Classification of Lava Tubes from Hydrodynamic Models for Active Lava Tube, Filled Lava Tube and Drained Lava Tube(Lava Tube Cave)

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Abstract

Lava tubes have been classified to three categories such as Active Lava Tube, Filled Lava Tube and Drained Lava Tube(Lava Tube Cave) according to the hydrodynamic models for the Bingham fluid flow inside the inclined tube under the action of magma pressure and gravity force. Controlling parameters of lava tube formation decisive for each category are identified. A case study has been performed for the lava tubes of Medicine Lake Volcano by using these models to check the feasibility of the models.

1.Introduction

In order to clarify the ambiguity of the term "lava tube","lava tube cave" or "lava tunnel", the discharge mechanism of lava in an inclined circular pipe model has been formulated and categorized, based on Bingham characteristics of lava flow under the action of magma pressure and gravity force. In the previous studies[1~3], only the gravity force is used for modeling . Here,the flow in the tube was characterized as a function of tube radius, viscosity, yield strength of lava, slope angle and magma pressure head. A case study has been performed for the drained lava tubes(lava tube caves) and filled lava tubes of Medicine Lake Volcano (MLV) by using these models to check the feasibility of these models. The active lava tube is out of scope for this case study because the active lava tube should be checked with actually eruption-on-going volcano.

2.Hydrodynamic Models and classification for Lava Tubes

A considered model is indicated on Fig.1 where M is head height by magma pressure, L is length of lava tube and R are the lava tube radius, and α is slope angle of the lava tube.
Case(A) shows the lava spouted from a crater goes down a slope and forms a lava tube. The flow in the lava tube is controlled by the magma pressure and gravity (forced flow). After the termination of eruption(disparition of magma pressure), two cases (B) and (C) are considered. Case(B) shows a "filled lava tube" in which lava is stayed in the tube without drained out from the tube. Case (C) shows a "lava tube cave" in which the lava in the tube can be drained out by the gravity (free flow), a hollow is formed in the tube.

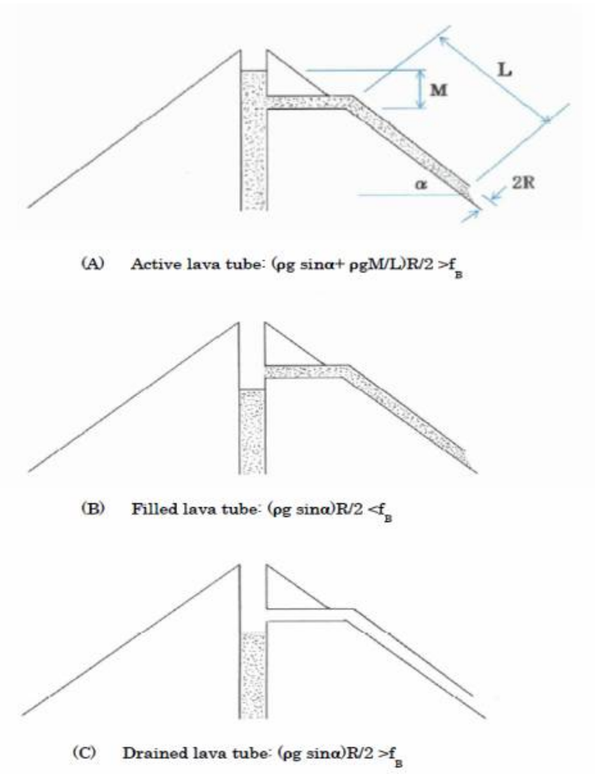

Fig.1 Hydrodynamic Model for Lava Tubes

The flow speed distribution in the tube is shown in Fig.2.

