximately one feature per 103 km² (Whitford-Stark and Head 1977). The high concentration of sinuous rilles suggests that these complexes are the sites of multiple eruptions with high effusion rates and large volumes and that these centers may be the source of much of the lava in Oceanus Procellarum emplaced during the Imbrian and Eratosthenian Periods (Whitford-Stark and Head 1977, 1980). Raitala (1980) mentioned that Marius Hills region is located at the intersection of two major structural trends. Marius Hills is structurally/tectonically controlled by two weak zones/fractures and it may be the mechanism responsible for the formation of a complex volcanic construct within Marius Hills (Head 1976; Raitala 1980). Based on spatial distributions of morphological features and topographic variations, of the Marius Hills region, Spudis *et al.* (2013) described the Marius Hills region as a large shield volcano equivalent to other terrestrial planets. Marius Hills volcanic complex (MHC) having the spatial extent of 330 km and summit near 14°N and 52°W. Lawrence *et al.* (2013) studied morphological variations of most of domes and cones at finer scales using Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) datasets.

Table 1. Details of Chandrayaan-1 Terrain Mapping Camera (TMC) datasets covering the Marius Hills region used in this study.

Sl. no.	Product ID	Date of pass	Orbit no.	Top left longitude	Top left latitude	Bottom right longitude	Bottom right latitude
1	TMC_NRN_20090419T131617453	19-Apr-09	1966	299.5	29.68	300.35	− 11.78
2	TMC_NRN_20090210T033859994	10-Feb-09	1132	300.6	29.23	301.64	− 30.79
3	TMC_NRN_20090113T183335421	13-Jan-09	798	301.2	30.35	302.29	− 31.02
4	TMC_NRN_20090419T051831680	19-Apr-09	1962	303.8	30.14	304.86	− 29.85
5	TMC_NRN_20090209T194640216	9-Feb-09	1128	304.8	29.57	305.97	− 30.43
6	TMC_NRN_20090419T012231496	19-Apr-09	1960	305.9	29.93	307.06	− 30.03
7	TMC_NRN_20090418T173100543	18-Apr-09	1956	310.2	31.57	311.48	− 28.9

Many earlier researchers studied the compositional variations of Marius Hills region (Weitz and Head 1999; Heather *et al.* 2003; Besse *et al.* 2011; Lawrence *et al.* 2013). Weitz and Head (1999) identified two units with mixed boundaries using Clementine multispectral data, a high-titanium basalt unit, and a low-titanium basalt unit. Heather *et al.* (2003) mapped six main lava flows of the Marius Hills volcanic complex using Clementine multispectral data based on the UV/VIS slope, the strength of 1 μm band and the estimated TiO_2 content. Besse *et al.* (2011), classified Marius Hills complex region into two major mare units of different volcanic episodes. Most of the basalts of the region are characterized by weaker 1 μm band depth (IBD1000), which is interpreted as having high calcium pyroxene signature. The domes are characterized by weakest band depth. A strong 1 μm band unit of localized lava flows within the plateau similar olivine rich signatures to those of nearby Oceanus Procellarum. Clear differences are not seen between domes and cones with respect to 1 μm band and spectra.

Mapping of domes and estimation of morphometric parameters is very much significant for the understanding of volcanic processes in the region. In the past, most of the morphometric and rheological studies (Wilson and Head 2003; Wöhler *et al.* 2006, 2007; Lena *et al.* 2007, 2009, 2013) of lunar domes was carried out using ground-based telescopic data in various mare basins and high land regions of Moon. In the Marius Hills region, telescopic data based morphometric study of domes is limited to 30 domes (Lena *et al.* 2009). They also estimated rheological parameters of three domes based on the assumption of two-phase eruption. Later to this study, rheological parameters of a dome located to the south of Rima Galilaei in the

Marius Hills region were estimated by Arya *et al.* (2014).

