

**Proceedings**  
of the  
**18<sup>th</sup> International Symposium**  
on  
**Vulcanospeleology**

**Lava Beds National Monument**  
**California, USA**  
**21-27 July 2018**

**Proceedings  
of the  
18th International Symposium on Vulcanospeleology  
Lava Beds National Monument, California, United States of America  
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## The International Union of Speleology and the Volcanic Caves Commission

by George Veni, President, International Union of Speleology

The International Union of Speleology (UIS) is essentially the United Nations of cave exploration and cave science. It is comprised of 54 member countries, each represented by their national speleological organization. Many UIS accomplishments are achieved by its commissions—special interest groups that focus on over 20 topics. The Volcanic Caves Commission is a very active commission with symposia every two years, a newsletter, website, and good international communication among its members. This presentation is an overview of the UIS, the role of the Volcanic Caves Commission and other commissions, the UIS' plans for the next few years, how those plans will benefit cave exploration, cave research, management, education, and funding, and how you can get involved.

# Photomonitoring at Lava Beds National Monument

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## Abstract

The Lava Beds National Monument Photomonitoring Project has been active for over 25 years. The project started in 1989 with the goal of setting up a photomonitoring system that could be carried on by monument staff. Due to limited staff availability, the project was restarted in 2008 with volunteers doing the field work. The project also changed from using film for the capture and storage of the photographic data to using digital capture and storage. During this time, much has been learned about how to use photography to monitor changes in the lava tubes of the Monument.

Significant results include:

- Baseline photos for the study of the disappearance of ice in Merrill Cave.
- Documenting the general disappearance of ice in the park.
- Validation of the assumption of low continuing impact of visitors in class 1 caves.
- Detection & documentation of vandalism of petroglyphs in Symbol Bridge Cave.

## Background

The Lava Beds (LAVE) Photomonitoring Project began in 1989 and has continued since then in various forms under the auspices of the National Park Service and the Cave Research Foundation (CRF). The CRF is a Kentucky based US non-profit organization that serves as a liaison between volunteer researchers and land management units of the US government.

The project started as an extension to a then new monument cave management plan. Its goal was and still is to produce a time series of reproducible photographs of specific locations in the caves for use as an input to monument management decisions.

Photomonitoring volunteers work with monument management to select monitoring sites, and to curate and interpret the data. Sites are selected based on anticipated impacts and the ability of photos to show those impacts.

## LABE Cave Management Plan:

The LABE Cave Management Plan identified four management classes for caves:

- Class 1: Open to the public with trails, stairs, and parking.
- Class 2: Open to the public but not advertised.
- Class 3: Closed. Not discussed with the public.
- Class 4: Unique issues require a specific management plan, e.g. Mushpot Cave

## Initial Project (1989 - 1995)

The initial project, conducted by Bill Frantz, worked with monument staff to select from one to three stations each in 16 caves, with at least one cave from each management class. These sites were then photographed using color slide, color print, and black and white negative films. By using three types of film, it was hoped that at least some of the photographs would survive the ravages of time. The objective in site selection was the reproducibility of each photo, including framing & lighting. It was not anticipated that this protocol would cover a large number of sites.

A photographic protocol was introduced and documented, designed to make it easy to reproduce the framing and lighting of each picture in later years. Each site was surveyed marking the locations of the camera and the flash. The orientation, 3 F stops, shutter speed, and lens focal length were also recorded. (see figure 1). The intent was that monument staff would curate the data and periodically re-shoot the photos and evaluate the results. The photographs and site information were kept in a binder in the monument's resource office.

**CRF  
Photomonitoring Log**  
Version 1

Cave name: \_\_\_\_\_ Site number: \_\_\_\_\_

Scale	Aperture	Height	Vertical Angle	Date	Time	Lens Focal Length	Shutter Speed
Camera							
				Film	Exposures	22:16:11	8:15:66
						4:2:61	2:1:41
Subject Description							
Comments							
Sketch of Setup: <small>(indicate location of camera, flash, and subject with enough survey data to allow it to be relocated.)</small>							

Figure 1: Early Photomonitoring Form

After the end of the initial project, the monument conducted some re-photography. However limitations in time and personnel made it difficult to do so systematically or consistently. In spite of these difficulties, the monument staff was able to add new stations as developments in the monument pointed to the need for additional monitoring.

It also proved difficult to manage and catalog the burgeoning mass of data. Comparing monitoring photos made at different times was difficult, hindering the ability to derive meaningful information from them.

Due to the staff limitations, and the difficulty of working with the data, as time passed, the data fell into disuse, and its existence was forgotten. When the ice floor in Merrill Cave developed a hole<sup>1</sup>, the photomonitoring data was retrieved because one of the stations included a 1991 photograph of the area where the hole appeared. It became a baseline for tracking and

<sup>1</sup> Janet Sowers lead a study of the ice hole in Merrill cave. The results were presented in the Lava Tube Symposium at the 2003 National Speleological Society convention in Porterville California. There is an abstract of the talk in the program for that convention.

studying the disappearance of the ice. It should be noted that the then current Resource staff was unaware that it had this set of baseline data. (A sequence of photographs of this station can be seen in figure 2.)



1991



1998



2000



2009

Figure 2: Merrill cave ice

## Project Restart (2008-Present)

In 2008, because of the proven value of photomonitoring during the ice floor investigation, the project was refreshed and revitalized by Bill & Peri Frantz in cooperation with the monument. The new project addressed the successes and failures of the original project, and the emergence of new digital photo-technologies. Digital photography techniques were adopted for both image creation and image storage.

All existing photos were scanned to make digital copies. Unfortunately, because of a need to minimize digital storage usage, the initial scans were predominately low resolution and included multiple exposures in a single scan. Since storage usage is no longer an issue, part of the current project activities are to rescan the photographs at higher resolutions with one image per scan.

The existing archive was reorganized and evaluated to preserve and enhance its the value by making it compatible with the new protocols. The existing binders of photographs, negatives, and slides are being reorganized removing obsolete material. Each new scan is based on a single exposure, color image.

A naming protocol for managing the photo files on mass storage devices was developed along with computer techniques for tracking and managing the archive. Each file name includes the date of the photo, a code for the cave, and a site number. The project reports regularly on the status of this new archive.

The field techniques and protocols were updated by converting the project to digital photography and a color checking card to achieve color and exposure consistency. In addition, a new station form was created which had space for multiple repetitions of the photograph as the site was rephotographed over the years, reducing the need to enter redundant data. (See figure 3.)

Established stations were rephotographed to test the new photomonitoring protocols. These photographs provide a bridge between the protocols. The photographs were analyzed to determine if there were any significant artifacts due to the change in protocols. None were observed.

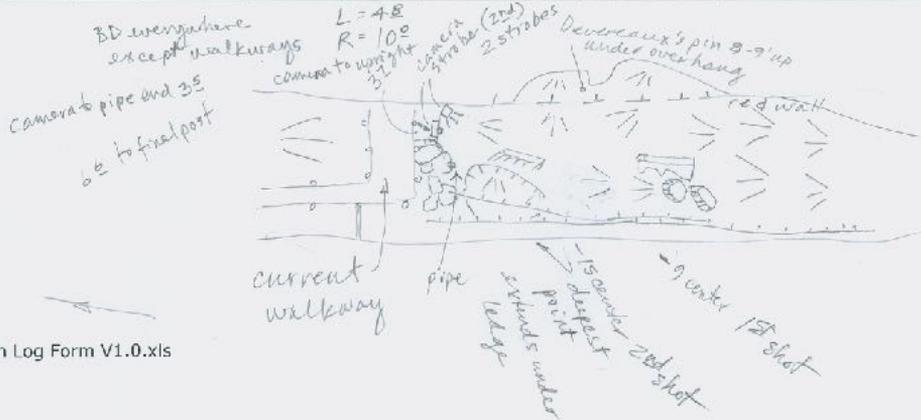
After reviewing the stations set up by the old project, it became obvious that some of them, in the more visited caves, needed to be rephotographed more frequently than others. A new part of project management is determining, in consultation with monument management, the appropriate intervals for reshooting each individual station. Also, some stations were added and some were dropped because the monitoring was demonstrated to be a high impact activity. The data from the dropped stations is being retained should there be a need to resume monitoring.

Some stations are at the entrances of caves. These stations may need to be rephotographed in the same season to achieve meaningful comparisons. Protocols were adapted for those stations to include seasonal controls.

The use of photo editing software makes it easier to match photographs of the same site so they can be meaningfully compared. Where it is useful, the old photographs have been adjusted to make them more consistent with the new protocols. This includes color and exposure adjustment. This process is still being formalized.

### Lava Beds National Monument Photomonitoring Log

Cave	Merri II	Objective:	recreate PM sta for ice monitoring photo sta.						
Station	Ice Cave								
Setup Info			Camera	Strobe	Station Description:				
Cave map		Asimuth	230		on edge of drop off 35' to the left of a pipe end on a BD piece.				
Station Map		Height	3 1/4	4					
		Angle	-9	-9					
		2nd	-15						
Photographer	Date	Time	Weather	Camera & lens	F-Stop	Shutter Speed	ISO/ASA	Photo File	Comments
	8 Sept 11			50			digital		



PMon Log Form V1.0.xls

Page 1

Figure 3: New Photomonitoring Form

Photographers now have the responsibility for the initial analysis of a site's photographs and for bringing any observed problems to the attention of the Monument staff.

In 2009, vandalism was noted in a site in Symbol Bridge cave while the site was being rephotographed. The damage was documented and reported to monument management. Just taking a close look at sites can occasionally reveal changes without the need to compare photographs. Having a photomonitoring site encourages such close examination.

## Significant Results:

The progress of ice disappearance from the former Merrill Ice Cave (Now Merrill Cave) has been well documented.

The general trend of ice disappearance in the monument has been documented.

Class 1 caves have exhibited a low level of additional damage over the years, validating their status in the Cave Management Plan.

The vandalism of petroglyphs in Symbol Bridge Cave has been documented.

## Lessons Learned:

Photomonitoring can cause significant damage to pristine caves. A site in one class 3 cave was removed from regular monitoring for this reason. The original photographs provide a baseline should monitoring become necessary in the future.

The conversion from film to digital was a great improvement in our ability to reproduce and archive photographs. Digital editing software makes it easy to correct the exposure and color balance.

The landmarks used to relocate a site may change, such as the removal of the walkway in Merrill Cave as shown in the 2009 photograph. (See figure 2.) This problem is more likely when using artificial landmarks, or infrastructure such as walkways and ladders. These items may be removed as part of normal monument management, making it difficult to relocate a site. Selection of future sites will strongly prefer natural landmarks for site location.

Changes in monument personnel can cause loss of information about the photomonitoring data. It is useful to have regular contact between photomonitoring personnel and monument management, so that the results of individual site changes can be captured and transmitted to the ever changing management personnel<sup>2</sup>.

With a long term project, the principle investigators grow old and need a plan to turn the project over to younger investigators. Both Bill and Peri find that they are now aging and need to train younger replacements. When suitable replacement project leaders have been identified, we will provide training. We note that other CRF projects in the Monument, such as Ice Level Monitoring, have been passed to the next generation.

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<sup>2</sup> For data redundancy, and to allow working off-site, photo monitoring volunteers should maintain at least one separate copy of all data give to the Monument.

# Ice in Lava Caves at Lava Beds National Monument

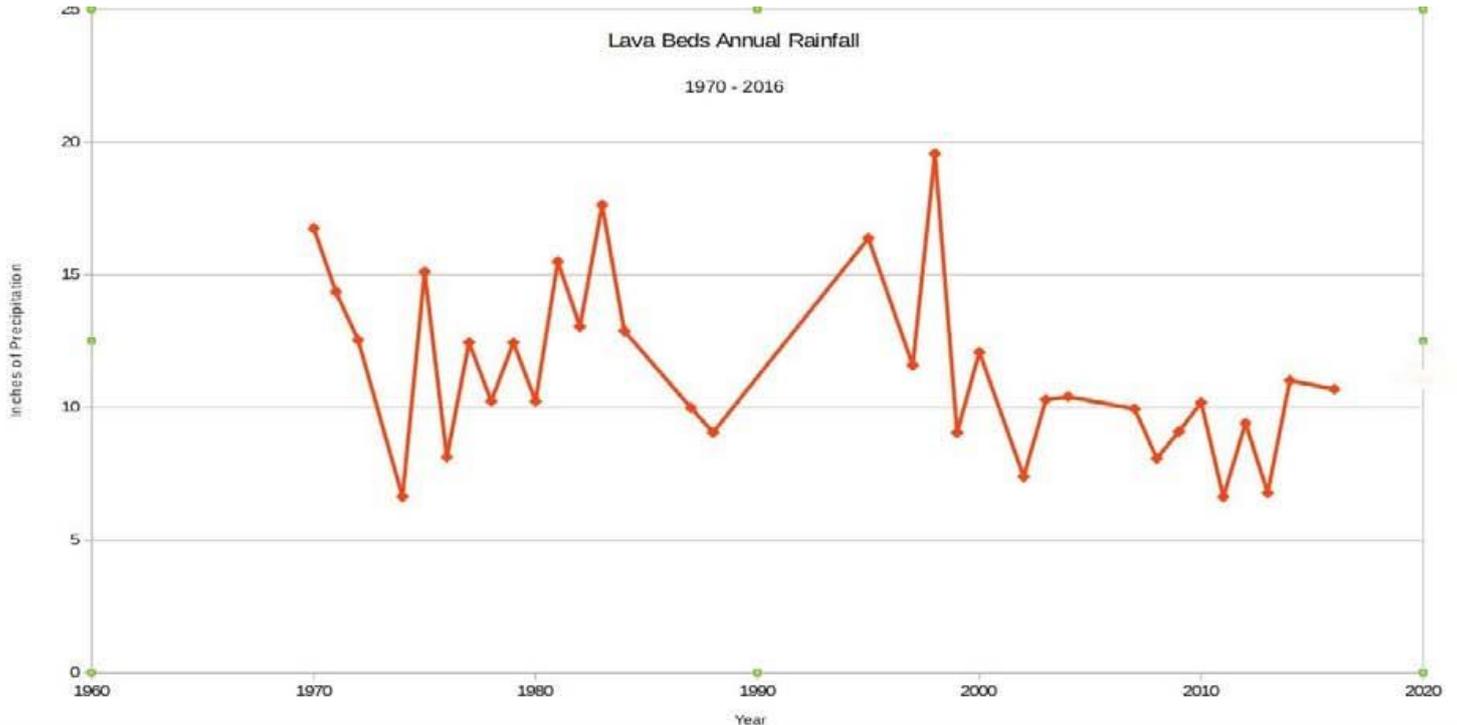
By Bill Devereaux and Mike Sims

In 1981, Members of the Willamette Valley Grotto of the National Speleological Survey were contacted by the resource officer at Lava Beds National Monument after observations that the ice in the caves appeared to be declining, particularly in Crystal Ice Cave. A project began in late 1981 to monitor the ice in selected caves.

