Yield strength and lava tube cave height estimated from pits and lava flows of the Moon and Mars

Tsutomu Honda(NPO Vulcano-Speleological Society,Japan)
mer4beau939tha@gmail.com

Abstract: The vertical pit, Marius Hills Hole (MHH) of the Moon, found by Haruyama et al(2009) has several lava layers in it's cross-section as reported by Robinson et al(2012) through LRO observation. As for pits of Mars, the cross sectional thickness is also reported from Cushing(2012) on the vertical pit in Martian Arsia Mons. On the other hand, the lava flow thickness of the Moon and Mars have been observed from the surface appearance of the lava flow from which lava yield strength were estimated, though these yield strengths had widely spread values. Here, the yields strengths are estimated from the thickness of the lava layers in a vertical pit and compared with those estimated from the lava flow surface appearance thickness. The height of lava cave tube possibly located under the vertical pit of the Moon and Mars should be estimated by using the proper value from the comparison of the yield strengths.
Image data of vertical pits size in the neighborhood of Elysium Mons obtained by HiRISE with Mars Reconnaissance Orbiter are listed by Y.Goto et al of JAXA(2017). Possible existence of a lava tube cave under these vertical pits are predicted by using proper yield strength estimated from the lava flow surface appearance thickness.

1.Introduction

The vertical pit, Marius Hills Hole (MHH) of the Moon, found by Haruyama et al(2009,2010,2012)(1~3) has several lava layers in it's cross-section as reported by Robinson et al(2012)(4) through LRO observation. As for pits of Mars, the cross sectional thickness is also reported from Cushing(2007,2012)(5,6) on the vertical pit in Martian Arsia Mons. On the other hand, the lava flow thickness of the Moon and Mars have been observed from the surface appearance of the lava flow from which lava yield strength were estimated, though these yield strengths had widely spread values. Here, the yields strengths are estimated from the thickness of the lava layers in a vertical pit and compared with those estimated from the lava flow surface appearance thickness. The height of lava cave tube possibly located under the vertical pit of the Moon and Mars should be estimated by using the proper value from the comparison of the yield strength.

2.Bingham fluid model for lava tube cave

The lava flow is modeled by Bingham fluid flowing on the inclined plane or in the inclined cylindrical pipe with gravity potential(7). For the lava flow of density ρ, and yield strength f_B, with slope angle α, under the gravity g, the lava flow stop condition is $H=nf_B/(\rho g \sin\alpha)$ where H is the lava thickness. The case which flows on the incline plane with a free surface is n=1, for the case of n=2, flow between infinite width parallel plates and the case which flows through an inclined circular tube is n=4.

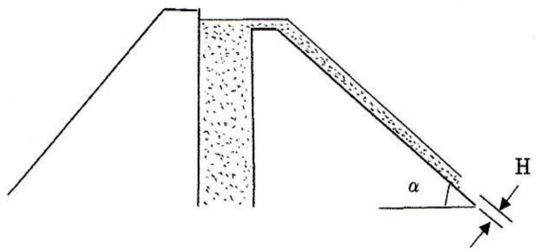

Fig.1 Lava flow model on the inclined plane

1)Surface lava flow for n=1

The case which flows on the inclined plane with a free surface is n=1
Flow stop condition is as follows:$H=1f_B/(\rho g \sin\alpha)$. Flow model is shown in Fig.2.

Velocity distribution is following
for $\tau_w=(\rho g \sin\alpha)H > f_B$,
$u=[z(2H-z)-2h_B z)](\rho g \sin\alpha)/2\eta_B$ $(0<z<H-h_B)$
$u=(H-h_B)^2[(\rho g \sin\alpha)/2\eta_B]$ $(H-h_B<z<H)$
for $\tau_w=(\rho g \sin\alpha)H < f_B$,
$u=0$

Here,η_B is Bingham viscosity,
From the flow stop condition as simple flow: $H=1f_B/(\rho g \sin\alpha)$, the yield strength of

lava can be obtained by putting the lava depth H.

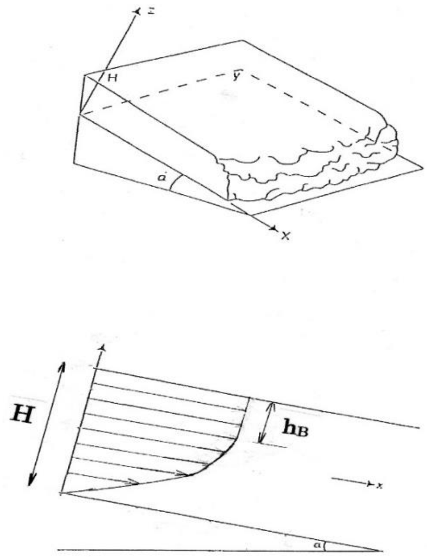

Fig.2 Lava flow on the inclined plane with a free surface

2) For the case of n=2, flow between infinite width parallel plates
Flow stop condition is as follow:H=2fB/(ρg sinα). Flow model is shown in Fig.3.