3. Data used and methodology

In this study domes/cones located in the Marius Hills region are mapped between longitude 300–310.5°E and latitudes 5.5–17°N. The Chandrayaan-1 TMC datasets acquired from an orbit height of 100 km, are used in this study. Details of datasets like date of a pass, orbit number etc., are given in table 1. The spatial resolution of the ortho-image and DEM datasets, used in this study are 5 and 25 m, respectively. Chandrayaan-1's TMC image coverage over Marius Hills region is shown in figure 2. Ortho-image and DEM datasets of SELENE's Terrain Camera (TC) are used in the gap areas Chandrayaan-1's TMC datasets. The Terrain Mapping Camera, onboard Chandrayaan-1 mission imaged in a push-broom mode in the panchromatic spectral band of 0.5–0.75 μm with a triplet view in the fore, nadir and aft directions of the spacecraft movement and has a base to height ratio of one (Kiran Kumar *et al.* 2009). DEMs and ortho-images of TMC are generated using an indigenously developed photogrammetric software (LDEM) consisting of imaging model, automatic image matching module. Separate software is used for quality control and DEM editing. Rational Polynomial Coefficients model generated from imaging geometry of Terrain Mapping Camera of Chandrayaan-1 have been used for geometrical modeling of the images. The Clementine mosaic images along with Lunar Orbiter Laser Altimeter (LOLA) DEM (Smith *et al.* 2010) have been used as reference control points. In the next step, stereo image matching is performed to generate image conjugate points. These points are

Figure 2. Ortho-image coverage of Chandrayaan-1 Terrain Mapping Camera (TMC) data over Marius Hills volcanic complex region and also showing the location of domes/cones mapped in this study.

common in overlapping areas of two or more images. They connect the images in a block to each other and are necessary input for the triangulation. The parallax between corresponding points is then used to determine 3D location. A surface generation step interpolates the calculated 3D points and resample the surface on a regular grid to produce the output DEM and corresponding co-registered orthoimage. Vertical datum used is based on the spherical figure of the Moon and a lunar radius of 1737.4 km (Gopala Krishna *et al.* 2009; Srivastava *et al.* 2009). A detailed assessment of the accuracy of the Chandrayaan-1's TMC DEM in terms of topographic variations has been carried out for a selected region. It shows that a crater of 250 m diameter with 6 m elevation (vertical extension) can be demarcated. Horizontal resolution of the DTM comes out to be approximately 50–75 m in the studied area.

The TC data of Japan's Kaguya mission provided stereo imaging at a spatial resolution of 10 m/pixel (Haruyama *et al.* 2008; Barker *et al.* 2016). Digital Terrain Model (DTM), ortho-images of SELENE (ex: DTMTCO_03_02738N085E3080SC.dtm, DTMTCO_03_02738N085E3080SC.img) are downloaded from SELENE's data archive (<http://l2db.selene.darts.isas.jaxa.jp/>). Mosaics of ortho-image (figure 3) and DTM datasets are

prepared for Marius Hills region using these tiles and utilized in this study.

4. Results

4.1 Mapping of lunar domes

The topography of Marius Hills varies between -3815 and 139 m. The topographic variations over the whole region are examined in detail for identification of localized topographic highs and prepared smaller sets of DEM. Topographic changes within these smaller subsets are analysed for identification of the domes/cones. Further smaller subsets of DEMs limited to dome/cones are examined in detail using three-dimensional perspective views (figure 4), cross-sectional profiles in four different directions and contour maps of topography (figure 5). The boundary of the individual domes is demarcated based on the flattening of the topography in the periphery of the domes and further refined by closing the nearest contour of topography, at the base of the domes. For a sample, boundary demarcated for the dome-35 is marked with a white polygon as shown in figure 5(a). Ortho-image, topographic profiles and 3D perspective views of dome no. 35, which is mapped using Chandrayaan-1 TMC data is shown in figures 4 and 5. Three-dimensional perspective views of

Figure 3. Ortho-image mosaic of Marius Hills volcanic complex region prepared using SELENE's Terrain Camera (TC) data. 106 domes/cones mapped using both Chandrayaan-1 TMC (31 no.) and Kaguya TC (75 no.) datasets in this study are outlined by black-coloured polygons. Location of region-R1 selected for surface age determination is shown by a white coloured box. Depressions mapped in this region are marked with red coloured polygons. Location of few domes (D1–D7), selected based on morphometric/rheological parameters are also shown on this map. Details of morphometric and rheological parameters of these domes D1–D7 are given in table 1 and three dimensional perspective views of these selected domes are given in supplementary figures S1–S2.