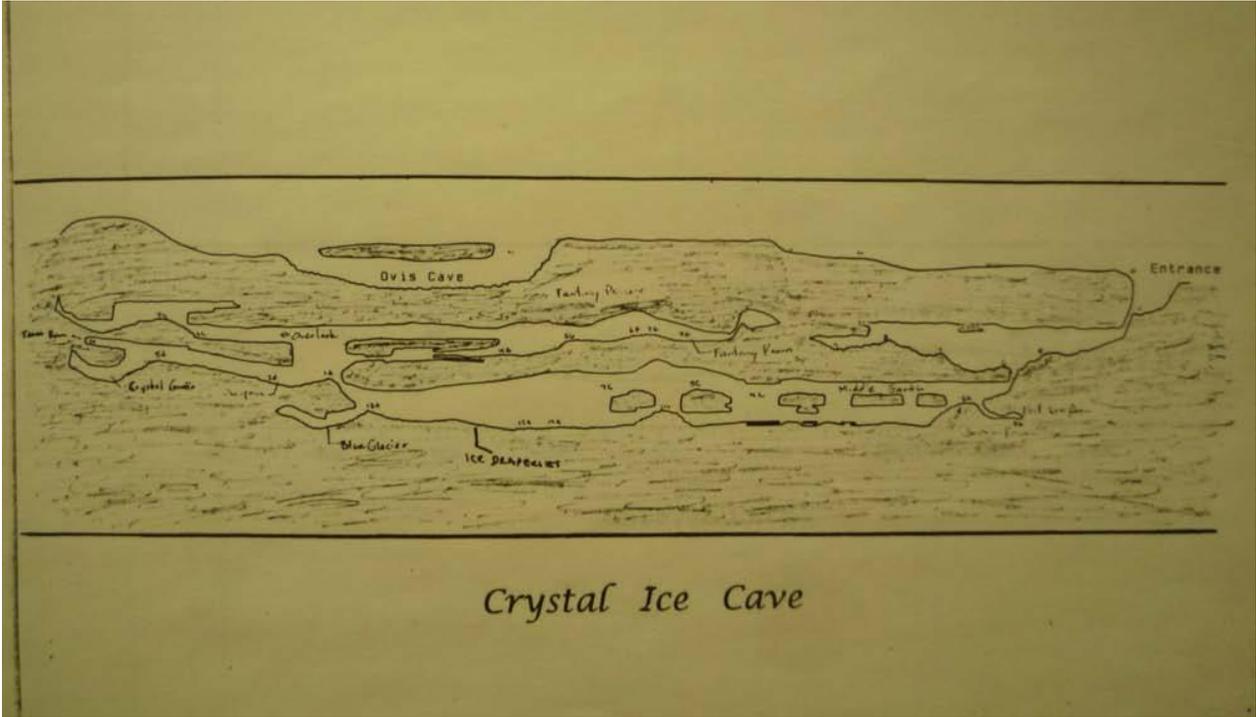
## Ice Level Measurements

Selected Caves:

- Crystal Ice Cave
- Big Painted Cave
- Caldwell Cave
- Cox Ice Cave
- Frozen River Cave
- Merrill Cave
- Skull Cave



**Crystal Ice Cave**



*Crystal Ice Cave*

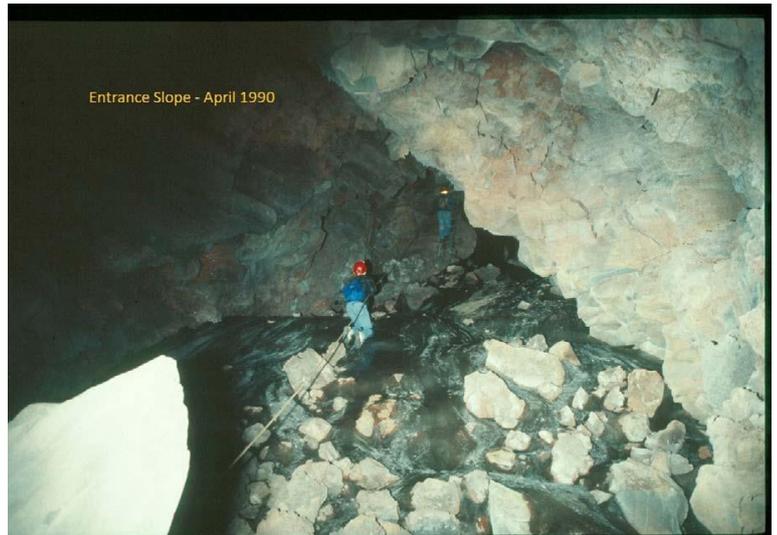
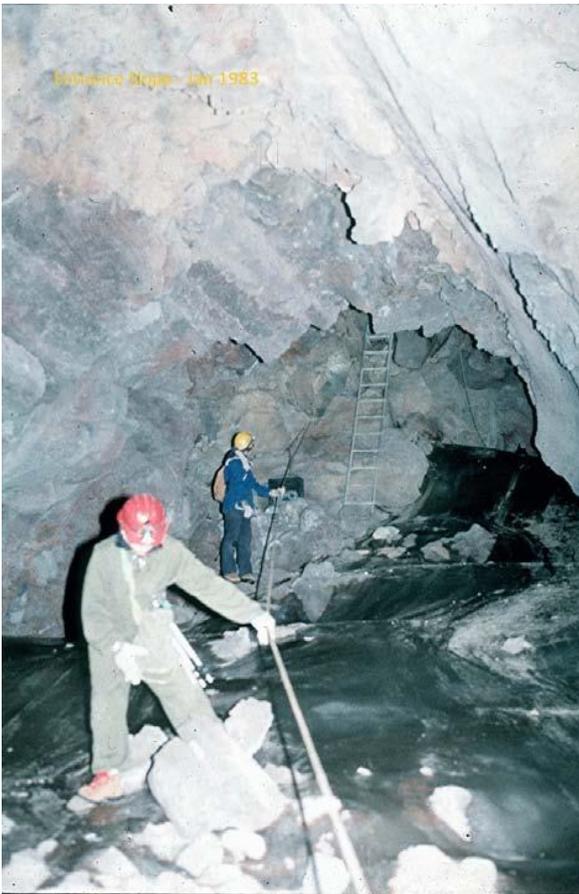
Entry Room Slope



1936

Entrance Room Slope (continued)

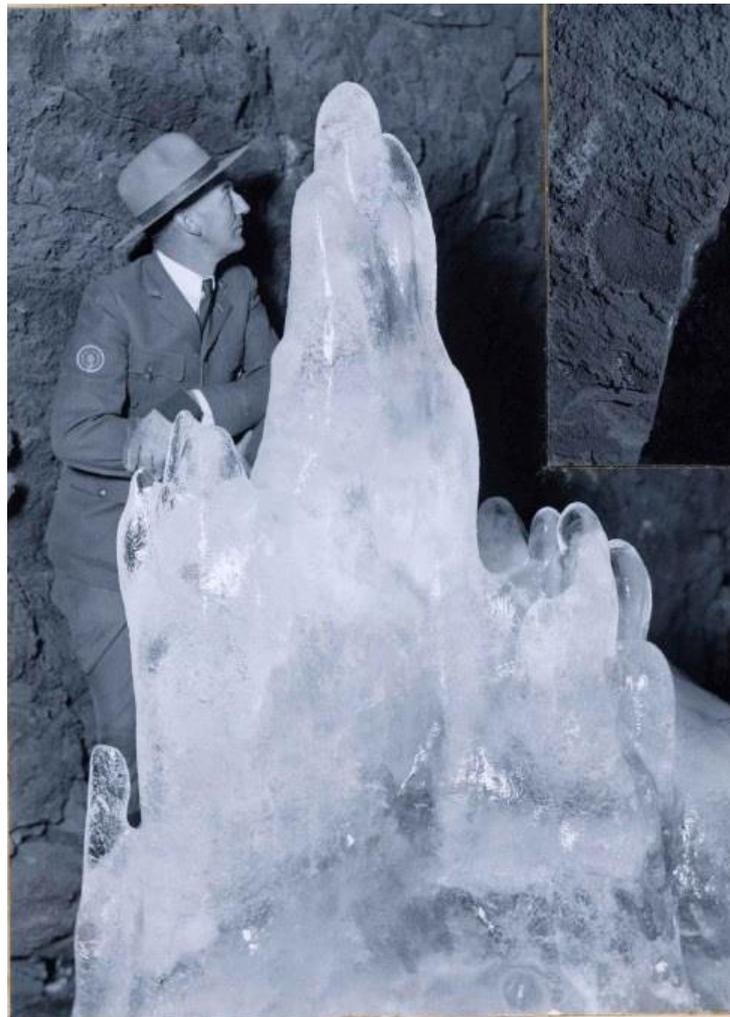
1983





Entrance Room Slope (continued)  
March 2002

Station 5

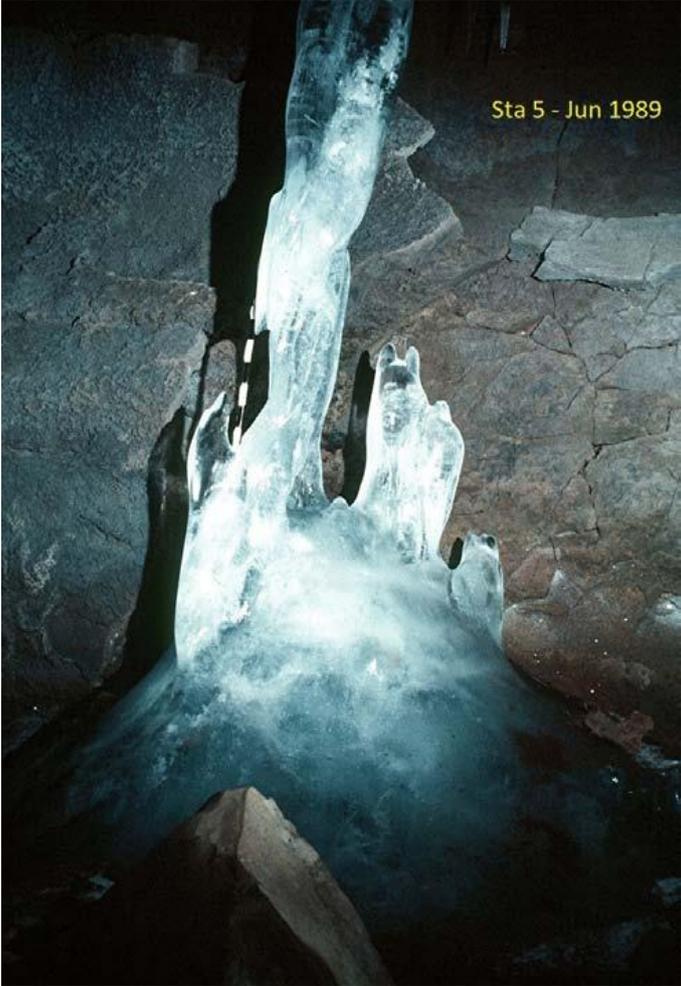


1936

Station 5 (continued)



Station 5 (continued)



Station 5 (continued)



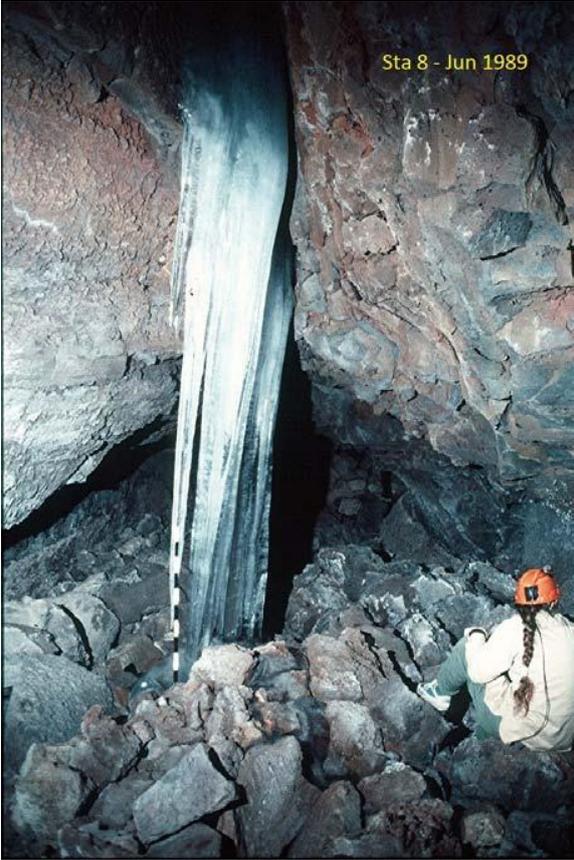
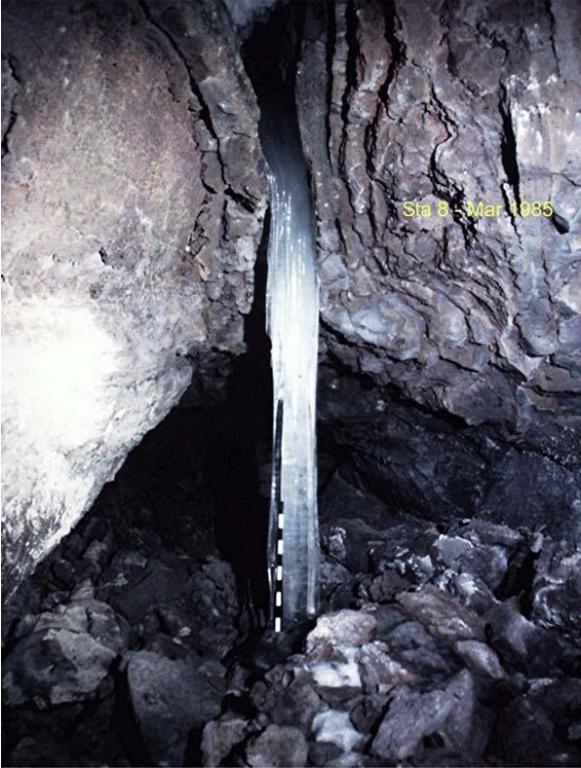
Station 5 (continued)



Station 8



Station 8 (continued)



Station 8 (continued)



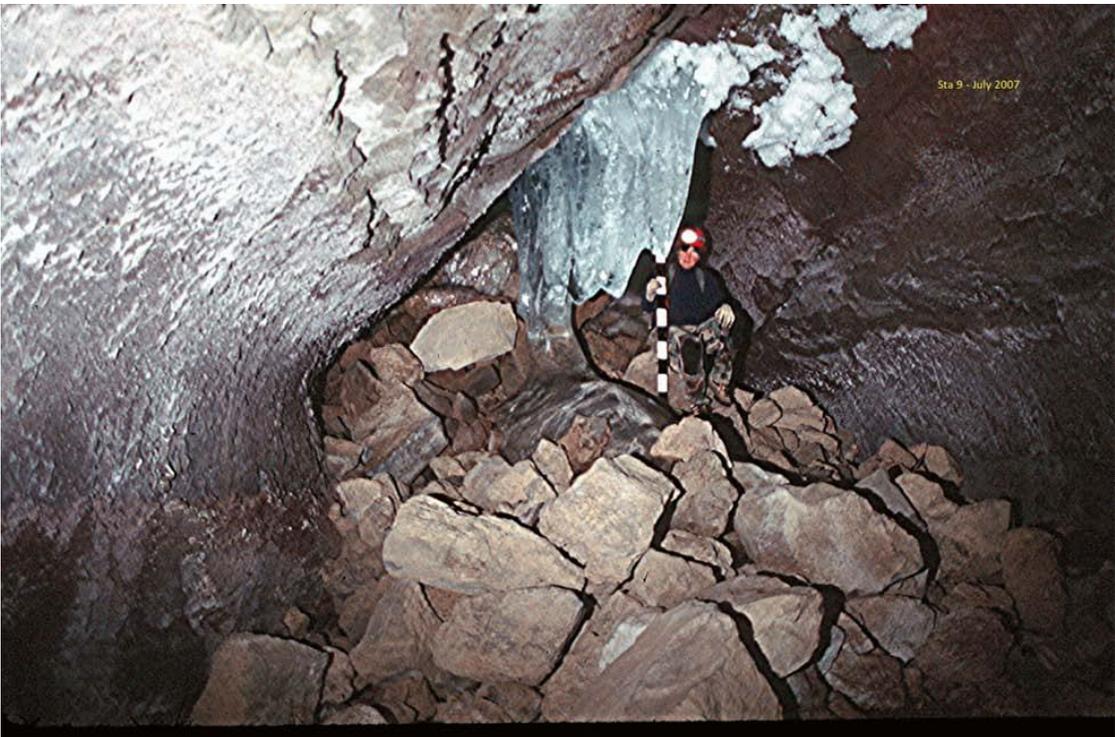
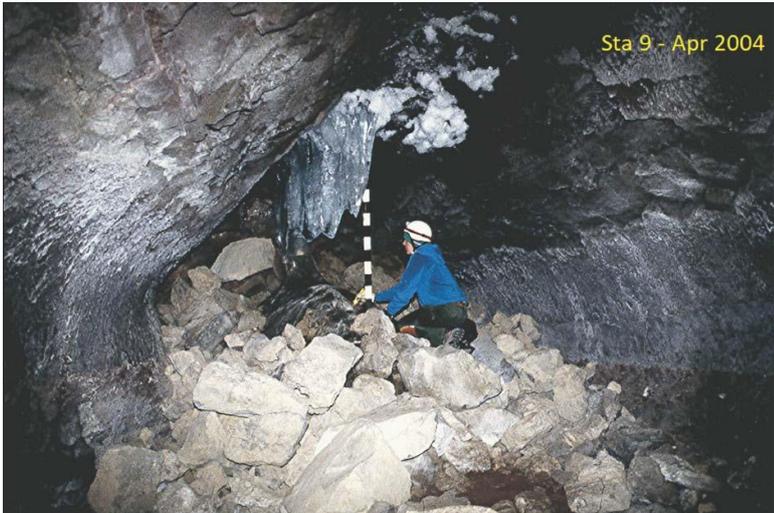
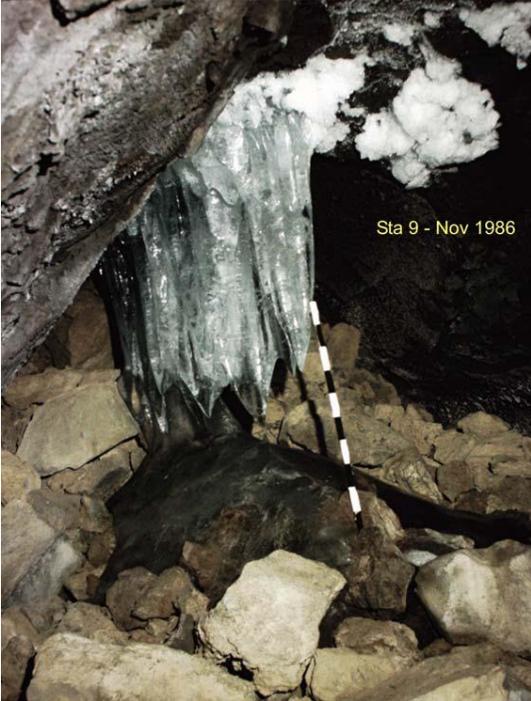
Station 8 (continued)