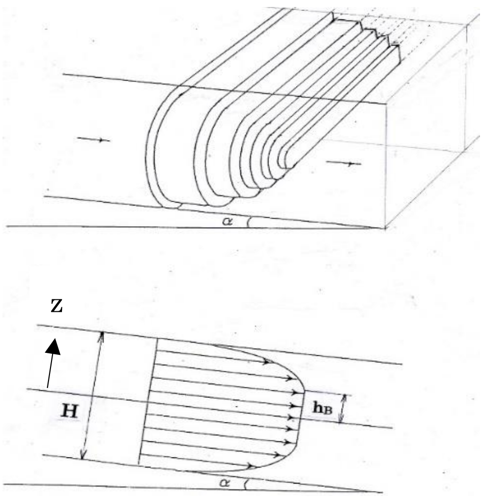

Fig.3 Lava flow between infinite width parallel plates

Velocity distribution u is following.
for $\tau_w = (\rho g \sin\alpha) H/2 > f_B$,
$u = (H/2 - h_B/2)^2 (\rho g \sin\alpha)/2\eta_B$
($-h_B/2 < z < h_B/2$)
$u = [(H/2)^2 - z^2 - 2h_B (H/2 - z)](\rho g \sin\alpha)/2\eta_B$
($H/2 > z > h_B/2$)
$u = [(H/2)^2 - z^2 - 2h_B (H/2 + z)](\rho g \sin\alpha)/2\eta_B$
($-H/2 < z < -h_B/2$)
for $\tau_w = (\rho g \sin\alpha) H/2 < f_B$,
$u = 0$

Here, η_B is Bingham viscosity, h_B is $z = h_B$ where the shear stress is equal to f_B.
From $H = 2f_B/(\rho g \sin\alpha)$,the yield strength can be obtained by putting lava tube cave height H. In this case, as flow is between infinite parallel plates, it should be H<< d . Here, d is width of the flow pass.

3) for the case of n=4, flow in the circular tube
Flow stop condition is as follows:$H = 2R = 4 f_B/(\rho g \sin\alpha)$.
Flow model is shown in Fig.4.
Velocity distribution u is following.
for $\tau_w = (\rho g \sin\alpha) R/2 > f_B$,
$u = (R - r_B)^2 (\rho g \sin\alpha)/4\eta_B$ $r < r_B$
$u = [R^2 - r^2 - 2r_B (R - r)](\rho g \sin\alpha)/4\eta_B$ $r > r_B$
for $\tau_w = (\rho g \sin\alpha) R/2 < f_B$,
$u = 0$

Here,r_B is $r = r_B$ where the shear stress is equal to f_B. From $H = 4f_B/(\rho g \sin\alpha)$,the yield strength can be obtained by putting lava tube cave height H.

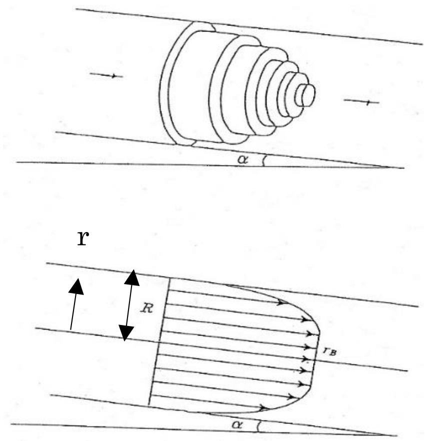

Fig.4 Lava flow in the circular tube

3.The yield strength estimated from stratified lava layer in the cross section of the vertical pit

Marius Hills Hole (MHH) consists of 4m-12m thickness of stratified lava layer in a vertical pit section(an average of 6m thickness(see

Fig.5)(Robinson,2012)[4].

When average thickness of H=6m and slope angle α=0.31 degree in Rille-A area(Greeley,1971)[8] are used for the lava flow stop condition of Simple flow, the yield strength is given as $f_B = \rho\ g\sin\ \alpha\ H$=131 Pa (Honda,2017)[9] where the lava density is ρ=2.5g/cm^3 and surface gravity is g=162 cm/s^2. On the other hand, the thickness of the stratified lava layer of the ceiling section of vertical Pits-I at the foot of north area in Arsia Mons is found to be H=3m(see Fig.6) (Cushing,2012)[6]. The stop condition of Simple flow of lava where slope angle of pit-I area is α=0.28deg gives the yield strength f_B=136 Pa[10]. For this estimation, the lava density ρ =2.5g/cm^3 and surface gravity g=371 cm/s^2 are used.