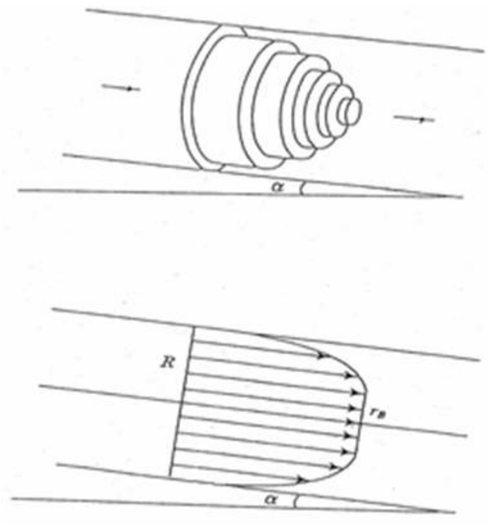

Fig.2 The flow speed distribution in the tube

The equation of the flow speed distribution u in the tube is shown as below:

For $\tau_W = (\rho g \sin\alpha + \rho g M/L)R/2 > f_B$

$u = (R - r_B)^2 (\rho g \sin\alpha + \rho g M/L)/4\eta_B \qquad r < r_B$

$u = [R^2 - r^2 - 2r_B(R - r)](\rho g \sin\alpha + \rho g M/L)/4\eta_B \qquad r > r_B$

For $\tau_W = (\rho g \sin\alpha + \rho g M/L)R/2 < f_B$

$u = 0$

Here, τ_W is shear stress on the tube wall surface, r_B is radius where shear stress is equal to f_B, f_B is Bingham yield strength, η_B is Bingham viscosity, g is the gravity force and ρ is lava density.

In summarizing the controlling parameters,
for Case (A), M/L>0 and
$\tau_W = (\rho g \sin\alpha + \rho g M/L) R/2 > f_B$,
for Case(B), M/L=0 and $\tau_W = (\rho g \sin\alpha) R/2 < f_B$,
for Case(C), M/L=0 and $\tau_W = (\rho g \sin\alpha) R/2 > f_B$,
Classification and controlling parameters are shown in Table1.

3. Case study for lava tubes in Medicine Lake Volcano(MLV)

Medicine Lake Volcano(MLV) is a very special volcano which has various lava flows of basalt,basaltic andesite, andesite,dacite and rhyolite in the same volcanic area and it's data are well documented[4~6]. This a good example for case study by using these models.

3.1 Lava tube cave and SiO_2 weight content

In the Table-1 and 2, arbitrary lava flows and existence or non-existence of the lava tube cave are listed in the order of the silica mean weight content[7]. Though, the lava tubes caves are found in the specific local area such as hotter effect near vent, and compositionally-zoned area of lowerSiO2wt % content in MLV lava field [8].

Lots of lava tube caves are found in the basaltic lava flows[5]. This is the case of M/L=0 and **$(\rho g \sin\alpha)R/2 > f_B$** and certainly **2R<h.** Tthough, the lava flows of silica content higher than 53~54% such as basaltic andesite, andesite, dacite and rhyolite have no lava tube caves, this is the case of M/L=0 and **$(\rho g \sin\alpha)R/2 > f_B$** but **2R>h**. The border of the existence between non-existence of the lava tube caves seems to be at about 53%~54% of SiO_2 weight content[7].

3.2 Characteristics of drained lava tubes and filled lava tubes in MLV

A critical condition to permit the drain of lava was determined from the yield strength of lava and the height(h=2R) and slope angle of the lava tube: $(\rho g \sin\alpha) h/4 = f_B$. From this relation, if h and α are known, the yield strength can be obtained. The yield strength of the lava can be in the range from 1.9×10^4 to 3.8×10^4 dyne/cm^2 for 10~20m height for 1.78 degree slope[9] of Crystal Cave(Map unit:bmc). This yield strength range is reasonable for basaltic lava of $SiO_2$48.6wt%[10].

Regarding the "filled lava tube", it should be mentioned that the "filled lava tube" has been found in the crater edge of Mammoth Crater as a hidden lava tube[6](see Photo1) . Schematic is shown in Fig3. This is a case of $\tau_W = (\rho g \sin\alpha + \rho g M/L)R/2 = 0 < f_B$、 then u= 0, because sinα=0 and M/L=0,certainly with 2R<h.