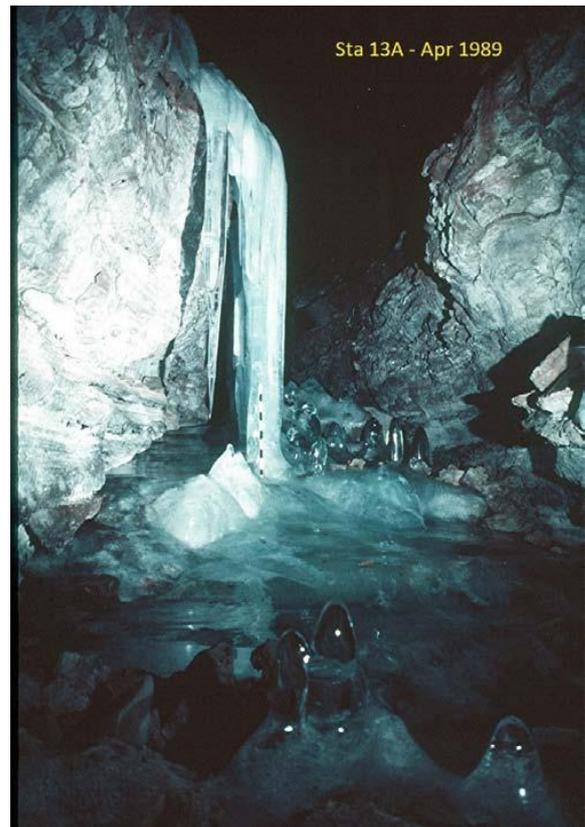
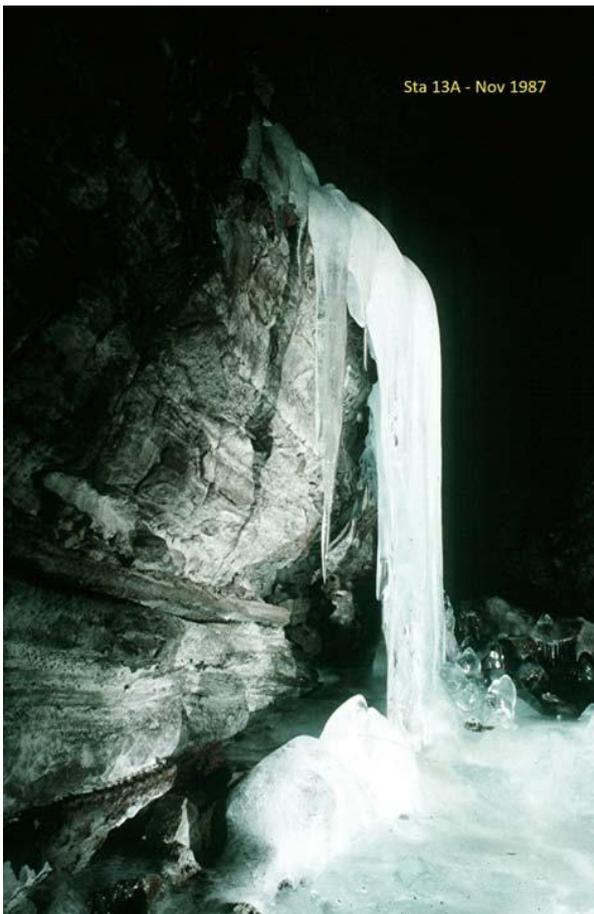
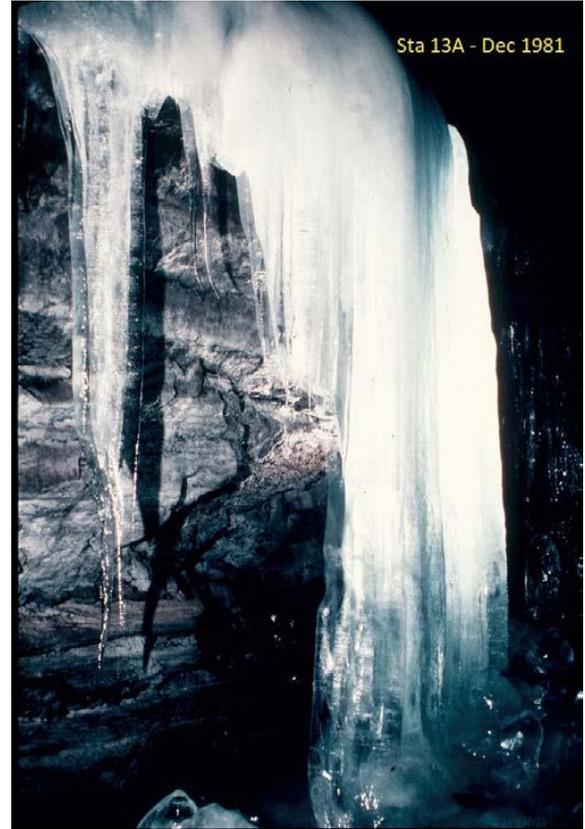
Station 9



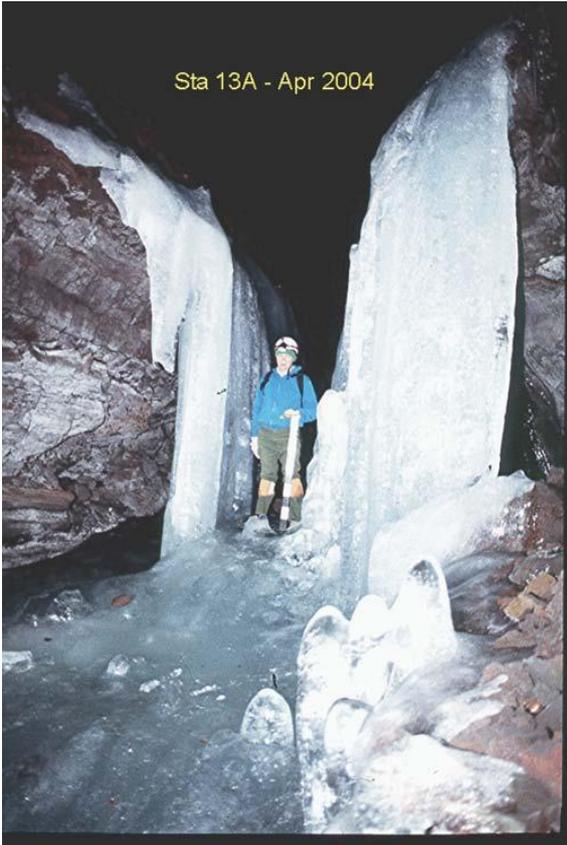
Station 9 (continued)



The Drapery Passage, Station 13a



The Drapery Passage, Station 13a (continued)



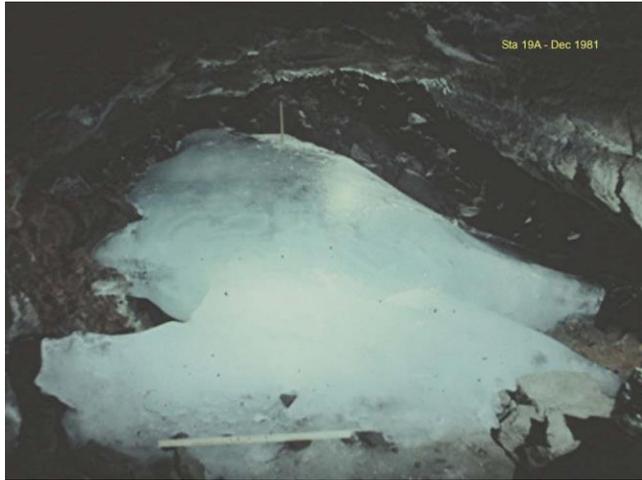
The Drapery Passage, Station 13a (continued)



The Blue Glacier, Station 19a



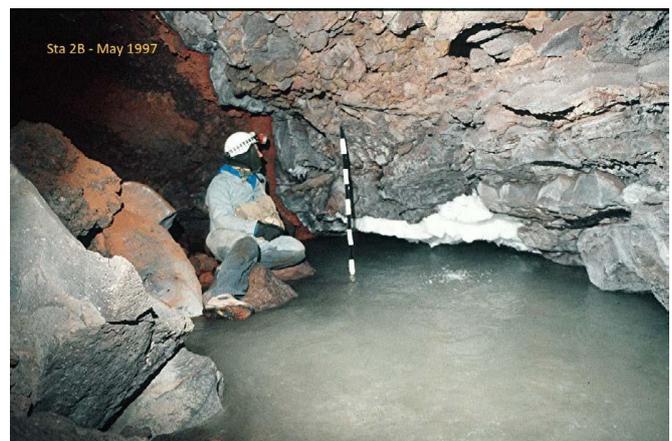
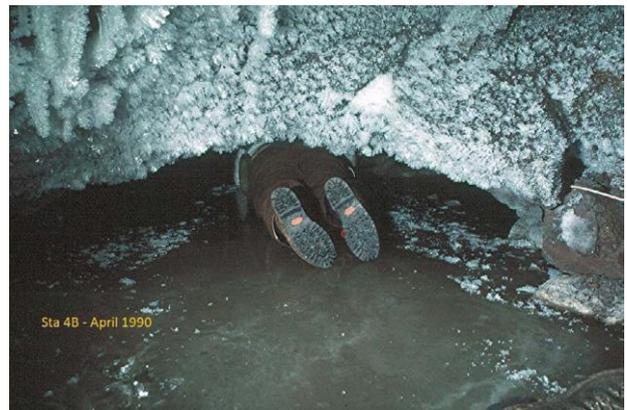
The Blue Glacier, Station 19a (continued)



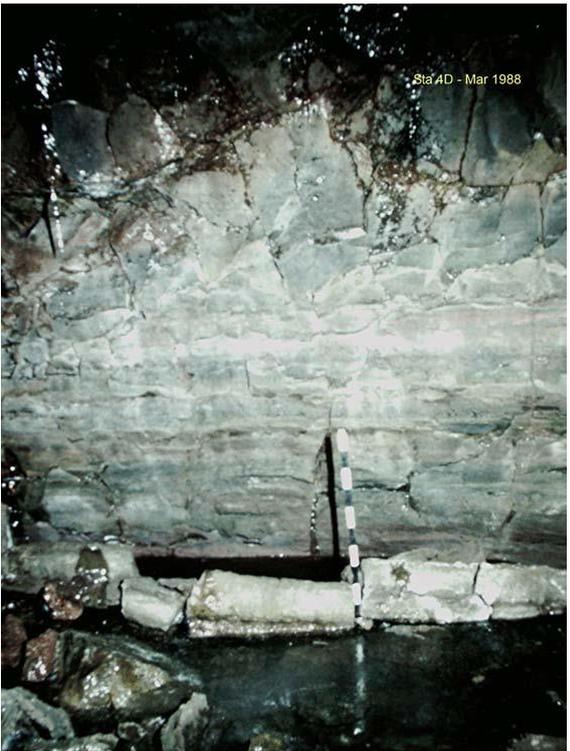
The Blue Glacier, Station 19a (continued)



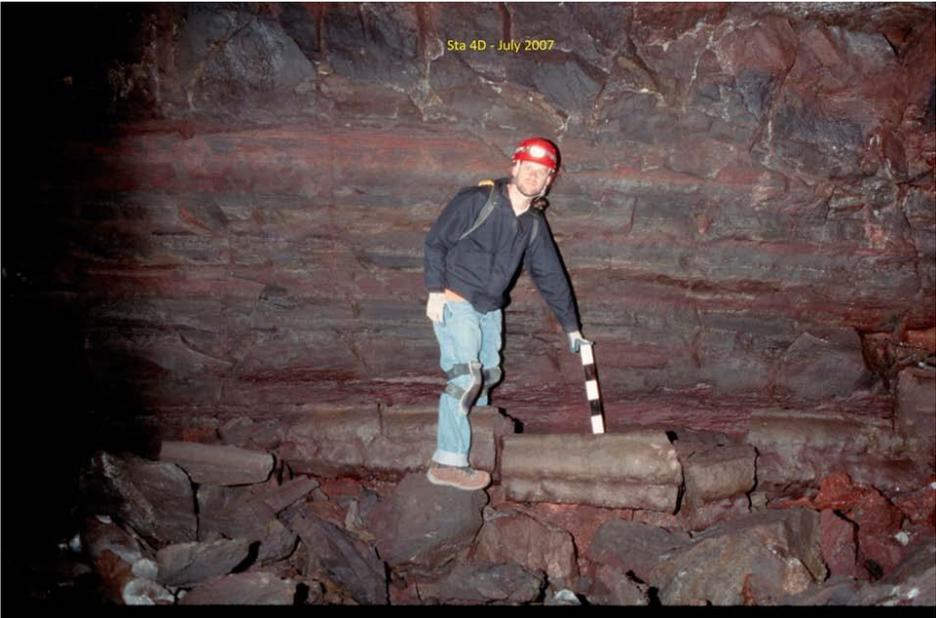
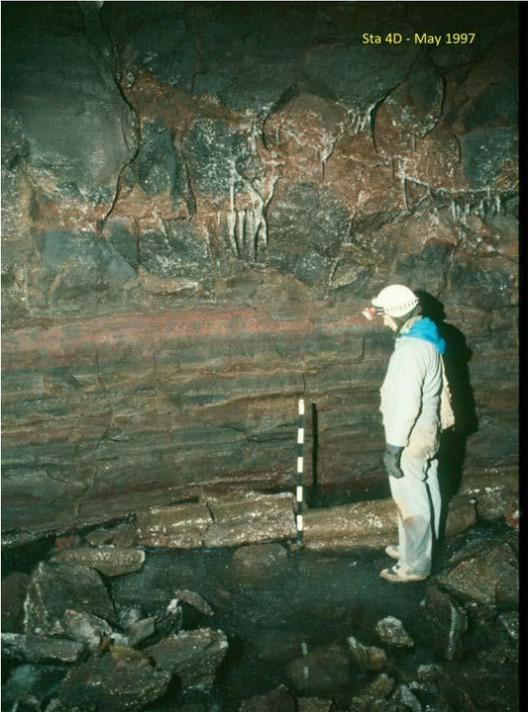
Red Ice Room Entry, Stations 2b and 4b



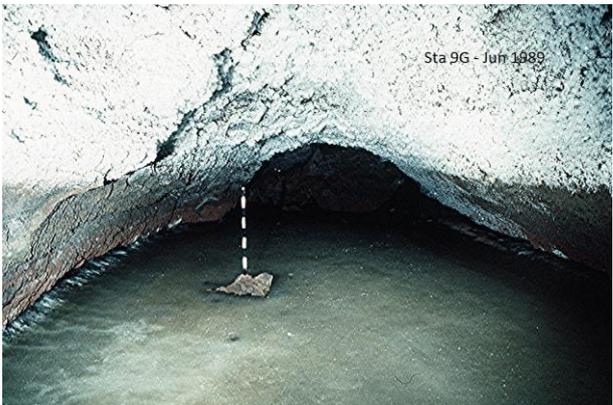
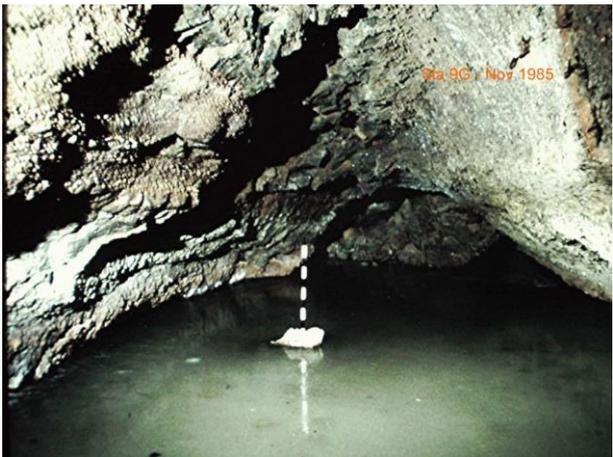
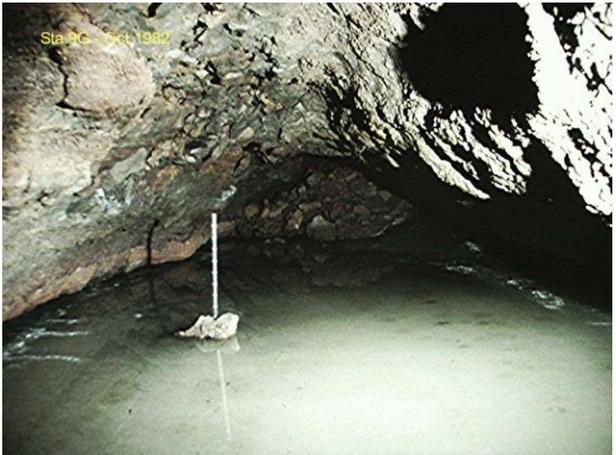
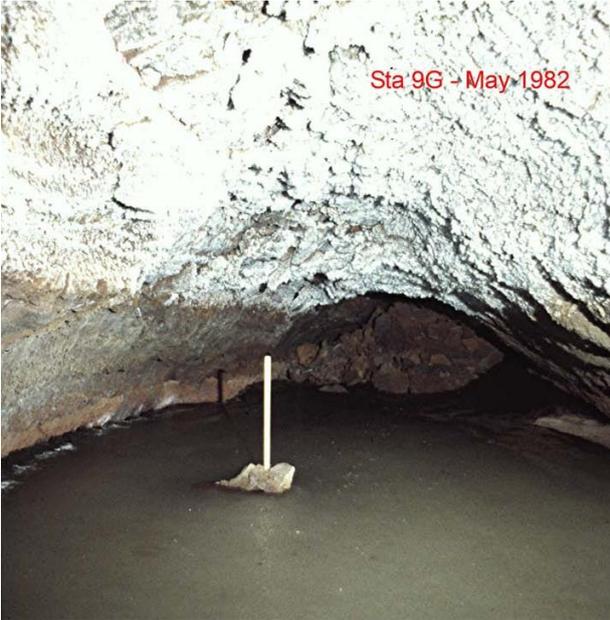
Station 4d