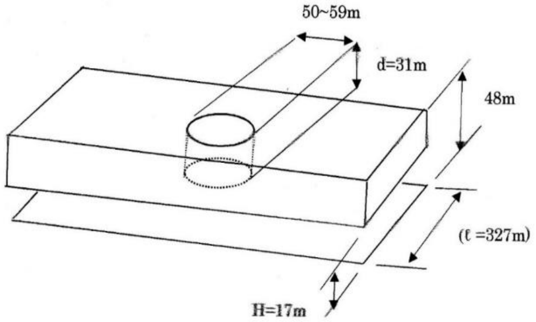

Fig.5 Schematic of Marius Hills Hole

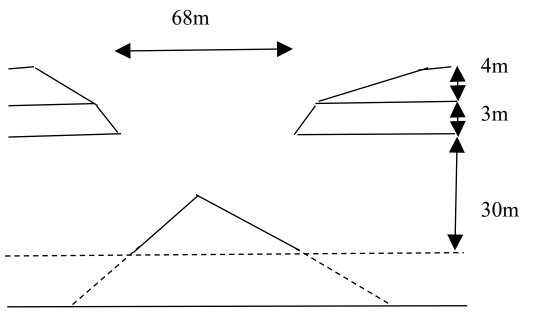

Fig.6 Schematic of the skylight of the volcano-tectonic fracture system (I):dust layer:4m, bedrock overhang:3m,the depth at the edge of the shadow:37 m. extracted and simplified from Fig.8 of G.E.Cushing: Journal of Cave and Karst Studies, April 2012

4.Estimation of the lava tube cave height under the pit for MHH and Arsia Mons

The lava tube cave height Hc under the MMH and the skylight of the volcano-tectonic fracture system (I) of Martian Arsia Mons will be estimated by the lava flow model on the inclined surface with slope angle α. The flow critical(stop) condition of the lava is expressed as $Hc = nf_B/\ (\rho\ g\ \sin\ \alpha)$, where-ρ is density, g is gravity, For the case of n=2, Hc is cave height between infinite width parallel plates, and for the case of n=4, Hc is cave height in the circular tube (Hulme,1974). The used yield strengths as proper value would be those obtained from the lava layer in the pit hole. For the MHH, for n=2 and n=4, Hc=12m and 24m respectively. As the observed Hc is 17m, n will be about 3. This possibly shows the cross section of the lava tube cave under MHH is rectangular(Honda,2017)[9]. For the skylight of the volcano-tectonic fracture system (I) of Martian Arsia Mons, for n=2 and n=4, Hc=6m and 12m respectively(see Table.1).

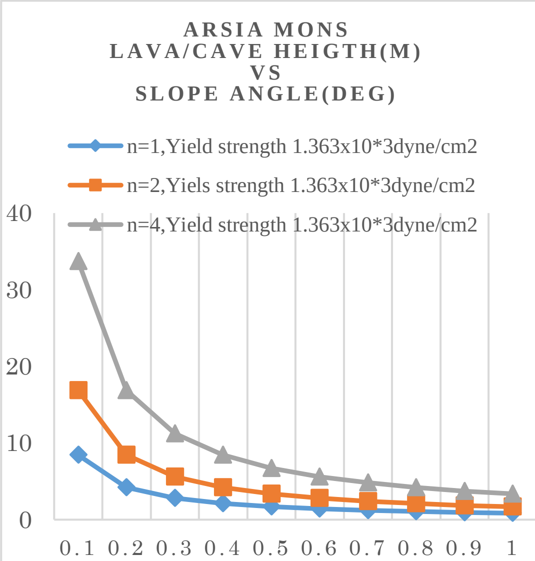

Fig.7 Lava tube cave height of Arsia Mos

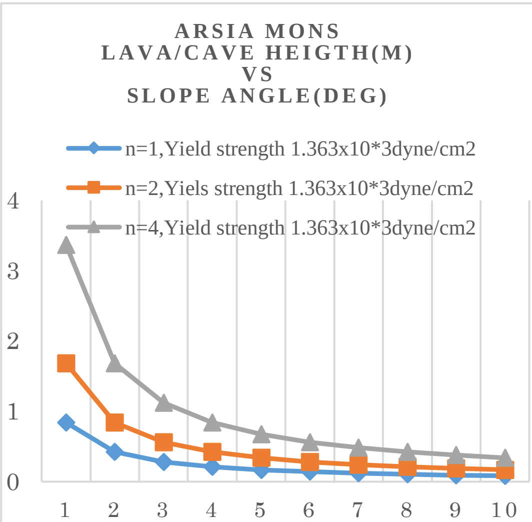

Fig.8 Lava tube cave height of Arsia Mons

Fig.7 and Fig.8 show lava thickness (n=1)and lava tube cave height(n=2 and n=4) of Arsia Mons for the case of the yield strength of 1.363×10^3dyne/cm^2.