ortho-image and DEMs of few domes (D1–D7, table 2), selected based on the variation of morphometric and rheological properties are also shown in figures: S1–S2. Based on this approach, 106 lunar domes (31 using Chandrayaan-1 and 75 using Kaguya datasets) are identified in the Marius Hills volcanic complex (MHC) region (figures 2 and 3). Then the morphometric parameters are measured and rheological parameters are estimated.

4.2 Morphometric parameter estimation

In general, domes are not perfectly circular in shape. So procedure for estimation of morphometric parameters, i.e., diameter, flank slope, circularity index and form factor in this study, is adopted from earlier studies (Wöhler and Lena 2009; Lena *et al.* 2013). The diameter of the dome is calculated along a major axis (a) and a minor axis (b) from the outline of the dome/cones demarcated from topographic contours. The geometric mean of the two axes (major axis and minor axis), i.e., $\sqrt{(ab)}$ gives the diameter. The circularity of the dome is calculated as $C = b/a$. Flank slope of the domes is computed using the formula

$$\text{Flank slope} = \tan^{-1} \left(\frac{2h}{d} \right) \quad (1)$$

where h is a height of a dome with reference to boundary demarcated from topographic variations and d is diameter of the dome derived from major and minor axis of boundary demarcated.

The volume is estimated from the DEM using 3D integration method referring a planar surface with respect to the boundary of the dome. For this, the volume of the dome surface is estimated with reference to planar surface demarcated based on periphery/boundary of the dome. Then, the estimated volume is used to redefine the shape of the dome. Using the equation of form factor (Lena *et al.* 2013)

$$\text{Form factor } (f) = \frac{V}{(\pi D^2 h)} \quad (2)$$

where f , V , D and h are the form factor, volume, diameter and height of the dome. The diameter and corresponding height of domes mapped in this study range from 1.5 to 12 km and 80 to 450 m, respectively. Out of 106, the diameter of 91

Figure 4. (a) Ortho-image (TC) mosaic of Marius Hills volcanic complex region showing the location of dome-35 (red coloured box). (b) Ortho-image (TMC data) of dome-35. (c) 3D perspective view of the topography of dome-35 (vertical exaggeration: $\times 1$).

domes/cones varies between 2 and 8 km diameter. The flank slope of the domes mapped in this study ranges up to 11° . Majority of the domes (90%) having flank slopes between 2 and 6° . The volume of the domes varies between 0.3 and 10.9 km^3 . The form factor of most of the domes ranges from 0.3 to 0.5 that suggest conical to parabolic shape for most of the domes. Circularity index gives an idea about the shape of the domes at their base. It varies between 0.5 and 1.0 and it means elliptical to circular in shape at the base of the domes. Histograms of morphometric parameters like diameter, height, circularity index, volume, flank slope, form factor are shown in figures 6 and 7.

4.3 Estimation of rheological parameters

In this section, rheological parameters such as viscosity and effusion rate are estimated based

on morphometric properties of the domes/cones determined in the previous section 4.2. Approach for estimation of rheological parameters of the domes in the study is adopted from earlier studies (Wilson and Head 2003; Wöhler *et al.* 2006, 2007; Lena *et al.* 2007, 2009, 2013; Arya *et al.* 2014). This model estimates several parameters like yield strength τ , the pressure or stress that must be exceeded for the lava to flow (Wolff and Sumner 2000), the plastic viscosity η , a measure for the fluidity of the erupted lava, the effusion rate E , the lava volume erupted per second, and the duration of the effusion process.