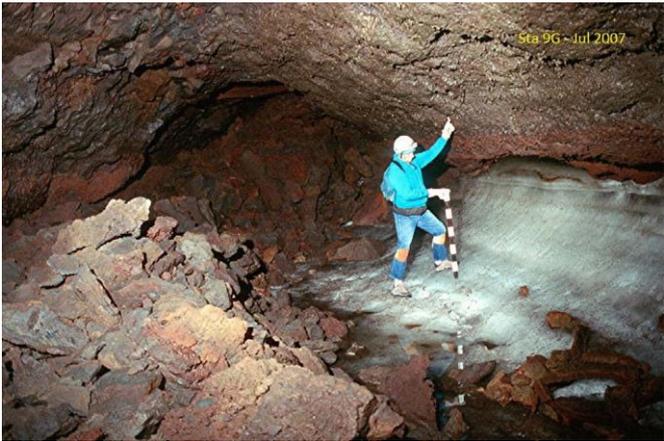
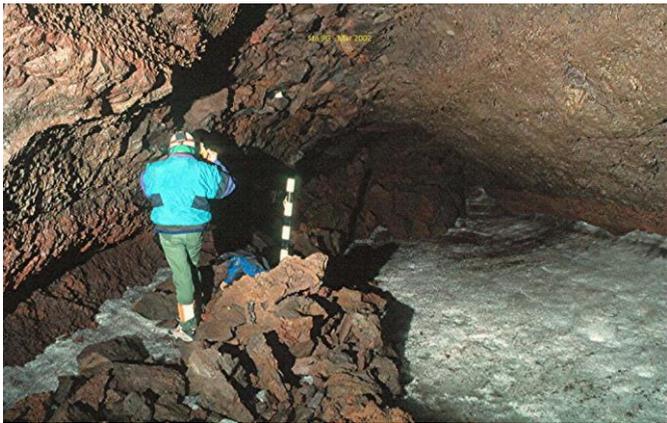
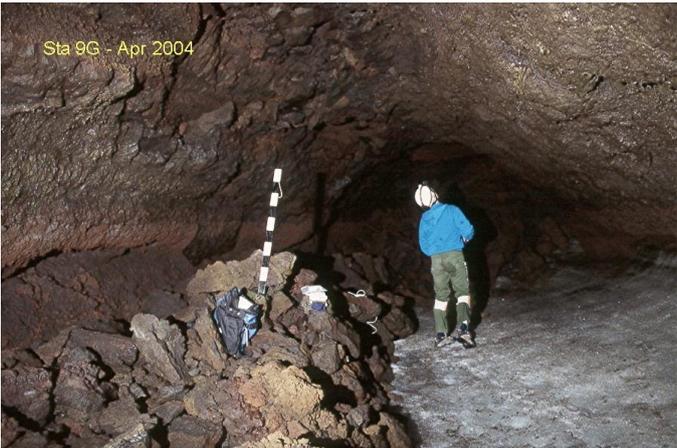
Station 4d (continued)



The Fantasy Passage, Station 9g



The Fantasy Passage, Station 9g (continued)



**Other Caves**

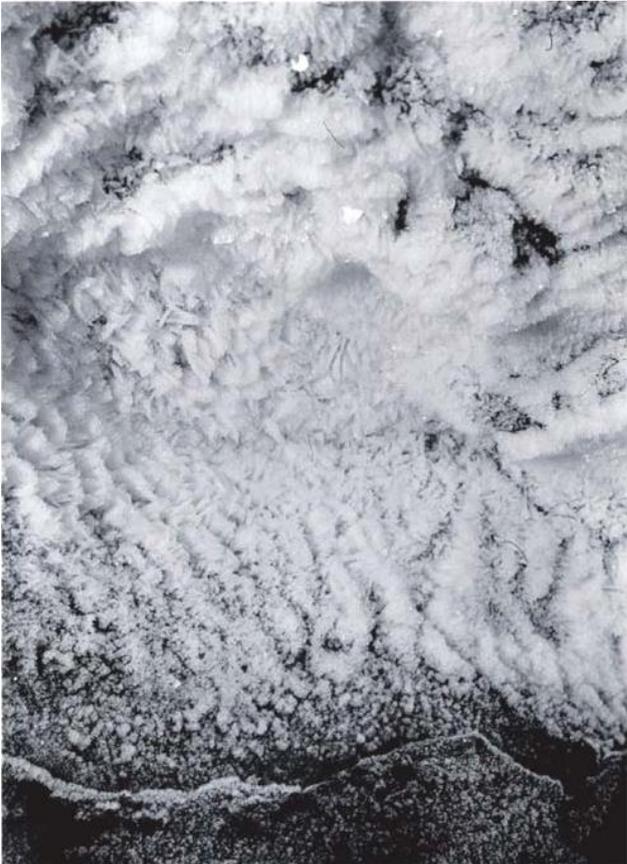
Cox Ice Cave

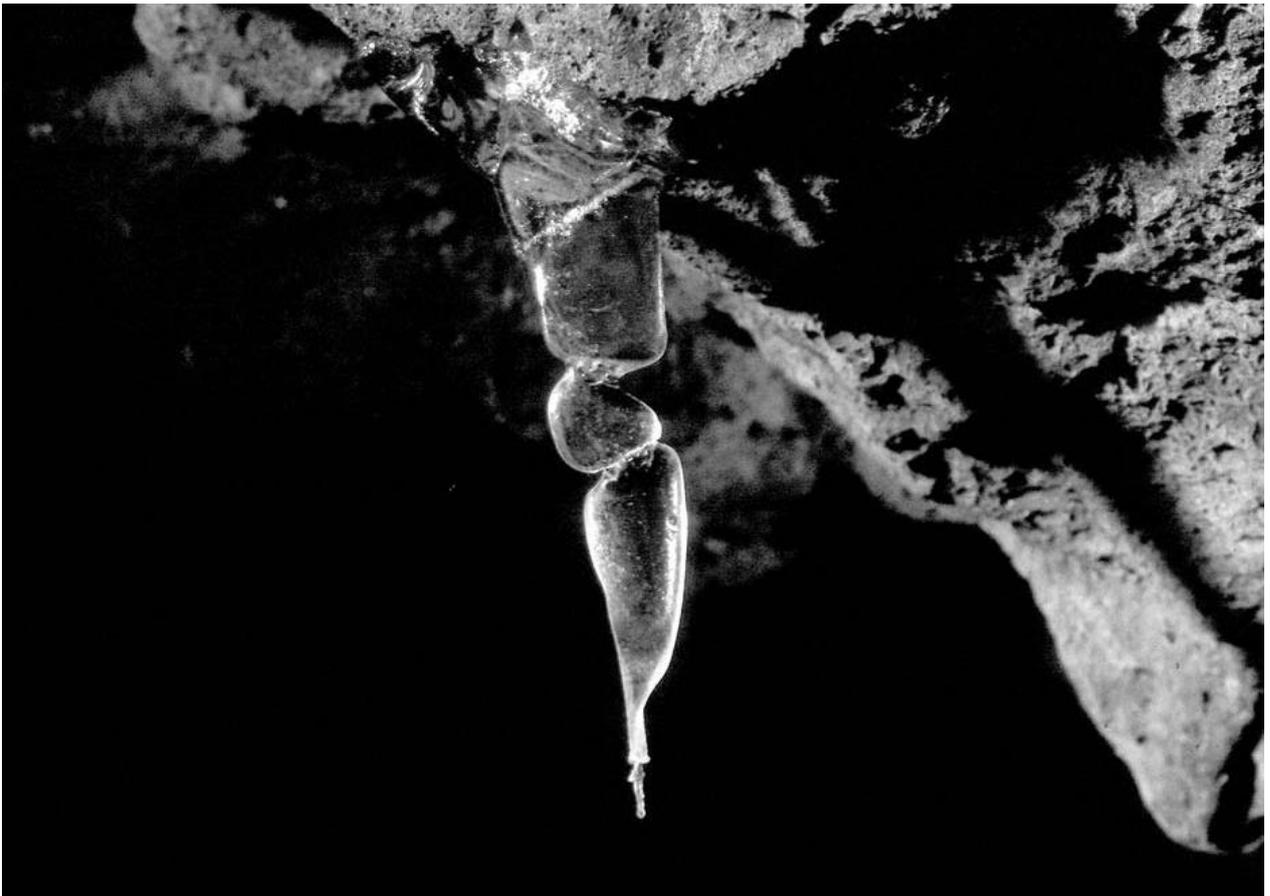
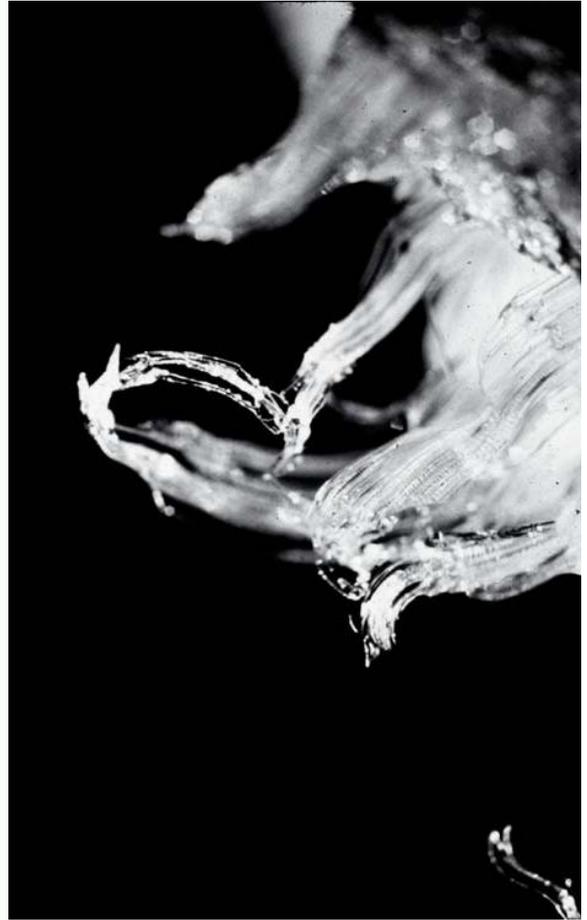


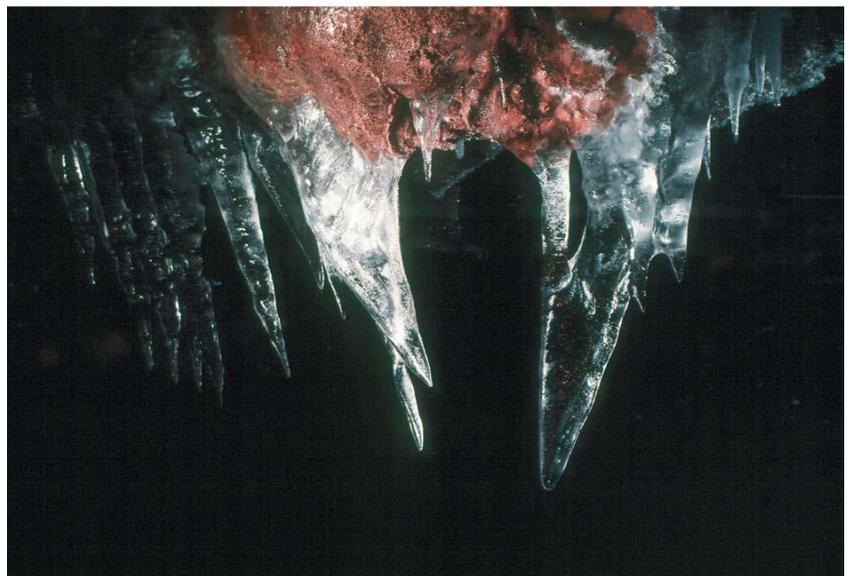
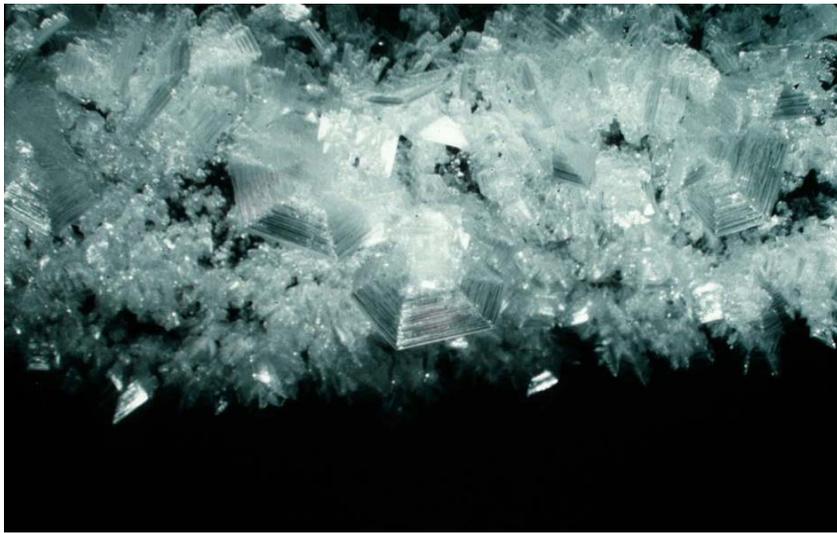
Skull Cave

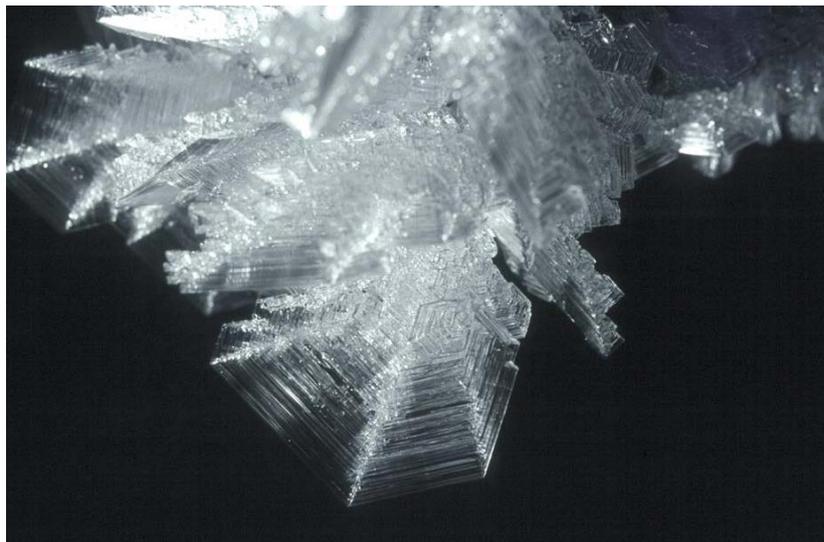
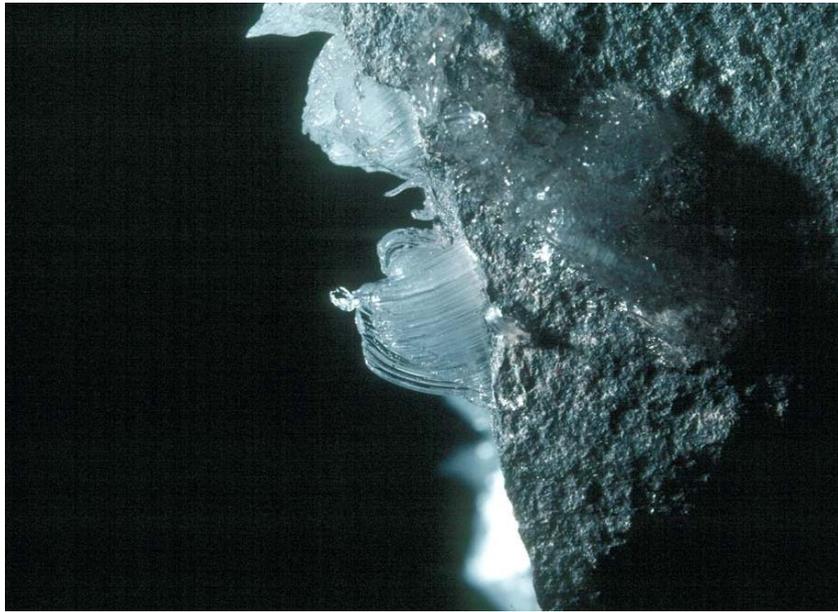