Table 2.and Table3 show the skylights of North foot of the cone of Arsia Mons and the skylights of north flank of the cone of Arsia Mons. Estimated lava tube cave heights are added and compared with the depth of skylights(11).

The depth of the pits in Table 2 is much higher than the lava tube cave height.So,the pits shown in Table.2 will not be the skylight of the lava tube cave though the small lava tube cave network exist under the pits.

The depth of the pits in Table 3 is comparable with the lava tube cave height. So,some of the pits shown in Table.3 will be the skylight of the lava tube cave.

5.The yield strength obtained from the surface appearance thickness of the lava flow and comparison

Lots of yield strength of lava were obtained for lava flows of the Moon and Mars by using Simple flow stop condition (Hulme,1974)(7), but these values are widely scattered. Table 4 and Table.5 show the minimum and maximum value for the Moon and Mars ever obtained(12~22). The minimum value 100 Pa in the Moon is near the yield strength 131 Pa which is obtained from cross sectional layer thickness of the MHH. When the yield strength shows a bigger values, it seems that a lava flow manifests Multiple flow or Inflation of lava instead of Simple flow, then, the yield strength is considered as an apparent yield strength. The yield strength indicates the smaller value for the lower slope angle(Honda,2017)(10). The minimum value 120 Pa is near 136 Pa which is obtained from cross sectional layer thickness of the skylight of the volcano-tectonic fracture system (I) of Arsia Mons of Mars.

Lava yield strength of lava flow of Mars as a function of slope angle are estimated by the outer appearance of the lava flow thickness for Arsia Mons(Fig.9 and Fig.10)(12),Pavonis Mons(Fig.11 and Fig.12)(17), Ascraeus Mons(Fig.13 and Fig.14)(20), and Elysium Mons(Fig.15 and Fig.16)(21). Table 5 shows the range of the obtained yield strength of the lava flow of Mars including Elysium Planitia(22). The minimum values obtained are almost between 100Pa(1×10^3dyne/cm^2) and 200Pa(2×10^3dyne/cm^2).

Low values of low slope angle show that the flow is near simple flow, and high value of higher slope shows that the flow is inflated or multiplied. For the lower slope angle, it seems probably to converge into the true yield strength.

[Arsia Mons(Moore et al (1978))]

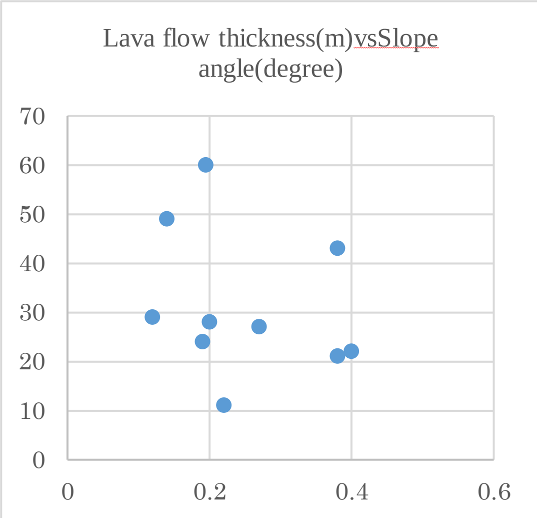

Fig.9 Lava flow thickness of Arsia Mons South Flank. (Moore et al (1978)