Lena *et al.* (2009) estimated rheological parameters of three domes in Marius Hills region, based on the assumption that these formed in the process of two-phase eruption, where the height of each partial dome was assumed to correspond to one-half of the measured full dome height. They

Figure 5. (a) Colour coded contour map of topography of dome no: 35, prepared using Chandrayaan-1 TMC DEM. Boundary/outline of dome demarcated from topographic variations is shown by white polygon. (b) Graphs showing the topographic variations along the four profiles across the dome (AB, CD, EF and GH) and location of these profiles on contour map of topography in (a).

also stated that this technique may not be directly applicable to Marius Hills region. However, rheological parameters are estimated by assuming domes considered in this study are monogenetic in nature, which are morphologically/topographically isolated from adjacent domes. Thus, rheological parameters are estimated for isolated domes and cones superimposed over low domes or that occur in isolation only. Therefore, the computed values for viscosity, effusion rate and the duration of the effusion process are upper limits to the respective

true values which can provide an idea about spatial variability of these parameters within this region. In the model by [Wilson and Head \(2003\)](#), the magma is treated as a Bingham plastic with a yield strength of

$$\tau = \frac{0.323h^2\rho g}{(D/2)}. \quad (3)$$

Plastic viscosity is estimated by the empirical relation

Table 2. Morphometric and rheological parameters of selected domes.

Dome no.	Height (m)	Minor axis (km)	Major axis (km)	Average diameter (km)	Flank slope (deg)	Volume (km ³)	Form factor	Circularity index	Height km	Radius (R) (km)	H by R	Yield strength (Pa)	Viscosity (Pas)	E (m ³ /s)	Te (yr)
D1	260	9.1	13.2	11.0	2.7	9.1	0.4	0.7	0.26	5.48	0.05	1.82E+04	1.00E+07	80.3	3.6
D2	185	5.8	6.2	6.0	3.5	1.5	0.3	0.9	0.19	3.00	0.06	1.68E+04	8.33E+06	33.8	1.4
D3	125	2.7	3.8	3.2	4.5	0.4	0.4	0.7	0.13	1.60	0.08	1.44E+04	5.71E+06	14.3	0.8
D4	175	3.9	4.1	4.0	5.0	0.9	0.4	1.0	0.18	2.00	0.09	2.26E+04	1.69E+07	15.9	1.8
D5	410	7.0	7.6	7.3	6.4	5.9	0.3	0.9	0.41	3.65	0.11	6.80E+04	2.37E+08	22.6	8.3
D6	270	3.2	3.5	3.3	9.3	0.9	0.4	0.9	0.27	1.65	0.16	6.50E+04	2.13E+08	7.0	3.9
D7	170	1.7	1.7	1.7	11.5	0.2	0.4	1.0	0.17	0.83	0.20	5.12E+04	1.20E+08	2.8	1.7

$$\eta = 6 \times 10^{-4} \tau^{2.4} \quad (4)$$

where τ is expressed in Pa and η in Pas, ρ denotes the magma density and g , the acceleration due to gravity on Moon, 1.63 m/s^2 . Earlier works on lunar domes (Wilson and Head 2003; Wöhler *et al.* 2006; Lena *et al.* 2007, 2009) assume the lava density to be 2000 kg/m^3 and states that assuming a higher density of $\rho = 2800 \text{ kg/m}^3$, this factor amounts to 2.2, compared to the values obtained with $\rho = 2000 \text{ kg/m}^3$. It is preferable to adopt $\rho = 2800 \text{ kg/m}^3$, which is more realistic in nature, since $\rho = 2000 \text{ kg/m}^3$ as the lunar lava density is too low for estimating the rheological and dyke parameters. Therefore, a magma density of $\rho = 2800 \text{ kg/m}^3$ is adopted here.

The lava effusion rate E (Wilson and Head 2003), is

$$E = \frac{0.323^{1/2} 300\kappa (D/2)^2}{0.65^{5/2} 0.72h}. \quad (5)$$

Here $\kappa = 10^{-6} \text{ m}^2 \text{ s}^{-1}$ the thermal diffusivity of the lava.

The duration T of the magma effusion process amounts to

$$T = v/E, \quad (6)$$

where v is the edifice volume.