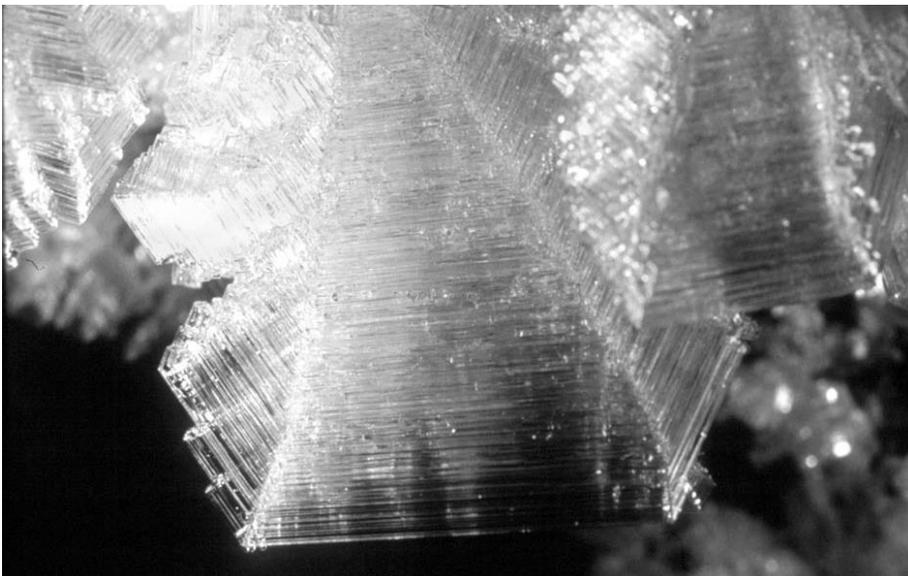
Things that we may never see again





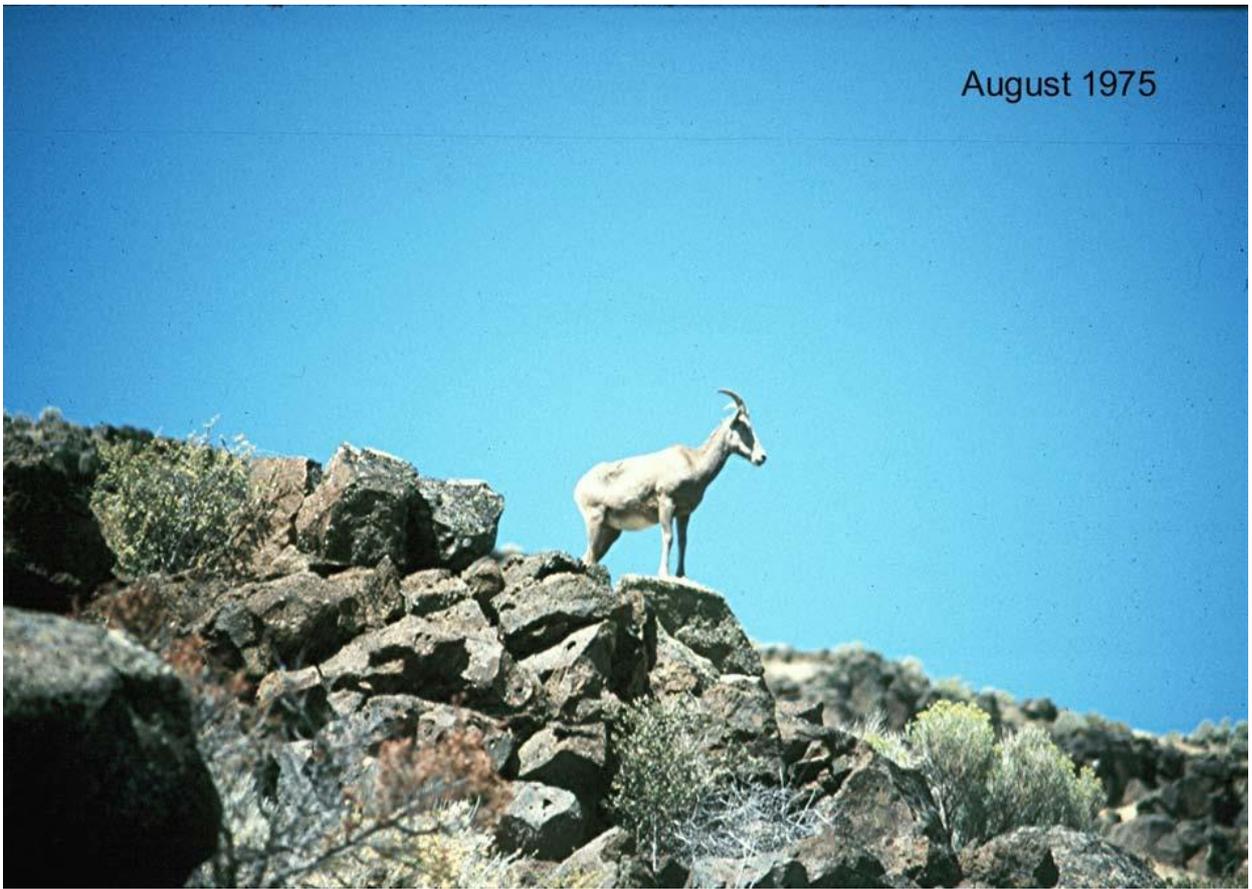




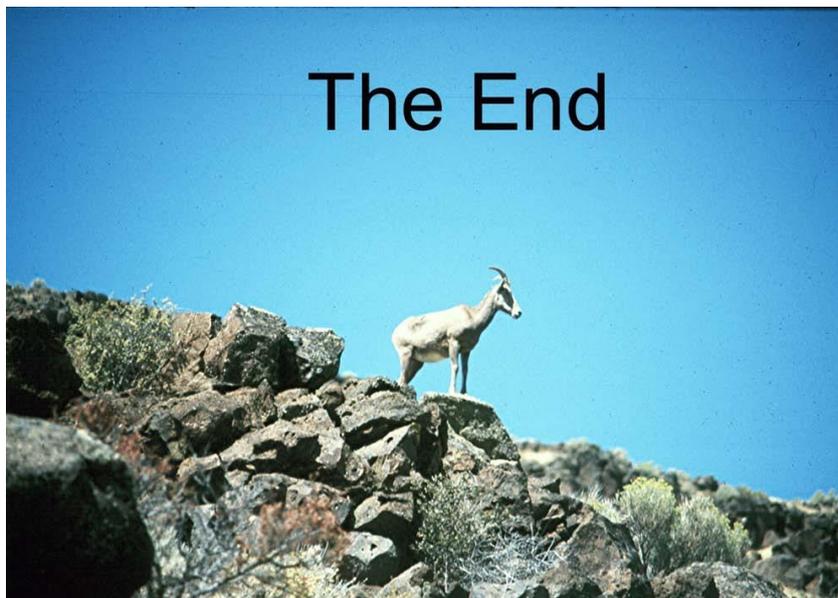




August 1975



The End



## Volcanic Caves of Central Oregon:

Ron Delano

Central Oregon is a predominantly volcanic landscape that presents many classic features of recent volcanic activity including numerous volcanoes of various types and stages, two major calderas and ample evidence of recent lava flows. There are over five hundred known lava caves spread over an extensive area. There are also "erosional piping caves" formed in volcanic ash formations. While lava tubes are common and numerous, these caves rarely exceed one mile in length. In select caves, ice formations form which are quite picturesque. Photographic examples of area caves will be presented.

## Emplacement of the basalt of Mammoth Crater

By Julie Donnelly-Nolan (jdnolan@usgs.gov), John Tinsley (jtinsley@usgs.gov), and Duane Champion (dchamp@usgs.gov), all at USGS, 345 Middlefield Road, Menlo Park CA 94025

The basalt of Mammoth Crater (bmc) covers ~250 km<sup>2</sup> in northern California, USA, including about two-thirds of Lava Beds National Monument, where it hosts most of the park's iconic lava-tube caves. The eruption took place ~35,000 years ago from several vents on the north flank of Medicine Lake volcano, a large shield-shaped composite volcano (Donnelly-Nolan, 2010 geologic map, <https://pubs.usgs.gov/sim/2927/>) located in the southern Cascades rear-arc. Although most of the erupted volume is basalt (<52 wt.% SiO<sub>2</sub>), the unit is compositionally zoned and early vent-related lava has SiO<sub>2</sub> contents as high as 55.9 wt.%. Lava was distributed via lava tubes across a broad E-W area on the lower north flank of the volcano forming a radial pattern reminiscent of the tentacles of an octopus. The vents, aligned N-S to NW-SE, are located at elevations as high as 1600 m (5,300 ft), and fed distal parts of the flow field at elevations <1250 m (4100 ft). The most primitive samples (SiO<sub>2</sub> as low as 48.4 wt.%, MgO as high as 9.61 wt.%) were mostly transported by lava tubes to distal locations. K<sub>2</sub>O contents of the primitive samples are as low as 0.15 wt.%, an order of magnitude lower than the ~1.5 wt.% contents of the high-silica samples. Despite the compositional range of the lavas, most samples contain few visible crystals, thus limiting the ability to map the emplacement sequence in the field. Paleomagnetic sampling of 25 sites yielded a single common direction of magnetization indicating that only decades were likely needed to emplace the full flow field. A similar study of the ~12,500-yr-old basalt of Giant Crater (Donnelly-Nolan et al., JGR, 1991) on the south flank of the volcano revealed a less common remanent magnetic direction showing a small angular variation (Champion and Donnelly-Nolan, JGR, 1994) indicating as little as a decade for emplacement of that 200-km<sup>2</sup> lava field. In the Giant Crater case, higher silica lavas also built the vent area and lower-silica lava with high MgO contents was transported to distal areas by lava tube, but the lavas displayed petrographic variation and were emplaced one lobe atop another in a graben allowing for direct stratigraphic control of the compositional variation through time.

The recent discovery of a major lava-tube cave at the south margin of Lava Beds National Monument has led to new chemical sampling in that cave and in other caves, as well as collection and analysis of new samples at the primary vent where late stage magma withdrawal created the 100-m-deep Mammoth Crater. Seventy chemical analyses allow characterization of the compositions present along each of the major lava tube systems. Together with a few stratigraphic relations derived from fieldwork and from air photo analysis, we propose an eruptive sequence. Initially, a small shield built at the location of Mammoth Crater and adjacent vents to the north. Surface flows extended to the NW and west and a lava tube formed on the east side of the shield and carried lava eastward through what is now the enlarged channel of Hidden Valley. Lava thence flowed through the new cave, and east as far as ~20 km from vent, but never having SiO<sub>2</sub> contents lower than 51 wt.%. The distal flow field produced by this lava tube is overlain by much more primitive lava from the tube system that

runs through the Visitor Center area, east through Craig Cave, and then NE ~25 km from the vent. A sample recently collected from a solid outcrop on the NE wall of Mammoth Crater has the low-SiO<sub>2</sub>, high-MgO composition of the distal NE lavas. Farther to the north, vents opened at and near Modoc Crater and fed lava tubes northward, with one set on the west side of the earlier Schonchin Flow, and another including Skull Cave around the east side. Compositional data indicate that the samples from these lava tubes have higher TiO<sub>2</sub> contents than those from the southern tube and from the Visitor Center-Craig Cave tube. Air photos indicate that lava associated with the Skull Cave tube is younger than lava from the Visitor Center tube. Another compositionally distinctive lobe was fed to the west from Mammoth Crater through Upper Ice Cave. This high-FeO, high-TiO<sub>2</sub> lobe is partially buried by younger lava flows, but can be traced ~20 km to the NW. The much higher FeO content (~1.3-1.5 wt.%) relative to the other erupted lavas (~0.9-1.1 wt.%) suggests a higher density, possibly indicating that this lobe might be the last-erupted from the subjacent magma reservoir.

# Estimation of the yield strength and lava flows structure of Mt.Fuji by lava tube cave height and lava tree mold depth

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[mer4beau939tha@gmail.com](mailto:mer4beau939tha@gmail.com)

## Abstract:

Many lava tube caves and lava tree molds exist in the lava flows of Mt. Fuji. Lava tube cave and lava tree mold coexists in Suyama Tainai lava flow, Ganno-Ana lava flow and Aokigahara lava flow.. Only lava tube cave exists in Subashiri-guchi lava flow located in the high altitude. Only lava tree mold exists in relatively thin lava flow such as Takamarubi lava flow, Higashisuzuka-South lava flow, Ohbuchi marubi lava flow, Kenmarubi I and Kenmarubi II lava flows. By using Bingham flow model, the yield strength of the Mt. Fuji lava flows was estimated from the hollow height of the lava tube cave and the depth of the lava tree mold, and compared each other. Then, the lava flow structure of these Mt.Fuji's is also discussed based on the apparent difference of these yield strength.

The lava flow is modeled by Bingham fluid flowing on the inclined plane or in the inclined cylindrical pipe with gravity potential. For the lava flow of density  $\rho$ , and yield strength  $f_B$ , with slope angle  $\alpha$ , under the gravity  $g$ , the lava flow critical(stop) condition is  $H=n f_B / (\rho g \sin \alpha)$  where  $H$  is the lava thickness.

The case of lava which flows on the incline plane with a free surface is  $n=1$ , and the case of lava which flows through an inclined circular tube is  $n=4$ . The yield strength is obtained from  $f_B = H_c (\rho g \sin \alpha) / 4$ , for  $n=4$ , where  $H_c$  is the lava tube cave height, and from  $f_B = H_t (\rho g \sin \alpha)$  for  $n=1$ , where  $H_t$  is lava thickness(depth of tree mold).

The followings are conclusions from the results, (1) The yield strength obtained from the lava flow thickness (the depth of the tree mold) is an apparent yield strength, because the lava flow has caused inflation and repeated accumulation of lava. (2) The minimum yield strength can be obtained from the thickness of the toe or the lobe in the front edge of lava flow. (3) The true yield strength of lava can be obtained from the hollow height of the lava tube cave. (4) The lava tube cave can be formed when a lava flow caused an increase of the thickness more than 4 times of the simple flow due to inflation of lava.

## 1.Introduction

Many lava tube caves and lava tree molds exist in lava flows of Mt. Fuji. Lava tube cave and lava tree mold coexists in Suyama Tainai lava flow , Ganno-Ana lava flow and Aokigahara lava flow.. Only lava tube cave exists in Subashiri-guchi lava flow located in the high altitude. Only lava tree mold exists in relatively thin lava flow such as Takamarubi lava flow, Higashiusuzuka-South lava flow, Ohbuchimarubi lava flow, Kenmarubi I and Kenmarubi II lava flows. The yield strength of the Mt. Fuji lava flows was estimated from the hollow height of the lava tube cave and the depth of the lava tree mold and compared each other by using Bingham flow model. The lava flow structure of these Mt.Fuji is also discussed based on the difference of these yield strength. A considered model for lava tree mold is shown in Fig.1, and used model for lava tube cave is shown in Fig.2.

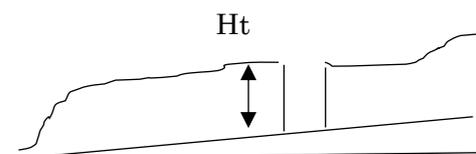


Fig.1 Lava tree mold and lava depth  $H_t$ ,  
Apparent yield strength  $f_B = H_t(\rho g \sin \alpha)$

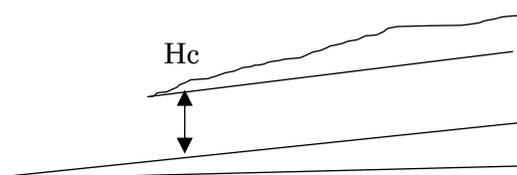


Fig2 Lava tube cave and cave height  $H_c$ ,  
Yield strength  $f_B = H_c(\rho g \sin \alpha) / 4$

## 2.Considered hydrodynamic model

The lava flow is modeled by Bingham fluid flowing on the inclined plane or in the inclined

cylindrical pipe with gravity potential(see Fig.3). For the lava flow of density  $\rho$ , and yield strength  $f_B$ , with slope angle  $\alpha$ , 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 of lava which flows on the incline plane with a free surface is  $n=1$ (see Fig.4)), and the case of lava which flows through an inclined circular tube is  $n=4$ (see Fig.5). The yield strength is obtained from  $f_B=H(\rho g \sin \alpha)$  for  $n=1$ , for free surface flow where  $H$  is lava thickness(depth of tree mold), from  $f_B =H(\rho g \sin \alpha)/4$ ,for  $n=4$ , where  $H$  is the lava tube cave height, for circular tube<sup>1)</sup>.