Photo 1 Mammoth Crater. The filled lava tubes are located at the right side edge of the crater.

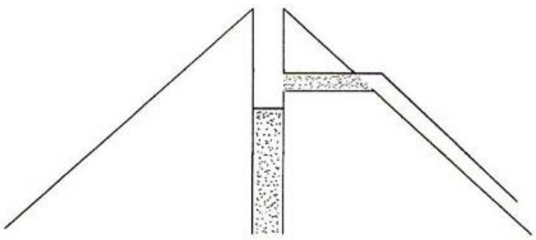

Fig.3 Schematic of Filled lava tube at the edge of the vent

3.3 Interpretation on " Why lava tube caves cannot be found in the andesite lava flow?"

As a yield strength is exponential function of SiO_2 content[10], lava tube cave formation ability is very sensitive to the yield strength of lava. The estimated yield strength by G.Hulme[10] for the andesite of 55% SiO_2 content is about $2.0x10^5$dyne/cm^2,which gives 105m as a limiting tube height for the same slope angle of 1.78 degree as shown in Fig.4. This means that the lava flow thickness should be higher than 105m for the formation of lava tube cave. This is not the case for MLV. So, the border between the existence and non-existence of the lava tube caves seems to be at about 53%~54wt% of SiO_2.

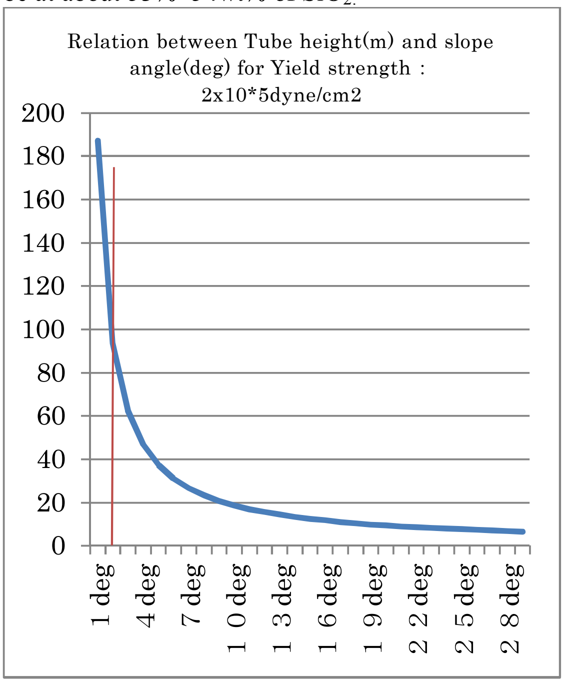

Fig.4 Tube height and slope angle for yield strength for $2.0x10^5$dyne/cm^2

4.Conclusions

The detailed categorization of lava tubes such as active lava tube, filled lava tube and drained lava tube(lava tube cave) is proposed. The controlling parameters to form the drained lava tube(lava tube cave) and the filled lava tube are applied for the case of MLV volcano. It seems that these models could well understand the lava tube formation phenomena. The next step is to apply the controlling parameters to the active lava tube for actually eruption-on-going volcano.

[Acknowledgement]

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Table 1 Classification and formation conditions of Lava Tubes