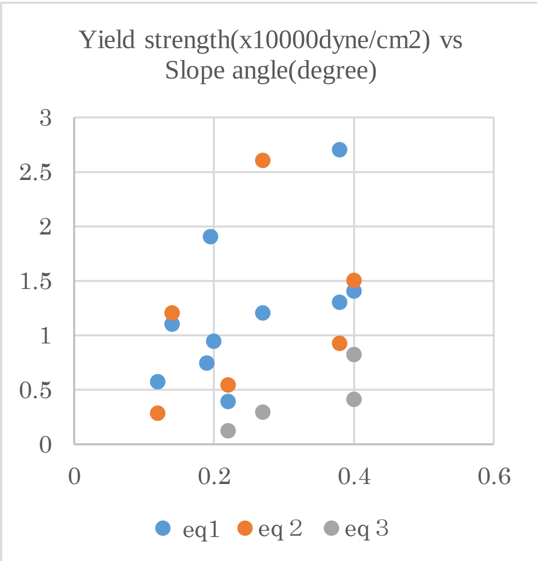

Fig.10 Arsia Mons South flank Yield strength:f_B (Moore et al(1978)) : Minimum:1200dyne/cm^2, Maximum:27000dyne/cm^2,eq1:f_B=H(ρgsinα), eq2: f_B =H^2ρg/W_f, eq3: f_B =2W_b (ρg$\sin^2$α), Here,H is lava flow thickness,$W_f$is lava flow width,W_b is lava levee width.(Moore et al(1987): f_B=1.2×10^3dyne/cm^2~2.7×10^4dyne/cm^2)

[Pavonis Mons]

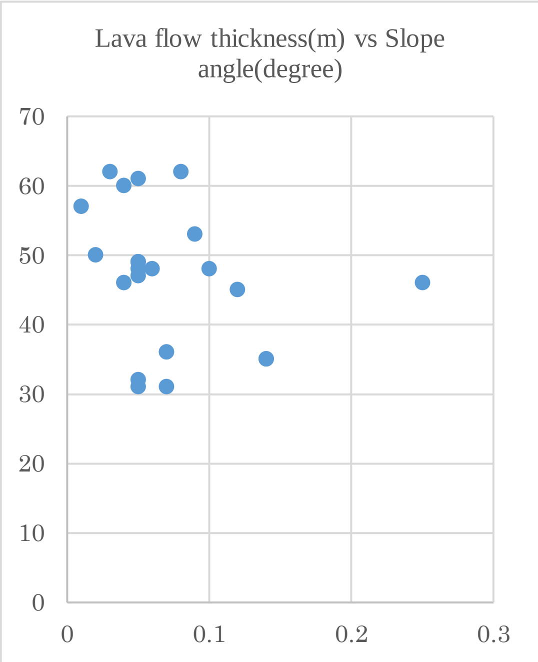

Fig.11 Lava flow thickness of Pavonis Mons, Baloga etal(2003)

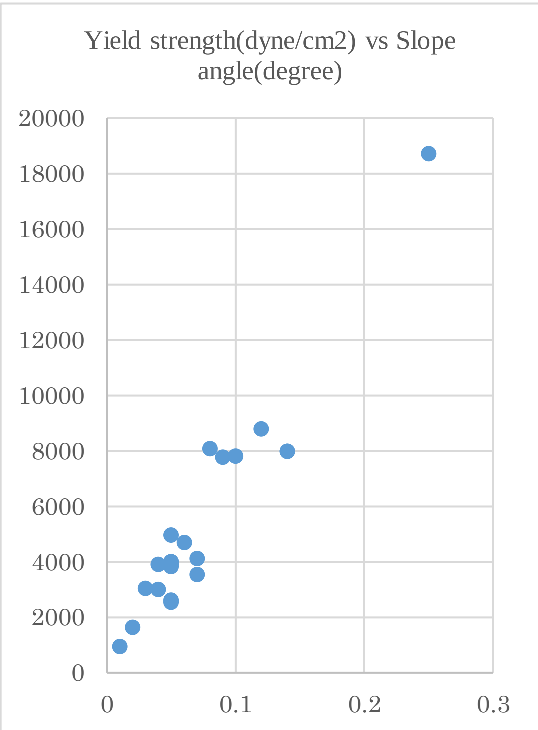

Fig.12 Yield strength of lava flow of Pavonis Mons,Baloga etal(2003), : from H,α、f_B is estimated by T.Honda: $f_B=0.93\text{x}10^3$dyne/cm^2~$1.9\text{x}10^4$dyne/cm^2

[Ascraeus Mons]

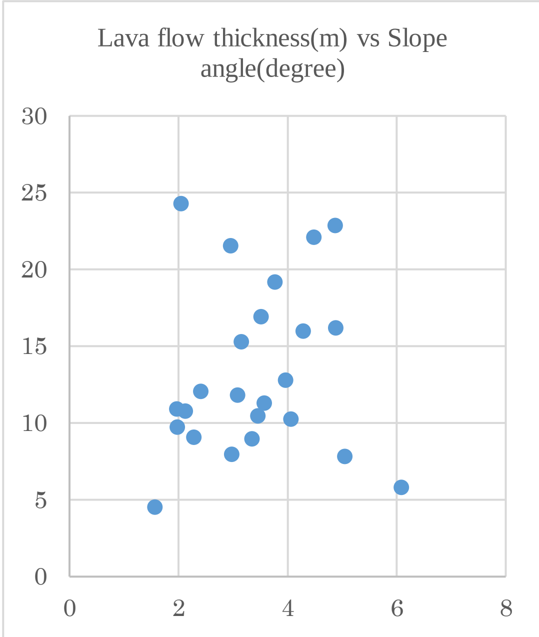

Fig.13 Lava flow thickness of Ascraeus Mons,Hiesinger etal(2007)