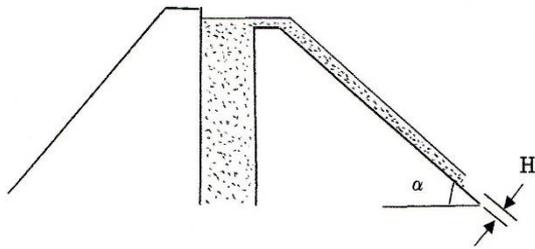


Fig.3 The lava flowing on the inclined plane or in the inclined cylindrical pipe with gravity potential

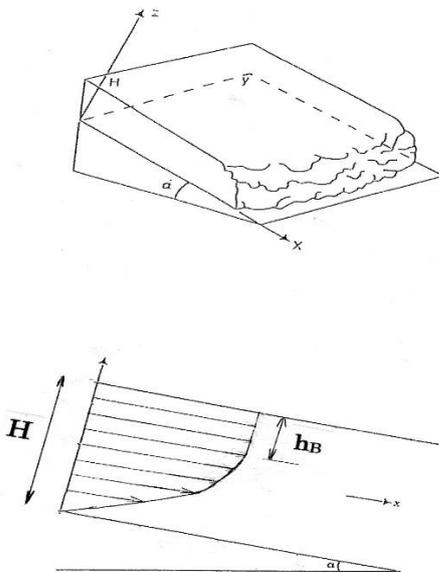


Fig.4 Lava flow on the incline plane with a free surface( $n=1$ )

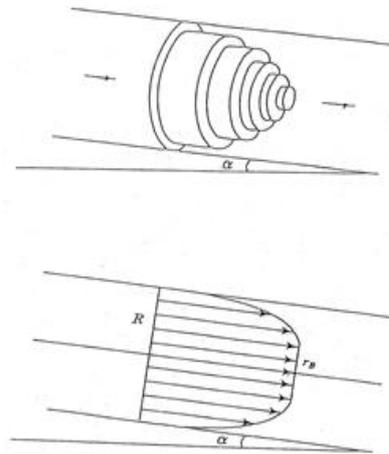


Fig.5 Lava flow through an inclined circular tube( $n=4$ )

### 3.Estimation of the apparent yield strength by the lava flow thickness (the tree mold depth)

The yield strength  $f_{Bt} = H_t(\rho g \sin \alpha)$  is estimated from the lava flow stop condition of the free surface of lava flow of lava depth  $H_t$  which is equivalent of the depth of lava tree mold. Slope angle  $\alpha$  is estimated from a contour line of the map. Some examples of lava tree mold depth and apparent yield strength together with photo and figures are shown for following several lava flows

#### [Suyama tainai lava flow]<sup>2)</sup>

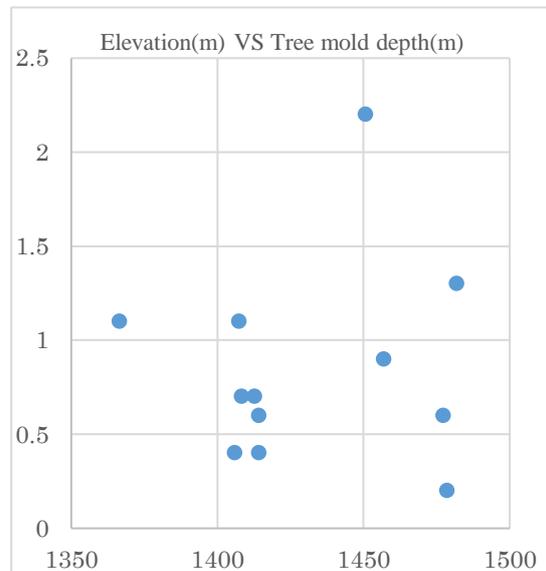


Fig.6 Lava tree mold depth of Suyama tainai



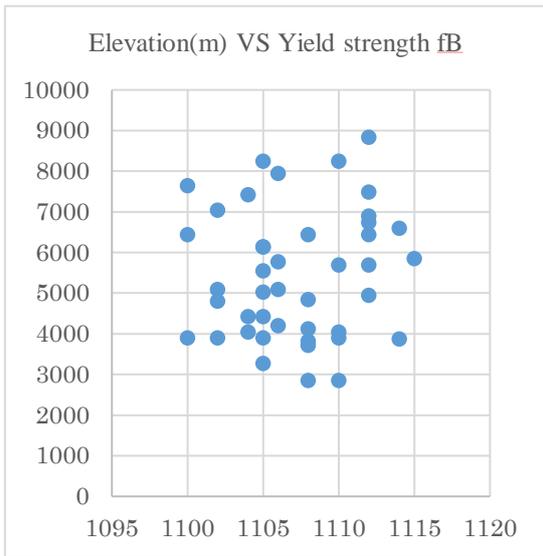


Fig.13 Yield strength of Takamarubi lava flow

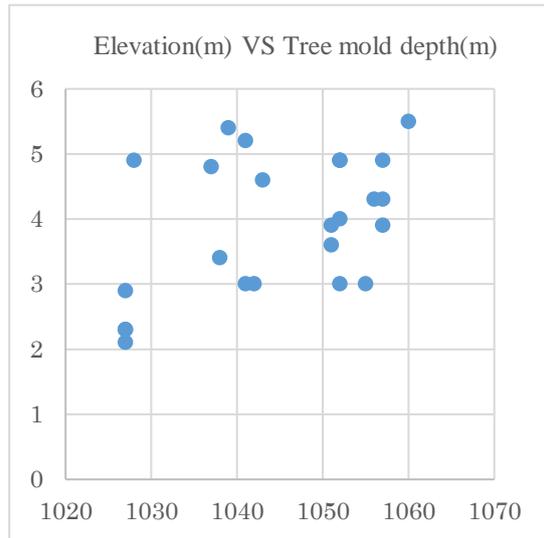


Fig.15 Lava tree mold depth of Kenmarubi-I

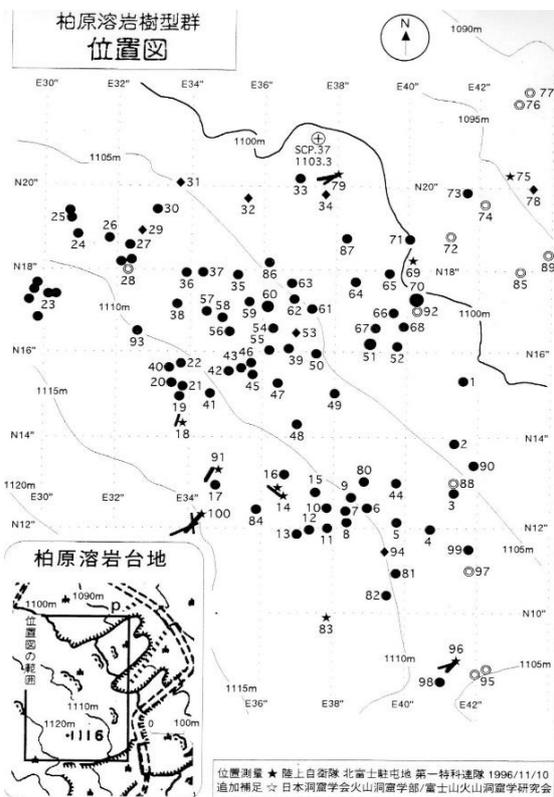


Fig.14 Lava tree mold distribution in the lower edge of Takamarubi lava flow.

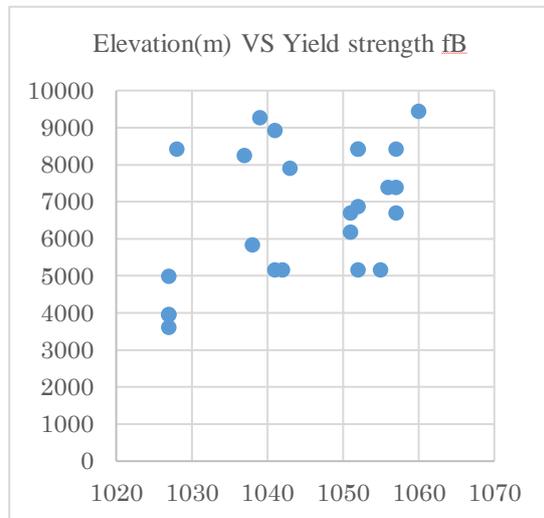


Fig.16 Yield strength of Kenmarubi-I

[Ohbuchi marubi lava flow]<sup>8)</sup>



Fig.17 Large tree mold of Ohbunchimarubi

[Kenmarubi-I lava flow]<sup>6,7)</sup>





Fig.21 Inside of Suyama tainai cave



Fig.22 Entrance of Suyama tainai cave

### 5.Summary

(1) The yield strength obtained from the lava flow thickness (the depth of the tree mold) is an apparent yield strength, because the lava flow has caused inflation and repeated accumulation of lava. (2) The minimum yield strength can be obtained from the thickness of the toe or the lobe in the front edge of lava flow. (3) The true yield strength of lava can be obtained from the hollow height of the lava tube cave. (4) The lava tube

cave can be formed when a lava flow caused an increase of the thickness more than 4 times due to inflation of lava.

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Table.1 Estimation of the yield strength of Mt.Fuji lava by lava tube caves height and lava tree mold depth

Name of lava flow	SiO <sub>2</sub> Wt %	Slope angle: $\alpha$	Height of lava tube cave : H <sub>c</sub>	Yield strength obtained from H <sub>c</sub> : $f_B = H_c(\rho g \sin\alpha)/4$	Depth of lava tree mold : H <sub>t</sub>	Apparent yield strength obtained from H <sub>t</sub> : $f_B = H_t(\rho g \sin\alpha)$
Suyamatainai	51.4	10 °	1.0m~1.8m (Subashiritainai cave)	1.1x10 <sup>3</sup> ~1.9x10 <sup>3</sup> N/m <sup>2</sup>	0.2m~2.2m	9.4x10 <sup>2</sup> ~9.4x10 <sup>3</sup> N/m <sup>2</sup>
Gannoana	51.1	5 °	1.5m~2.0m (Nagara Ana cave)	0.8x10 <sup>3</sup> ~1.1x10 <sup>3</sup> N/m <sup>2</sup>	1.8m~5.4m	3.8x10 <sup>3</sup> ~1.2x10 <sup>4</sup> N/m <sup>2</sup>
Aokigahara	51.3	3°~10°	2m~10m(Karunizu cave,etc.,)	1.6x10 <sup>3</sup> ~3.8x10 <sup>3</sup> N/m <sup>2</sup>	3.3m~5.3m	8.0x10 <sup>3</sup> ~1.3x10 <sup>4</sup> N/m <sup>2</sup>
Subashiriguchi	50.9	20° 15°	1m 2m (Subashiritainai cave)	2.1x10 <sup>3</sup> N/m <sup>2</sup> 3.2 x10 <sup>3</sup> N/m <sup>2</sup>	No lava tree molds	—
Takamarubi	50.9	3.5 °	No lava tube caves	—	1.9m~5.9m	2.8 x10 <sup>3</sup> ~8.8 x10 <sup>3</sup> N/m <sup>2</sup>
Higashiusuzukaminami	51	9°	No lava tube caves	—	1m~2m	3.8x10 <sup>3</sup> ~7.6x10 <sup>3</sup> N/m <sup>2</sup>
Kenmarubi-I	51.1	4°	No lava tube caves	—	2.1m~5.5m	3.6x10 <sup>3</sup> ~9.3x10 <sup>3</sup> N/m <sup>2</sup>
Kenmarubi-II	51.2	4 °	No lava tube caves	—	2m~6m	3.4x10 <sup>3</sup> ~10.1x10 <sup>3</sup> N/m <sup>2</sup>
Oobuchimarubi	51.2	7.7°	No lava tube caves	-	0.4m~5m	1.3x10 <sup>3</sup> ~1.65x10 <sup>4</sup> N/m <sup>2</sup>

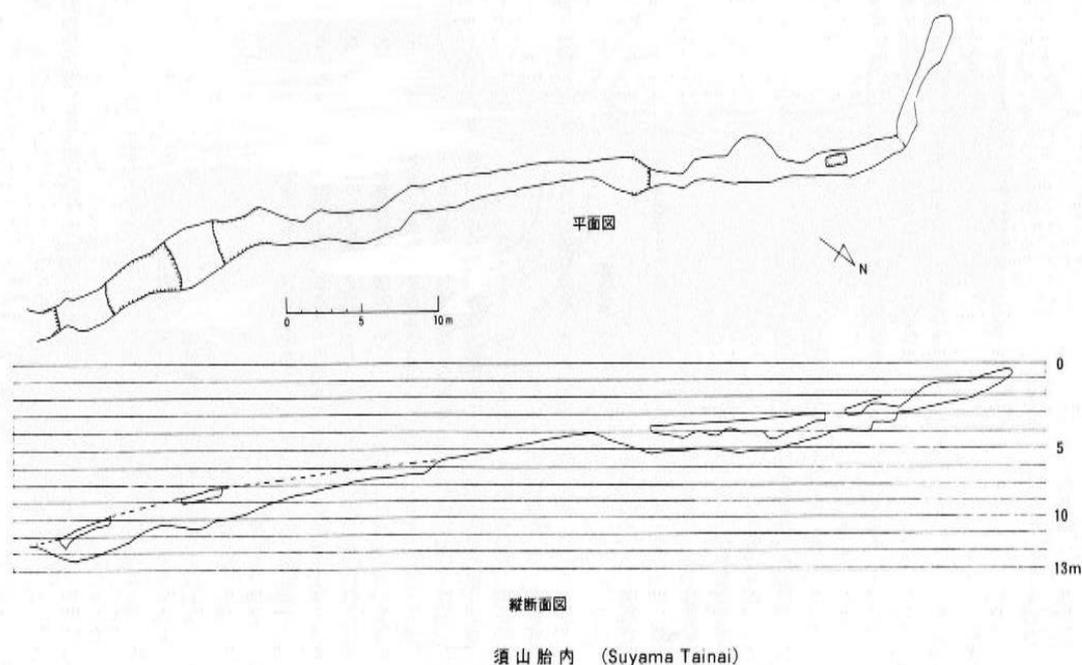


Fig.23 Lava tube cave of Suyama tainai lava flow

## IMPACTS OF INDIRECT AND DIRECT VISITATION ON MICROBIAL COMMUNITIES FROM LAVA CAVES IN LAVA BEDS NATIONAL MONUMENT, USA.

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### **Abstract**

We compared indirect and direct impacts of human activity on bacterial diversity of overlying soils to microbial mats in lava caves in Lava Beds National Monument. We worked with LABE personnel to select seven lava caves to cover a range of parameters including the extent of human visitation. Bacterial communities are distinctly different between surface soils and caves, with only an 11.2% overlap, showing that the bacteria in the cave are not simply a subset of surface microbes infiltrating into the cave. There was little evidence of direct human impact in LABE caves. Two microbial mat samples with probable direct human impacts were distinctly different from the surface soil and microbial mat communities, and from each other. Bacteria usually associated with humans were very limited; only one *Staphylococcus* and *Streptococcus*, and 25 *Enterbacteriaceae* detected from any LABE cave or surface sample. Indirect effects of human visitation showed minimal differences in mat community richness among caves. Our high visitation (about 30,000 people a year) and low visitation (up to 10 visitors some years) caves are comparable in terms of alpha diversity and show no major differences in microbial community structure. In contrast, in Carlsbad Cavern, a karst cave, with over 400,000 visitors per year, studies showed differences in bacteria and fungi on and off the tourist trails. There was a general decrease with distance from the entrance, but with a peak in the Lunchroom where visitors rest,

eat, and wait for the elevator to return to the surface. The authors concluded that humans were important sources of non-indigenous microorganisms into Carlsbad Cavern, and recommended mitigation steps. What we may be seeing is a threshold of visitors before we see indirect human impacts; finding the threshold merits further study.

## **Lava tube mineralogy, Medicine Lake Volcano, California**

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PO Box 230  
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Medicine Lake Volcano is located in northeastern California at an elevation of about 2680 m. It is the largest Cascadian volcano in volume. Lavas ranging from 2Ma to about 900 years old carpet the volcano. Within Lava Beds National Monument, the Basalt of Mammoth Crater (~36,000 ybp) and the Valentine Flow (~12,500 ybp) are the two major lava tube flows. The 12,500-year old Giant Crater flow and Burnt Lava Flow (2,950 ybp) on the southern side of the volcano are also a major lava tube producing flow.

Seventeen cave minerals and mineraloids present include ice, calcite, barite, gypsum, cristobalite, opal-a', "amorphous" silica, quartz, silhydrite, "basalt," "andesitic basalt," pyrolucite, romanechite, two very unstable, undescribed hydrous sodium sulfite and hydrous sodium sulfo-carbonate salts, plus uric acid and amberat. The ice is seasonally frozen ground and seepage rainwater. The calcite was derived primarily from adjacent seasonally dry, high calcium lake sediments. The sulfates were derived from volcanic sulfur deposits combining with adjacent dry lake sediments. Most of the silicate minerals origin is solution of unstable pumice and ash carpeting the volcano and subsequent rapid evaporation of modestly saturated groundwater. The romanechite and pyrolucite apparently is derived from limited solution of iron-manganese-bearing basalts. The uric acid and amberat are byproducts of woodrats.

Speleothems include stalactites, draperies, spathites, helictites, stalagmites, flowstone, moonmilk, coralloids, crusts, and conulites. The lava speleothem-like decorations may be either primary and contemporary with tube formation or secondary from a re-melt episode.