Classification of lava tubes	Basalt 45-52% SiO_2	Basaltic Andesite 52-57% SiO_2	Andesite 57-63% SiO_2	Condition for formation
Active lava tube	Possible if $2R<h$ and $(\rho g \sin\alpha + \rho g M/L)R/2 > f_B$	Possible if $2R<h$ and $(\rho g \sin\alpha + \rho g M/L)R/2 > f_B$	Possible if $2R<h$ and $(\rho g \sin\alpha + \rho g M/L)R/2 > f_B$	$M/L>0$ with Magma pressure
Filled lava tube	Possible if $2R<h$ and $(\rho g \sin\alpha)R/2 < f_B$	Possible If $2R<h$ and $(\rho g \sin\alpha)R/2 < f_B$	Possible if $2R<h$ and $(\rho g \sin\alpha)R/2 < f_B$	$M/L=0$ without Magma pressure
Drained lava tube (Lava tube cave)	Possible if $2R<h$ and $(\rho g \sin\alpha)R/2 > f_B$	Possible if $2R<h$ and $(\rho g \sin\alpha)R/2 > f_B$ (Though, the border line is 53-54% in practice because of high yield strength and $2R > h$)	Possible If $2R<h$ and $(\rho g \sin\alpha)R/2 > f_B$ (Though, in practice, impossible because of too high yield strength and $2R > h$)	$M/L=0$ without Magma pressure

Table 2 North Area of Medicine Lake Volcano*

Map unit	Name of lava flow	SiO_2weight %	Age of eruption	Lava tube caves?
bt	Basalt of Tionesta	48.3%	late Pleistocene	Existing
bc	Basalt of The Castles	48.6%	late Pleistocene	Existing
bdh	Basalt of Devils Homestead	51.3~51.4%	12320yrBP	Existing
bec	Basalt east of Cinder Butte	51.6%	late Pleistocene	Existing
bmc	Basalt of Mammoth Crater	52.3% Avg	36±16ka	Existing**
bci	Basalt of Caldwell Ice Caves	52.8%	late Pleistocene	Existing
bvc	Basalt of Valentine Cave	53.0% Avg	12,260yrB.P.	Existing
mna	Basaltic andesite northeast of Aspen Crater	53.7% Avg	late Pleistocene	Existing
mts	Basaltic andesite of Three Sisters	54.4%	late Pleistocene	None
mcf	Basaltic andesite of Callahan Flow	55.1% Avg	1,120yrB.P.	None**
asb	Andesite of Schonchin Butte	57.2% Avg	65±23ka	None
anr	Andesite of north rim	60.7% Avg	100±3 ka	None
rgm	Rhyolite of Glass Mountain	61.3~74.6%	890 yr B.P.	None

*made from the data and descriptions in: Donnelly-Nolan, J. M. (2010). Geologic map of Medicine Lake Volcano, Northern California. U.S. Geological Survey Scientific Investigations Map , 2927, 48 p.

**Remarks by private communication with Donnelly-Nolan, J. M. (2015.6.01): There is a small tube near-vent in the lower-silica part(52.5%) of the Callahan Flow. Also, there is some new evidence that a tube in the basalt of Mammoth Crater formed at 54% SiO_2, although most of the flow through it had lower SiO_2.

Table 3 South Area of Medicine Lake Volcano*

Map unit	Name of lava flow	SiO_2weight %	Age of eruption	Lava tube caves?
bug	Basalt under Giant Crater lava field	49.3, 50.8%	445±27 ka	Existing
bgc	Basalt of Giant Crater	49.5%Avg	12,430yrB.P.	Existing
byb	Basalt of Yellow jacket Butte	49.5–53.1%	86±14 ka	Existing
bdc	Basalt of Deep Crater	50.3%	middle Pleistocene	Existing
bwc	Basalt of Water Caves	52.4%Avg	late Pleistocene	Existing
mdp	Basaltic andesite of Doe Peak	55.2%	middle Pleistocene	None
abl	Andesite of Burnt Lava Flow	57.3%Avg	2,950 yr B.P.	None
asr	Andesite of south rim	61.4%Avg	124±3 ka	None
rlg	Rhyolite of Little Glass Mountain	72.6–74.2%	940 yr B.P.	None

*made from the data and descriptions in: Donnelly-Nolan, J. M. (2010). Geologic map of Medicine Lake Volcano, Northern California. U.S. Geological Survey Scientific Investigations Map , 2927, 48 p.