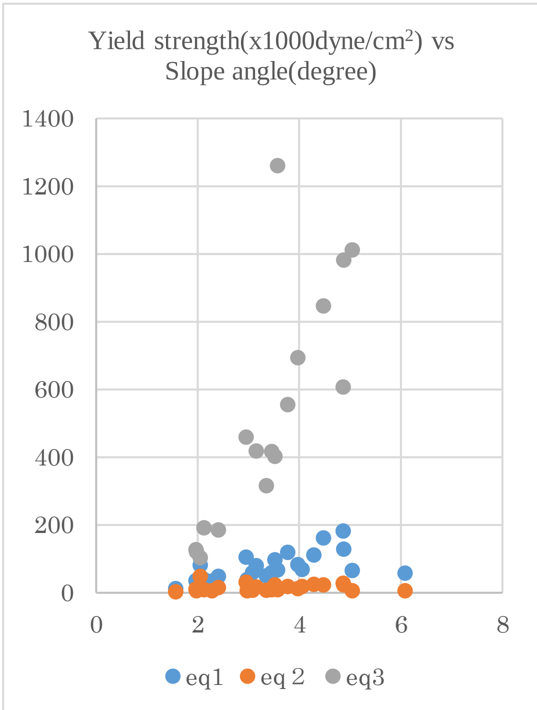

Fig.14 Yiels strength of Ascraeus mons,Hiesinger et al(2007), $f_B=1.99\text{x}10^3$dyne/cm^2~$1.26\text{x}10^6$dyne/cm^2 eq1:$f_B=H(\rho g\sin\alpha)$, eq2: $f_B=H^2\rho g/W_f$, eq3: $f_B=2W_b(\rho g\sin^2\alpha)$, Here,H is lava flow thickness,W_f is lava flow width,W_b is lava levee width.

[Elysium Mons]

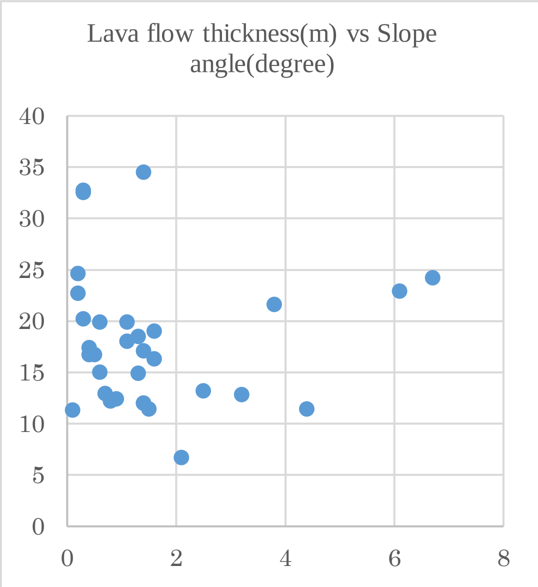

Fig.15 Lava flow thickness of Elysium Mons,Pasckert et al(2012)

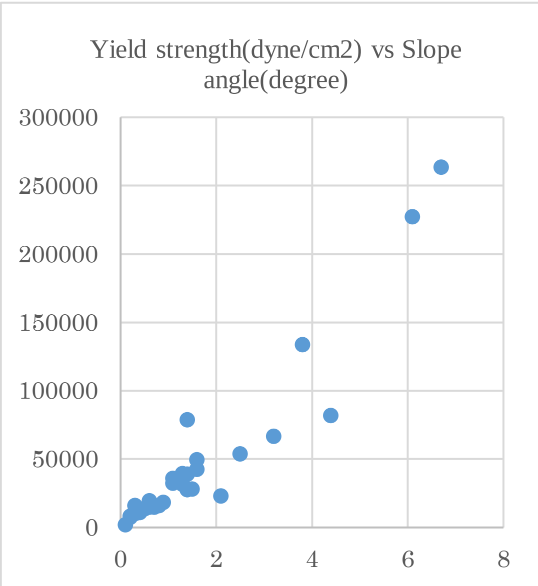

Fig.16 Yield strength of lava flow of Elysium Mons, Pasckert etal(2012) , $f_B=1.84\text{x}10^3$dyne/cm^2 ~$2.7\text{x}10^5$dyne/cm^2