To maintain the consistency with earlier studies rheological parameters like viscosity, yield strength, effusion rate, duration of effusion are estimated for both densities of $\rho = 2800 \text{ kg/m}^3$ and $\rho = 2000 \text{ kg/m}^3$. The viscosity of these domes calculated for the magma densities of $\rho = 2800 \text{ kg/m}^3$ and $\rho = 2000 \text{ kg/m}^3$ shows a factor of 2.24, which is similar to the earlier studies (Lena *et al.* 2013).

Effusion rate is computed using diameter and height as described in equation (5) and duration of lava effusion process using equation (6). The viscosities of domes estimated using magma density of 2800 kg/m^3 varies between 4.6×10^5 and $3.3 \times 10^8 \text{ Pas}$. The variation of the estimated rheological parameters (viscosity and effusion rate) for 106 domes mapped in this study are shown in figures 7(c and d) and 8. The majority of domes having the viscosities in the range of 10^6 – $20 \times 10^6 \text{ Pas}$ followed by 20×10^6 – 100×10^6 and 100×10^6 – $340 \times 10^6 \text{ Pas}$. The estimated viscosities of mapped domes in Marius Hills region exhibits moderate to high viscosities. The effusion rate of the domes mapped

Figure 6. Histograms of (a) diameter, (b) height, (c) circularity index, and (d) volume of the domes/cones mapped in Marius Hills region.

in this study varies between 2 and $82 \text{ m}^3 \text{ s}^{-1}$. Duration of lava effusion of the domes ranges between 0.24 and 3.7 years.

5. Determination of surface ages using crater counting technique

The theory and methodology of determining absolute ages for cratered planetary surface units have been discussed in many of recent papers (Hiesinger *et al.* 2000; Ivanov 2001; Neukum *et al.* 2001; Shylaja 2005; Michael and Neukum 2010; Arya *et al.* 2011, 2012). This method is based on the fact that the flux and size of impact craters are functions of time. This method was calibrated using the age of samples returned from the Moon (Stöffler and Ryder 2001; Stöffler *et al.* 2006; Michael and Neukum 2010). The concept is to fit the observed crater size-frequency distribution (CSFD) of a given surface unit to a known crater production function (PF), and to use the

crater frequency for certain sizes together with a calibrating chronology function (CF) to obtain an absolute age. The production function describes how many craters of a given size are formed in relation to the number of any other size (Michael and Neukum 2010).

The region located at NW edge of Marius Hills region is selected for an understanding sequence of events along with surface age estimation using CSFD approach. The selected area consists of about 14 domes, rilles cutting across the wrinkle ridges trending in NW–SE direction (figures 3 and 9). The visual interpretation of topography and image datasets of this region implies that wrinkle ridges are older compared to rilles, which are cutting across ridges. Rilles are originated at the domes located on the eastern side. The surface ages for the region R-1 (figure 9a, the location of this region is shown as a white rectangle in figure 3) are estimated using CSFD technique. In this study, craters are mapped using ‘cratertools’ software (Kneissl *et al.* 2011) in GIS

Figure 7. Histograms of (a) flank slope, (b) form factor, (c) viscosity (estimated for magma density of 2800 kg/m^3), and (d) effusion rate of the domes/cones mapped in Marius Hills region.

using the ortho-image. As the compositional maps prepared from M^3 and other datasets do not show much variability in the selected region (Besse *et al.* 2011; Lawrence *et al.* 2013), so the area of interest for CSFD is selected based on the distribution of domes/cones, the extent of rilles in this region. Measured crater diameters were plotted on to crater size-frequency distribution curve using ‘craterstat’ IDL subroutine, which contains coefficients for Moon Chronology and production functions (Ivanov 2001; Neukum *et al.* 2001; Michael and Neukum 2010). By fitting the observed points of the range of crater diameters with lunar production curve, as small segments, yielded the age of the lunar surface under investigation. The crater size-frequency plot (figure 9b) is shown displaying the margin of errors also. The surface ages estimated using CSFD technique yields 1.91 and 2.98 Ga. This implies that domes in this region might be formed at about 2.98 Ga and adjoining basalts might be embayed during latter phases around 1.98 Ga ago. An age of basaltic unit is also consistent

with the age of basalts located at SW edge of Marius Hills region (Arya *et al.* 2014). Recent studies by Gebhart *et al.* (2016) also show that Absolute Model Ages (AMA) of low shields varies between 1.03 and 3.65 Ga and AMAs of adjacent mare basalts vary between 1.2 and 3.69 Ga. They had also mentioned that AMAs of these domes do not show a clear spatial correlation of ages *vs.* location of dated domes. Thus, derived ages in this study are also consistent with that of earlier studies (Arya *et al.* 2014; Gebhart *et al.* 2016; Hiesinger *et al.* 2016).