# Moon and Mars habitation in lava tubes: The first explorers will be cave men again. Stefánshellir test site in Iceland

**Martin Gasser** and Michael  
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**4th Planet Logistics (4PL)** is establishing a lava tube test site for expeditions to the Moon and Mars. The cave, called Stefánshellir, is situated in western Iceland, in the Hallmundarhraun lava field, (figure 1).

The project focuses on the development needed to establish facilities on the Moon and Mars, utilizing naturally occurring lava tubes which will serve as habitable zones for human exploration (figure 2). The cave will provide a development test site suitable for work with robots, materials, equipment and inflatable habitats with the aim of providing key data for future human missions to the Moon and Mars.



Figure 1: Inside Stefánshellir lava tube, West Iceland.  
Credits Björn Hróarsson.

Lava tubes offer future explorers a way to greatly reduce the time, resources and effort needed to initially construct safe and practical habitats and other pressurized support facilities such as greenhouses and maintenance enclosures.

Lava tubes will protect these explorers from harmful radiation, extreme temperature changes and deadly meteorites. Besides that, vestigial or fossil life forms on Mars will most likely be found in caves.

Iceland has been selected for this development test site as it has many parallels to the Moon and Mars, including a barren landscape, rocky soils, limited accessibility, and naturally stable lava tubes.

Thanks to an international team of experts in logistics, geology, engineering and expedition planning, as well as a broad network within the country and to the exclusive right to access a major lava tube, 4PL is also able to assist and support projects of various kinds and magnitude proposed by third parties.

Moreover, 4PL focuses on educational outreach programs supporting and developing different projects, including a [museum](#) exhibit in Húsavík, Iceland, with aims to produce additional exhibits in continental Europe.

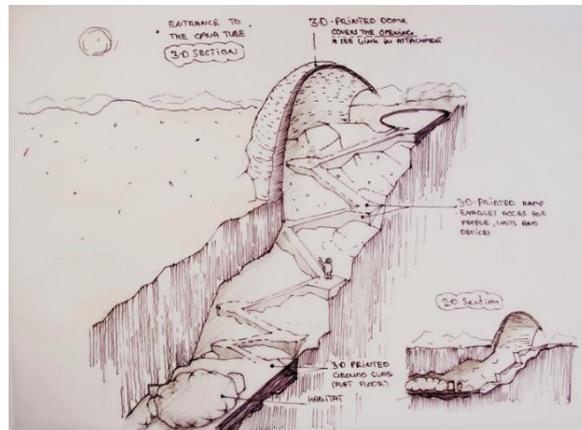


Figure 2: Drawing of a possible outlook of a lava tube habitat, by architect Dmitry Zhuikov, [zaarchitects.com](http://zaarchitects.com), advisory board of 4<sup>th</sup> Planet Logistics.

## Acknowledgements

The Exploration Museum in Húsavík, Iceland; 4<sup>th</sup> Planet Logistics advisory board; Landowners of Stefánshellir (Ólafur Jes Kristófersson and Bryndís Jónsdóttir), Icelandic Speleological Society, Árni B. Stefánsson; Örlygur H. Örlygsson; Francesco Perini; Christa M. Feucht; Bernard Foing

## References

[Homepage 4th Planet Logistics: 4thplanetlogistics.com](http://Homepage4thPlanetLogistics.com)

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

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**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)<sup>(1-3)</sup> has several lava layers in it's cross-section as reported by Robinson et al(2012)<sup>(4)</sup> through LRO observation. As for pits of Mars, the cross sectional thickness is also reported from Cushing(2007,2012)<sup>(5,6)</sup> 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<sup>(7)</sup>. For the lava flow of density  $\rho$ , and yield strength  $f_B$ , with slope angle  $\alpha$ , 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  $n=4$ .

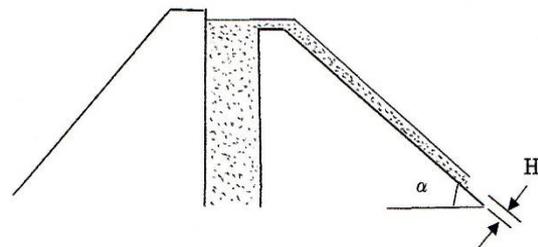


Fig.1 Lava flow model on the inclined plane

### 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

$$\text{for } \tau_w = (\rho g \sin \alpha)H > f_B,$$

$$u = [z(2H-z) - 2h_B z] (\rho g \sin \alpha) / 2\eta_B$$

$$(0 < z < H - h_B)$$

$$u = (H - h_B)^2 [(\rho g \sin \alpha) / 2\eta_B]$$

$$(H - h_B < z < H)$$

$$\text{for } \tau_w = (\rho g \sin \alpha)H < f_B,$$

$$u = 0$$

Here,  $\eta_B$  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.

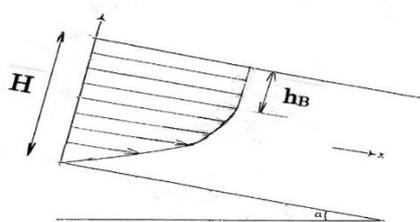
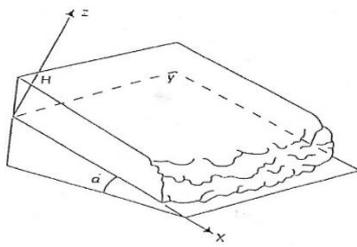


Fig.2 Lava flow on the inclined plane with a free surface

2) For the case of  $n=2$ , flow between infinite width parallel plates  
Flow stop condition is as follow:  $H=2f_B/(\rho g \sin\alpha)$ . Flow model is shown in Fig.3.

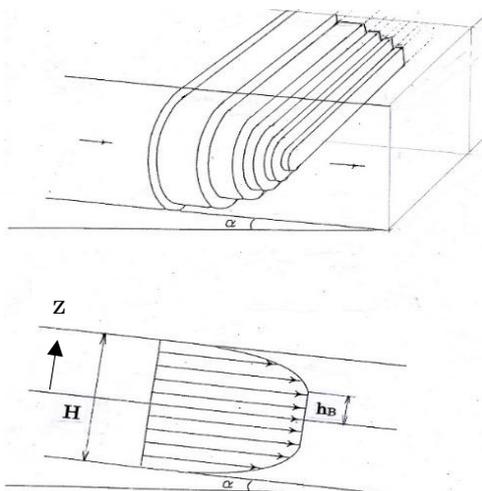


Fig.3 Lava flow between infinite width parallel plates

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,  $\eta_B$  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  $H \ll d$ . 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:  $H = 2R = 4f_B/(\rho g \sin\alpha)$ .

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  $H$ .

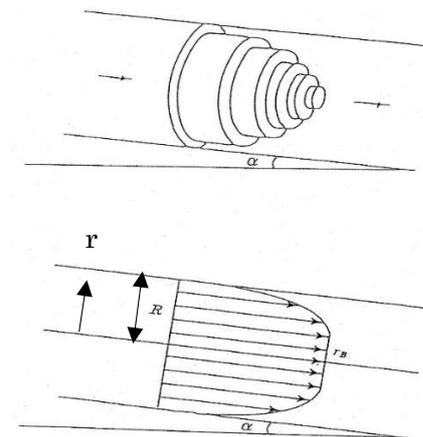


Fig.4 Lava flow in the circular tube

### 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)<sup>(4)</sup>.

When average thickness of  $H=6\text{m}$  and slope angle  $\alpha=0.31$  degree in Rille-A area(Greeley,1971)<sup>(8)</sup> are used for the lava flow stop condition of Simple flow, the yield strength is given as  $f_B = \rho g \sin \alpha H = 131 \text{ Pa}$  (Honda,2017)<sup>(9)</sup> where the lava density is  $\rho=2.5\text{g/cm}^3$  and surface gravity is  $g=162 \text{ cm/s}^2$ . 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  $H=3\text{m}$ (see Fig.6) (Cushing,2012)<sup>(6)</sup>. The stop condition of Simple flow of lava where slope angle of pit-I area is  $\alpha=0.28\text{deg}$  gives the yield strength  $f_B=136 \text{ Pa}$ <sup>(10)</sup>. For this estimation, the lava density  $\rho=2.5\text{g/cm}^3$  and surface gravity  $g=371 \text{ cm/s}^2$  are used.

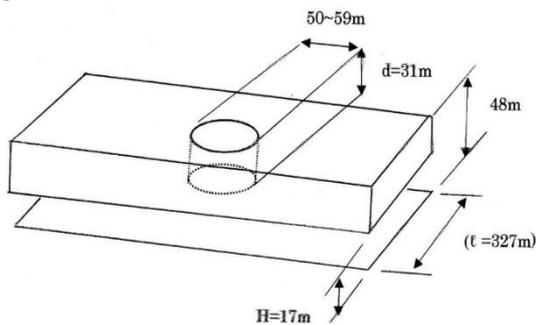


Fig.5 Schematic of Marius Hills Hole

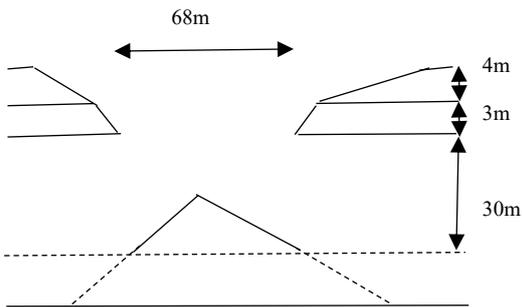


Fig.6 Schematic of the skylight of the volcano-tectonic fracture system (I):dust layer:4m, bedrock overhang:3m,the depth at the edge of the shadow:37 m. extracted and simplified from Fig.8 of G.E.Cushing: Journal of Cave and Karst Studies, April 2012

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

The lava tube cave height  $H_c$  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  $\alpha$ . The flow critical(stop) condition of the lava is expressed as  $H_c = n f_B / (\rho g \sin \alpha)$ , where  $\rho$  is density,  $g$  is gravity, For the case of  $n=2$ ,  $H_c$  is cave height between infinite width parallel plates, and for the case of  $n=4$ ,  $H_c$  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  $n=4$ ,  $H_c=12\text{m}$  and  $24\text{m}$  respectively. As the observed  $H_c$  is  $17\text{m}$ ,  $n$  will be about 3. This possibly shows the cross section of the lava tube cave under MHH is rectangular(Honda,2017)<sup>(9)</sup>. For the skylight of the volcano-tectonic fracture system (I) of Martian Arsia Mons, for  $n=2$  and  $n=4$ ,  $H_c=6\text{m}$  and  $12\text{m}$  respectively(see Table.1).

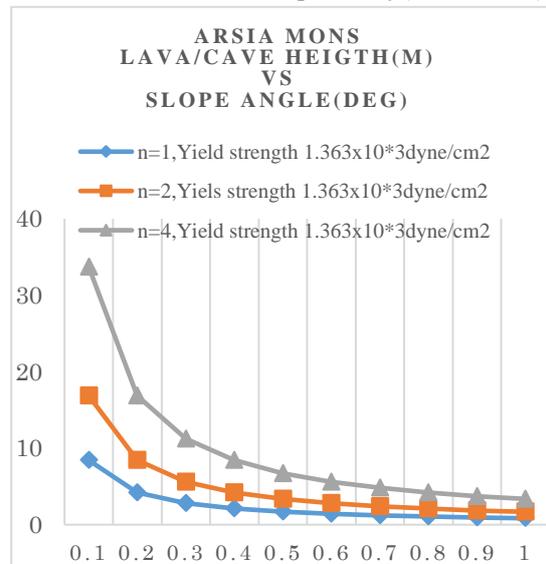


Fig.7 Lava tube cave height of Arsia Mos

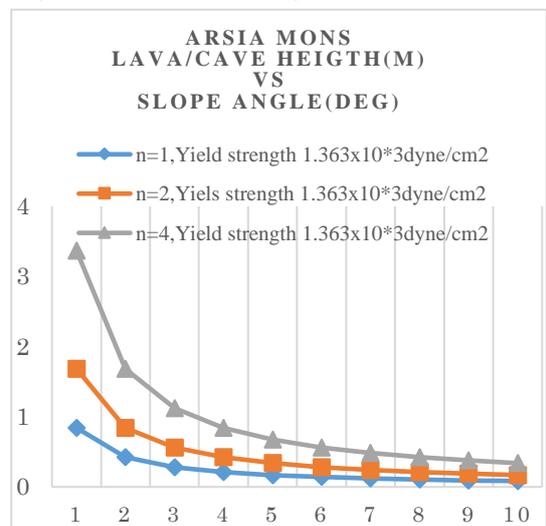


Fig.8 Lava tube cave height of Arsia Mons

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  $1.363 \times 10^3 \text{ dyne/cm}^2$ .

Table 2 and Table 3 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<sup>(11)</sup>.

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)<sup>(7)</sup>, but these values are widely scattered. Table 4 and Table 5 show the minimum and maximum value for the Moon and Mars ever obtained<sup>(12-22)</sup>. 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)<sup>(10)</sup>. 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)<sup>(12)</sup>, Pavonis Mons (Fig.11 and Fig.12)<sup>(17)</sup>, Ascraeus Mons (Fig.13 and Fig.14)<sup>(20)</sup>, and Elysium Mons (Fig.15 and Fig.16)<sup>(21)</sup>. Table 5 shows the range of the obtained yield strength of the lava flow of Mars including Elysium Planitia<sup>(22)</sup>. The minimum values obtained are almost between  $100 \text{ Pa} (1 \times 10^3 \text{ dyne/cm}^2)$  and

$200 \text{ Pa} (2 \times 10^3 \text{ dyne/cm}^2)$ .

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))]

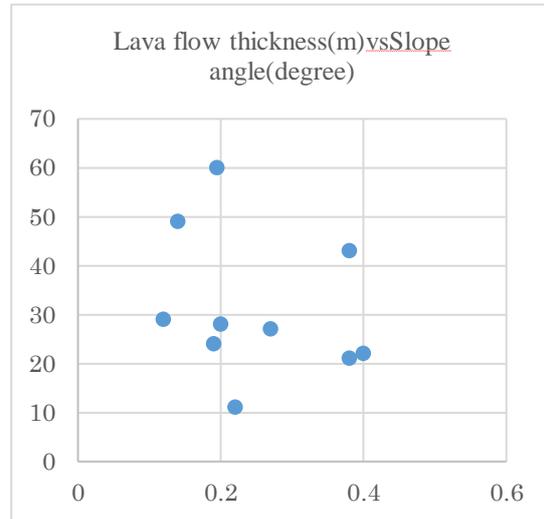


Fig.9 Lava flow thickness of Arsia Mons South Flank. (Moore et al (1978))

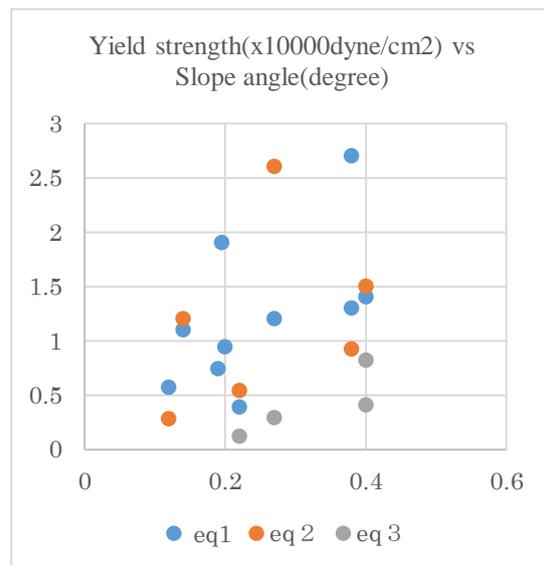


Fig.10 Arsia Mons South flank Yield strength:  $f_B$  (Moore et al (1978)) : Minimum:  $1200 \text{ dyne/cm}^2$ , Maximum:  $27000 \text{ dyne/cm}^2$ , eq1:  $f_B = H(\rho g \sin \alpha)$ , eq2:  $f_B = H^2 \rho g / W_f$ , eq3:  $f_B = 2W_b (\rho g \sin^2 \alpha)$ , Here, H is lava flow thickness,  $W_f$  is lava flow width,  $W_b$  is lava levee width. (Moore et al (1987):  $f_B = 1.2 \times 10^3 \text{ dyne/cm}^2 \sim 2.7 \times 10^4 \text{ dyne/cm}^2$ )

**[Pavonis Mons]**

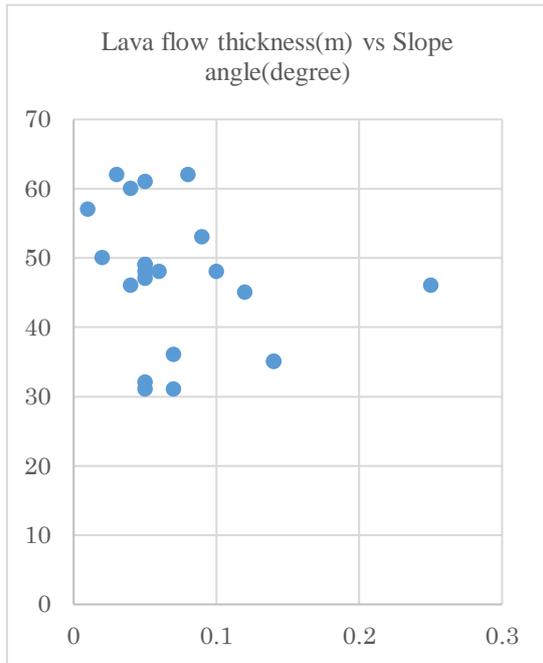


Fig.11 Lava flow thickness of Pavonis Mons, Baloga etal(2003)