6.Possible existence of lava tube caves under the pits and lava yield strength of Elysium Mons

As shown in Fig.14, the lava flow thickness of the neighborhood of the Elysium Mons is obtained by J.H.Paschert et al(21) .By using this lava flow thickness H, the yield strength can be obtained from $f_B=H\ (\rho\ g \sin \alpha)$ as shown in Fig.15. The used value for density is ρ =2.5g/cm^3, for gravity is g=373cm/s^2. The calculated yield strength decreases from upstream to downstream from $2.63\text{x}10^5$ dyne/cm^2 to $1.84\text{x}10^3$ dyne/cm^2. These values are considered to be an apparent yield strength because of a deviation from simple flow structure due to lava flow inflation or lava flow accumulation. For estimation of lava tube cave height, the minimum value of $1.84\text{x}10^3$ dyne/cm^2 for 0.1 degree and for 11.3 m of lava thickness is used so that the influence of inflation or accumulation is considered as minimum.

The depth and diameter of the pits are listed by Y. Goto et al(23) as shown in the left column of Table 6. The slope angle at the position of the pits are estimated from a contour line of Elysium volcano in the geologic map (24). The limiting conditions used for estimation of the lava tube cave height is the $Hc=4f_B/(\rho\ g \sin \alpha)$ and Hc is indicated in the right column of Table 6. There is a possibility that a lava tube cave exists under the vertical pit because it's H>>Hc at all vertical pits.

There is a possibility that a lava tube cave exists under the vertical pits of Elysium Mons, but its cave height is small compared with the vertical pit depth. Many lava tube caves may intersect in the lava layer through the vertical pit. The vertical pits would be regarded as the pit crater similar to devil's throat(25,26) of Hawaii Kilauea instead of skylight of a lava tube cave.

7.Summary

From the cross sectional observation of lava layer of the vertical pit, Marius Hills Hole (MHH) of the Moon and of the vertical pit in Martian Arsia Mons, the yield strength of lava flow is estimated,then,height of the possible lava tube cave is predicted. On the other hand, from the remote surface appearance of the lava flow for the Moon and Mars. the minimum yield strength of lava flow of Arsia Mons,Pavonis Mons, Ascraeus Mons and Elysium Mons is estimated, then, the height of the possible lava tube cave of Elysium Mons as an example is predicted.

For the two methods of estimation of the yield strength,there is still a concern whether the yields strength obtained from surface appearance is not minimun or the yield strength obtained from cross sectional observation contains still an influence of lava inflation. Therefore, on site sampling and chemical/physical examination is necessary to obtain the true yield strength. With the true yield strength, the lava tube cave height can be predicted.

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Table1 Estimated lava yield strength observed from stratified lava thickness of the pits

Lava flow area	Lava layer thickness (n=1)	Slope angle	Estimated Yield strength	Possible cave height
Moon, Marius Hills Hole	6m	0.31 deg	131Pa(1.31x10^3dyne/cm^2)	12m(n=2) ~24m(n=4)
Mars,Arsia Mons, the skylight of the volcano-tectonic fracture system (I)	3m	0.28 deg	136Pa(1.36x10^3dyne/cm^2)	6m(n=2) ~12m(n=4)

Table 2 Skylights(Pits) of North foot of the cone of Arsia Mons

Pit Name of Arsia Mons[2)]	Diameter[2)]	Minimum depth[2)]	Elevation[2)]	*Slope angle*	*Estimate of H for n=4*	*Estimate of H for n=2*	*Estimate of H for n=1*
Annie	225m	101m	11055m	*3.1 deg*	*1.2m*	*0.6m*	*0.3m*
Dena	162m	80m	9100m	*3.5 deg*	*1.0m*	*0.5m*	*0.25m*
Jeanne	165m	75m	9970m	*1.0 deg*	*3.4m*	*1.7m*	*0.85*
Wendy	125m	68m	15500m	*3.5 deg*	*1.0m*	*0.5m*	*0.25m*
Chloe	252m	N/A	5700m	*1.7 deg*	*2.0m*	*1.0m*	*0.5m*
Abbey	100m	N/A	111500	*3.5 deg*	*1.0m*	*0.5m*	*0.25m*
Nikki	180m	N/A	111500	*1.0 deg*	*3.4m*	*1.7m*	*0.85m*