6. Summary and discussion

Mapping of domes and estimation of morphometric, rheological parameters is very much significant for the understanding of volcanic processes in the region. In the past, most of the morphometric and rheological studies (Wilson and Head 2003; Wöhler *et al.* 2006, 2007; Lena *et al.*

Figure 8. Graphs showing the variation of (a) height *vs.* diameter, (b) volume *vs.* diameter, (c) viscosity *vs.* volume, (d) viscosity *vs.* flank slope, (e) effusion rate *vs.* viscosity, and (f) duration of effusion *vs.* viscosity of the domes/cones mapped in Marius Hills region.

2007, 2009, 2013) of lunar domes were carried out using ground-based telescopic data in various mare basins and highland regions of the Moon. Recent lunar missions: Chandrayaan-1, Kaguya and Lunar Reconnaissance Orbiter (LRO) provided the images and Digital elevation model (DEM) at a higher-resolution. Estimation of morphometric parameters of domes/cones using the DEM and images provides better results compared

to earlier studies. Lawrence *et al.* (2013) had given emphasis to the study of the morphology of cones in the Marius Hills region, having diameters between 1 and 2 km using high-resolution LRO Narrow Angle Camera (NAC) datasets.

In the past, morphometric parameters of 30 domes in Marius Hills region were estimated using telescopic based data by earlier researchers (Lena *et al.* 2009). However, the rheological parameters

Figure 9. (a) The ortho-image of the region (R-1) selected for age determination using CSFD technique. Craters mapped are marked with red coloured circles. (b) Cumulative crater size-frequency distribution (CSFD) plot. PF: production function; CF: chronology function. Location of the region (R-1) shown by white coloured rectangle in figure 3.

were estimated for only three domes assuming two-phase eruption (Lena *et al.* 2009). For the first time, 106 lunar domes/cones are mapped using the high-resolution DEM and image datasets of Chandrayaan-1's TMC (31)/Kaguya's TC (75) in Marius Hills region of Oceanus Procellarum in this study. The spatial resolution of ortho-image and DEM datasets of Chandrayaan-1's TMC and Kaguya's TC are 5, 25 and 10, 10 m, respectively. Rheological parameters are also estimated for all the domes and cones mapped in this study.

Study of variation of rheological and morphometric parameters of domes are carried out, including the one dome studied by Arya *et al.* (2014). Coordinates of domes mapped by Lena *et al.* (2009) are not matched well with those mapped in this study, may be due to the spatial inaccuracy of telescopic based observations. So this study may include domes, studied by Lena *et al.* (2009). Another recent study by Lawrence *et al.* (2013) emphasized to the study of the morphology of cones in the Marius Hills volcanic complex region, having diameters up to 1–2 km using high-resolution LRO Narrow Angle Camera (NAC) datasets. Due to non-availability of coordinates of domes/cones mapped by Lawrence *et al.* (2013), the comparison of new domes/cones mapped in our study could not be accomplished.

Some interesting observations from morphological mapping are given as follows:

- Domes/cones are distributed as groups or clusters. Cones are also superimposed over low domes.
- Few rilles are associated with the domes (figure 9a).
- Irregular shaped topographic depressions are located in the periphery of Marius Hills region.
- These depressions can be interpreted as volcanic depressions formed due to the withdrawal of magma in these regions.
- Few domes are bisected by rilles.

Morphometric parameters like diameter, height, circularity index, flank slope, form factor, volume and rheological parameters are estimated for all the mapped domes and cones (figures 6 and 7). Variations of height and volume *vs.* diameter of the domes/cones are shown in figure 8. The form factor varies between 0.3 and 0.5, indicating that most of the domes/cones fall into the category of conical to a parabolic shape. The circularity index of domes/cones varies between 0.5 and 1.0, indicating an elliptical to circular in shape at the base of the domes. The steepness (flank slope) of the domes varies between 2 and 6°. Morphometric parameters estimated in this study are broadly correlating with parameters of 30 domes mapped in this region (Lena *et al.* 2009).

In this study, rheological parameters are estimated for domes in isolation and cones superimposed over low domes or that occur in isolation only. The viscosities of domes estimated using magma density of 2800 kg/m³ varies between

4.6×10^5 and 3.3×10^8 Pas. The estimated values of viscosities represent lunar mare basalts. The majority of domes having the viscosities in the range of 10^6 – 20×10^6 Pas followed by 20×10^6 – 100×10^6 and 100×10^6 – 340×10^6 Pas. The estimated viscosities of mapped domes in Marius Hills region exhibit moderate to high viscosities. Effusion rate of the domes mapped in this study varies between 2 and $82 \text{ m}^3\text{s}^{-1}$. The duration of lava effusion of the domes ranges from 0.24 to 3.7 yrs. The study of the effect variation of temperature on the viscosity values of individual domes is out of scope for this study.

The flank slope and volume of the domes is proportional to viscosity (figure 8). These signatures indicate that higher the viscosity of domes, higher the corresponding flank slope and volume (figure 8). The duration of effusion is proportional and effusion rate is indirectly proportional to the viscosity of magma. This means higher the viscosity of magma, longer the period of effusion. Range of values of viscosity of magma flow and effusion rate determined in this study are comparable to those derived in earlier studies carried out in the Marius Hills region (Lena *et al.* 2009) and also group of steeper domes located in the mare region near to Hortensius crater (Wöhler *et al.* 2006, 2007; Lena *et al.* 2013).

Qualitative interpretation of Bouguer and free-air gravity anomaly maps derived from recent GRAIL mission (Zuber *et al.* 2013) and crustal thickness map (Wieczorek *et al.* 2013) shows the regional trend (NW–SE) of gravity highs, and regions of crustal upwarp in Oceanus Procellarum, which also covers the Marius Hills region located at the central part of Oceanus Procellarum region. Most of the mare domes (Kapral and Garfinke 2005; Lena *et al.* 2009) distributed indifferent volcanic complexes of Oceanus Procellarum are spatially correlated with the regions of crustal upwarp. This indicates that the Marius Hills region could also have undergone compression in NE–SW direction. The spatial correlation of volcanic morphological features such as domes, wrinkle ridges with major crustal fractures suggests that mare magma erupted to the lunar surface through fractures (Raitala 1980).

Classed post maps of morphometric (diameter, height, flank slope and form factor: figures S3 and S4) and rheological (viscosity and effusion rate: figure S5) parameters are prepared by binning them into three different classes and also superimposed/plotted over topographic map prepared

using DEM of Lunar Reconnaissance Orbiter's Wide-angle Camera (LRO-WAC) (Scholten *et al.* 2012) to understand the spatial variation of these parameters within the Marius Hills volcanic complex region. The domes and NW–SE trending wrinkle ridges crossing across the Marius Hills region are clearly seen in these maps (supplementary figures S3 and S5) due to the enhancement of topography. These maps did not show any specific spatial pattern or trend in variation of morphometric and rheological parameters such as from the central portion to boundary of Marius Hills region and *vice versa*. The majority of domes are aligned along the NW–SE oriented wrinkle ridges (topographic highs), at the edge/flank of topography. As discussed earlier, only two mare units are mapped in this region using high resolution hyperspectral remote sensing datasets of Chandrayaan-1 M³ instrument (Besse *et al.* 2011) and no clear spectral signatures are observed between domes and cones. So spatial variation of morphometric parameters can be attributed to the changes in effusion rate within this region. Further detailed rheological analysis of the clusters of domes along with surface age determination will be helpful in better understanding the process of multiphase evolution of Marius Hills region.

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