from G.E.Cushing etal(2007):Geophys.Res.Letters,Vol.34,L17201

Table3 Skylights(Pits) of north flank of the cone of Arsia Mons

Feature[5)]	Number of skylight[5)]	Minimum depth[5)]	Total Length[5)]	Average Slope[5)]	*Estimate of H for n=4*	*Estimate of H for n=2*	*Estimate of H for n=1*
A(Tube-fed)	4	~10m	>35km	0.12 deg	*28m*	*14m*	*7m*
B(Tube-fed)	4	~18m	32.5km	0.23 deg	*14.8m*	*7.4m*	*3.7m*
C(Tube-fed)	9	~24m	71.0 km	0.25 deg	*13.4m*	*6.7m*	*3.4m*
D(Tube-fed)	5	~10m	>19 km	0.46 deg	*7.4m*	*3.7m*	*1.9m*
E(Tube-fed)	4	~12m	>15 km	0.31 deg	*10.9m*	*5.5m*	*2.8m*
F(Tube-fed)	32	~23m	47.0 km	0.34 deg	*10m*	*5m*	*2.5m*
G(Tube-fed)	5	~19m	>55 km	0.54 deg	*6.3m*	*3.2m*	*1.6m*
H(Tube-fed)	1	~15m	>35 km	0.45 deg	*7.4m*	*3.7m*	*1.9m*
I(Tectonic fracture)	9	>35m	>100 km	0.28 deg	*12m*	*6m*	*3m*

from G.E.Cushing(2012): CANDIDATE CAVE ENTRANCES ON MARS,Journal of Cave and Karst Studies, April 2012

Table4 Minimum and Maximum lava yield strength estimated from lava flow thickness by outer appearance

Lava flow area	Min .yield strength	Max. yield strength	References
Moon,Mare Imbrium	100 Pa(1.0x10^3dyne/cm^2)	400 Pa(4.0x10^3dyne/cm^2)	Moore et al(1975),Hulme et al(1977)

Table.5 Minimum and Maximum lava yield strength obtained from lava flow thickness by outer appearance

Mars Volcano name	Min.yield strength	Max.yield strength	References
Arsia Mons	120 Pa (1.2x10^3dyne/cm^2)	5.19 x10^4 Pa (5.19x10^5dyne/cm^2)	Moore et al(1978),Warner et al(2003),Hiesinger et l(2015)
Pavonis Mons	93 Pa (0.93x10^3dyne/cm^2)	1.3 x 10^4 Pa (1.3x10^5dyne/cm^2)	Baloga et al(2003), Hiesinger et al(2008) ,Hiesinger et al(2015)
Ascraeus Mons	199 Pa (1.99x10^3dyne/cm^2)	1.3 x 10^5 Pa (1.3x10^6dyne/cm^2)	Zimbelman(1985),Hiesinger et al(2007),Hiesinger et al(2008)
Elysium Mons	184 Pa (1.84x10^3dyne/cm^2)	2.63 x10^4 Pa (2.63x10^5dyne/cm^2)	Pasckert et al(2012), Hiesinger et al(2015)
Elysium Planitia	100 Pa (1.0x10^3dyne/cm^2)	500Pa (5.0x10^3dyne/cm^2)	Vaucher et al (2009)

Table 6 Pit depth of Elysium Mons: H and Estimated lava tube cave height: Hc

*Pit number	*Diameter	*Depth :H	Slope Angle (Estimated by contour)	Tube height of circular tube cross section forn=4, $Hc=4f_B/(\rho g \sin\alpha)$, ($f_B$ is1.84x10^3 dyne/cm^2)	Remarks
1	358.8m	98.7m	*0.6°*	*7.5m*	*H>>Hc*
2	88.0m	12.5m	*1.0°*	*4.5m*	*H>>Hc*
3	121.5m	42.0m	*0.6°*	*7.5m*	*H>>Hc*
4	140.5m	63.2m	*1.0°*	*4.5m*	*H>>Hc*
5	243.8m	61.1m	*0.6°*	*7.5m*	*H>>Hc*
6	143.5m	29.2m	*0.6°*	*7.5m*	*H>>Hc*
7	17.1m	-	*0.6°*	*7.5m*	-
8	192.0m	42.1m	*1.0°*	*4.5m*	*H>>Hc*
9	254.8m	84.8m	*0.6°*	*7.5m*	*H>>Hc*
10	94.5m	69.9m	*6°*	*0.76m*	*H>>Hc*
11	110.3m	17.7m	*6°*	*0.76m*	*H>>Hc*
12	115.2m	25.2m	*6°*	*0.76m*	*H>>Hc*

* Yuki Goto et al(2017): List of Hole Pits taken by MRO HiRISE at the foot of Elysium Mons on Mars,JAXA-RM-16-008