**[Ascræus Mons]**

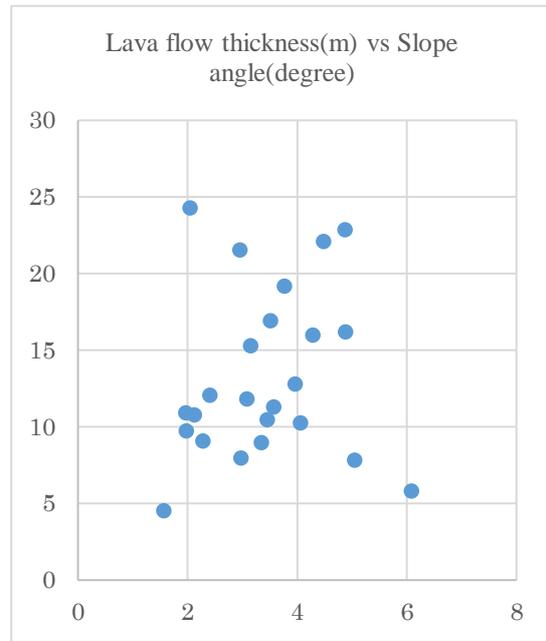


Fig.13 Lava flow thickness of Ascræus Mons, Hiesinger etal(2007)

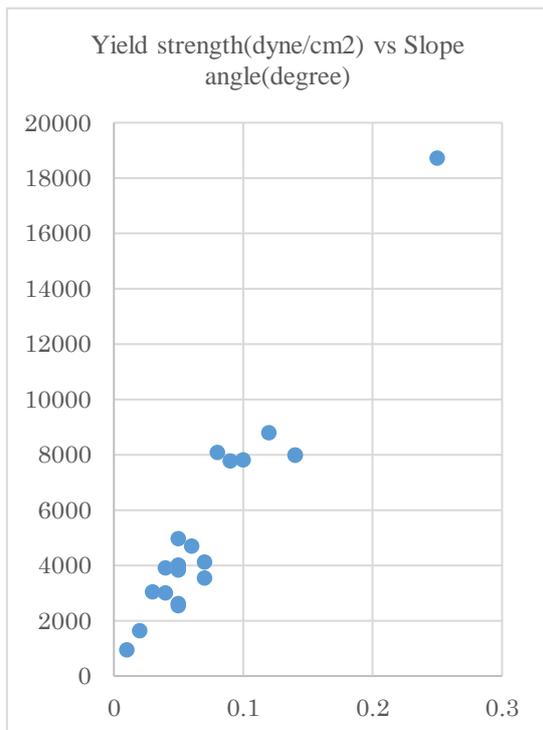


Fig.12 Yield strength of lava flow of Pavonis Mons, Baloga etal(2003), : from  $H, \alpha$ ,  $f_B$  is estimated by T.Honda:  
 $f_B = 0.93 \times 10^3 \text{ dyne/cm}^2 \sim 1.9 \times 10^4 \text{ dyne/cm}^2$

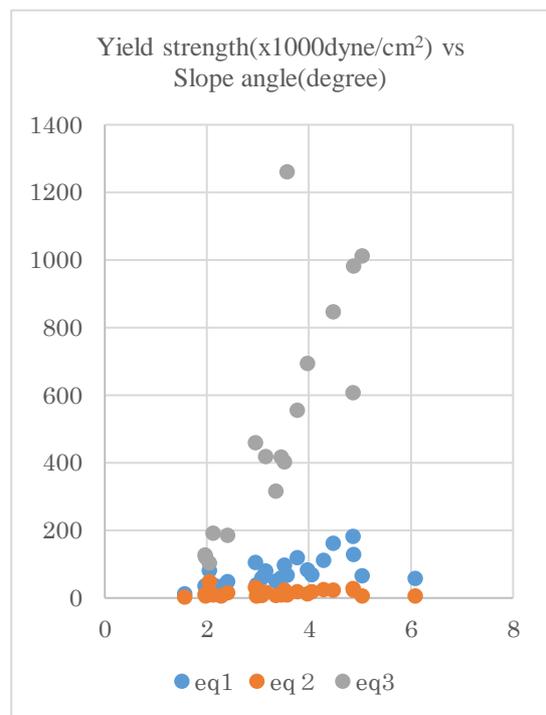


Fig.14 Yields strength of Ascræus mons, Hiesinger et al(2007),  
 $f_B = 1.99 \times 10^3 \text{ dyne/cm}^2 \sim 1.26 \times 10^6 \text{ dyne/cm}^2$   
 eq1:  $f_B = H(\rho g \sin \alpha)$ , eq2:  $f_B = H^2 \rho g / W_f$ , eq3:  $f_B = 2W_b (\rho g \sin^2 \alpha)$ , Here,  $H$  is lava flow thickness,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

**[Elysium Mons]**

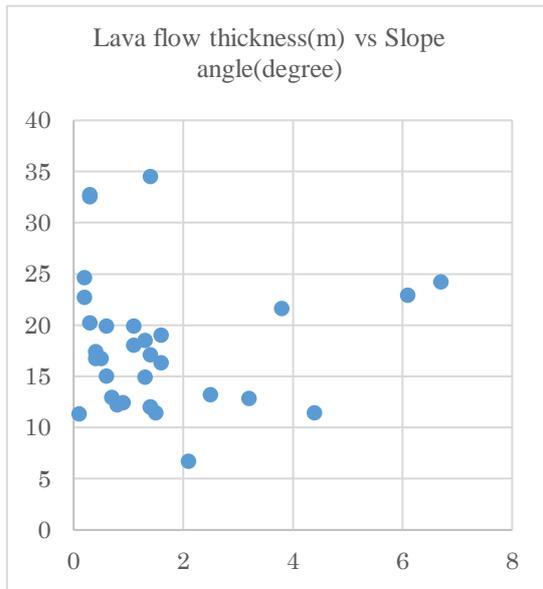


Fig.15 Lava flow thickness of Elysium Mons, Pasckert et al(2012)

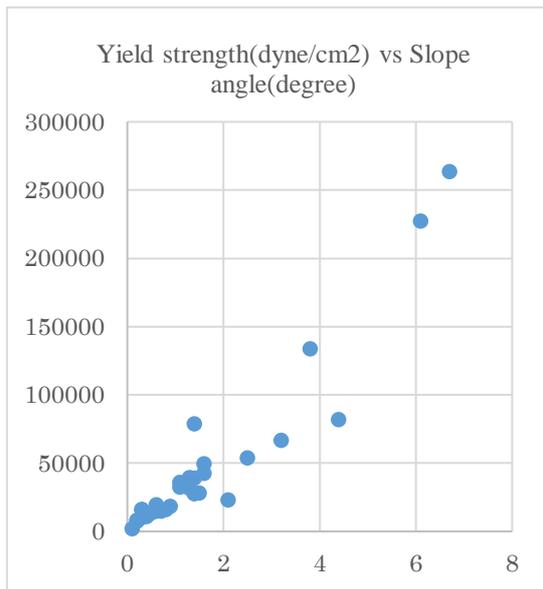


Fig.16 Yield strength of lava flow of Elysium Mons, Pasckert et al(2012),  
 $f_B = 1.84 \times 10^3 \text{ dyne/cm}^2 \sim 2.7 \times 10^5 \text{ dyne/cm}^2$

**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<sup>(21)</sup>. 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  $\rho = 2.5 \text{ g/cm}^3$ , for gravity is  $g = 373 \text{ cm/s}^2$ . The calculated yield strength decreases from upstream to downstream from  $2.63 \times 10^5 \text{ dyne/cm}^2$  to  $1.84 \times 10^3 \text{ dyne/cm}^2$ . 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  $1.84 \times 10^3 \text{ dyne/cm}^2$  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<sup>(23)</sup> 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<sup>(24)</sup>. The limiting conditions used for estimation of the lava tube cave height is the  $H_c = 4f_B / (\rho g \sin \alpha)$  and  $H_c$  is indicated in the right column of Table 6. There is a possibility that a lava tube cave exists under the vertical pit because its  $H \gg H_c$  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<sup>(25,26)</sup> 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 minimum 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 <sup>3</sup> dyne/cm <sup>2</sup> )	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 <sup>3</sup> dyne/cm <sup>2</sup> )	6m(n=2) ~12m(n=4)

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

Pit Name of Arsia Mons <sup>2)</sup>	Diameter <sup>2)</sup>	Minimum depth <sup>2)</sup>	Elevation <sup>2)</sup>	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 <sup>3)</sup>	Number of skylight <sup>5)</sup>	Minimum depth <sup>5)</sup>	Total Length <sup>5)</sup>	Average Slope <sup>5)</sup>	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 <sup>3</sup> dyne/cm <sup>2</sup> )	400 Pa(4.0x10 <sup>3</sup> dyne/cm <sup>2</sup> )	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 <sup>3</sup> dyne/cm <sup>2</sup> )	5.19 x10 <sup>4</sup> Pa (5.19x10 <sup>5</sup> dyne/cm <sup>2</sup> )	Moore et al(1978),Warner et al(2003),Hiesinger et l(2015)
Pavonis Mons	93 Pa (0.93x10 <sup>3</sup> dyne/cm <sup>2</sup> )	1.3 x 10 <sup>4</sup> Pa (1.3x10 <sup>5</sup> dyne/cm <sup>2</sup> )	Baloga et al(2003), Hiesinger et al(2008) ,Hiesinger et al(2015)
Ascraeus Mons	199 Pa (1.99x10 <sup>3</sup> dyne/cm <sup>2</sup> )	1.3 x 10 <sup>5</sup> Pa (1.3x10 <sup>6</sup> dyne/cm <sup>2</sup> )	Zimbelman(1985),Hiesinger et al(2007),Hiesinger et al(2008)
Elysium Mons	184 Pa (1.84x10 <sup>3</sup> dyne/cm <sup>2</sup> )	2.63 x10 <sup>4</sup> Pa (2.63x10 <sup>5</sup> dyne/cm <sup>2</sup> )	Pasckert et al(2012), Hiesinger et al(2015)
Elysium Planitia	100 Pa (1.0x10 <sup>3</sup> dyne/cm <sup>2</sup> )	500Pa (5.0x10 <sup>3</sup> dyne/cm <sup>2</sup> )	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 form=4, Hc=4f <sub>B</sub> /(pg sinα), (f <sub>B</sub> is 1.84x10 <sup>3</sup> dyne/cm <sup>2</sup> )	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

## **Mineral to Microbe: Investigating the Continuum in Lava Cavesto Best Predict Life Detection Targets**

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Microbial communities in lava caves create a variety of features visible to the unaided eye. These range from hard to soft—from mineral deposits to microbial mats that line cave walls. We investigated the bacterial and archaeal diversity of this continuum of features in Lava Beds National Monument (LBE, northern California, USA) in October-November 2018 as part of BRAILLE (Biologic and Resource Analog Investigations in Low Light Environments), a research project sponsored by NASA's Planetary Science and Technology in Analog Research program. One of BRAILLE's objectives is to characterize mineral biosignatures in lava caves, in order to enhance remote capabilities for detection of life (past or present) on other planets such as Mars, where lava caves have been detected. In particular, the work aims to illuminate the connection between secondary mineral deposits and microbial life in caves for the refinement of future robotic life detection strategies. We hypothesized that secondary mineral shape and texture would be predictive of the diversity and extent of potential microbial content. Samples were collected aseptically from two lava caves in LBE, distinct in age and human visitation intensity. Mineral samples were selected that encompassed relatively pristine bare rock and a variety of secondary textures and shapes such as mineral patina, polyps, round knobs, and cauliflower-like structures. Microbial mat samples were also sampled, distinguished on the basis of color.

Scanning electron microscopy (SEM) revealed several common putative microbial forms, including fuzzy and smooth filaments, spheroids, rods, and beads-on-a-string structures. Energy-dispersive X-ray spectroscopy (EDX) revealed that, silica-rich films covered extensive portions of most of the samples examined. Secondary mineral samples displayed fewer microbial morphologies and contained a higher abundance of smooth filaments. In contrast, microbial mats exhibited extensive microbial morphologies, with a greater proportion of fuzzy rods, fuzzy filaments, and beads-on-a-string shapes.

Microbial community structure was characterized on the Illumina platform using domain-specific primer sets targeting Bacteria and Archaea, using the bacterial specific primer 27F, and archaeal specific primer 519F. Both mineral and microbial mat samples exhibit extensive microbial diversity, with more DNA being recovered from microbial mat samples. In contrast to our previous studies of mineral versus microbial mat samples, composition at the bacterial phylum level was similar across mineral and mat samples. Actinobacteria, a dominant cave bacterial phylum, was present at moderate abundance across both mineral and mat samples. One bacterial phylum in particular, Nitrospirae, was more abundant in microbial mat samples than in mineral samples, however. On a finer scale, nonmetric dimensional scaling (NMDS) plots of diversity dissimilarities of both archaeal and bacteria sequences revealed that mat samples are more similar to each other than mineral samples are to each other. Microbial community assemblages of bare rock and patina samples are distinct from other mineral samples and cluster more closely to mat samples. The other mineral samples were very dissimilar to mat samples. Our results suggest that both secondary mineral deposits and microbial mats are worth investigating further as potential targets for life detection in Earth and extraterrestrial caves. Understanding which mineral textures, shapes, and compositions are most predictive of the presence and extent of microbial life will enhance future robotic life detection strategies.

# Genesis of Pyroducts of the Galápagos Islands, Ecuador

by

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## Abstract

Little has been published on the development of lava tubes, or "pyroducts" of the Galápagos. Here we report on fieldwork conducted during the 16<sup>th</sup> International Symposium on Vulcanospeleology which was held in the islands in March 2014. During the week the major volcanic caves were visited and studied in context. Santa Cruz is the most central island of the Galápagos. It is a large shield volcano with a high abundance of parasitic cones, large lava caves and enormous pit craters (e.g. Los Gemelos). Santa Cruz is subdivided into an older, uplifted Platform Unit with an age of 1.3-1.1 Ma, while the younger unit is represented by lavas (mainly exhibiting olivine tholeiites and transitional alkalibasalts besides some hawaiites) of the Shield Series with ages as young as 30-20 ka.

A total of eleven pyroducts were investigated prior to and during the symposium: Cueva del Cascajo, Cueva de Gilda and Gallardo, Mirador de los Túneles (Cueva de Kübler), Cueva de Chato 1, Cueva de Royal Palm, Tortoise Junction tourist cave, Cueva La Llegada, and Cueva de Premisias on Santa Cruz Island and Triple Volcán (a vent), Cueva de Sucre and Túnel del Estero on Isabella Island. In addition, detailed surveys were conducted in Cueva del Cascajo and Mirador de los Túneles/Cueva de Kübler. These caves fall into two groups, those with one pāhoehoe sheet as primary roof (5) and those with a much thicker roof (6) composed of a primary pāhoehoe roof, reinforced by successive 'a'ā flows of the same eruption. In the latter group the primary pāhoehoe

sheet often collapsed during activity, being transported away so that the cores of the 'a'ā flows are now giving stability to the roofs. All caves show very low braiding (i.e. they are mono-trunked).

The longest cave, Cueva del Cascajo, estimated to be about 3 km long, was investigated by the participants. The uphill, 150 m long section was surveyed in great detail to understand its genesis. This section has four collapse holes (the fifth downhill serves as the normal entrance to the cave). The section is divided by a septum (a secondary ceiling) throughout, separating the passage into an upper and a lower level. In places up to five septa are present. This suggests a gradual downcutting of the flowing lava during activity. The space below the lowest septum amounted to about 5 m<sup>2</sup>, a measure of the cross-section of the lava river. Another indicator of downcutting is the presence of a prominent lava-fall. Where the lining had fallen away, we noticed 'a'ā rubble- and core-layers along the walls, showing that the lava flow has in fact down-cut into older rock. The survey showed that the downcutting amounted to 10 m in this section, decreasing to 5 m at the entrance collapse. Thus, the present cave represents a canyon down-cut by a stepped river of lava, originally flowing at its bottom.

We found evidence of downcutting in most of the caves (exception Túnel del Estero), confirming the observations from Hawai'i that show that lava caves are not created at the end of the eruption "when the tube runs empty", as popular views suggest. Rather prolonged activity creates a gas-space above the down-cutting lava river. We were able to divide the caves into three states according to the importance of the observed erosion. Overall the caves of Galápagos appear to best fit the "inflation" model whereby the primary roof consists of one or a stack of pāhoehoe sheets with the conduit developing below. Evidence for roof formation by "crusting over of a channel" was not observed.

# THE DELISSEA CAVE SYSTEM

by Bob Richards, Carol Vesely, Peter Bosted  
Hawai'i Speleological Survey

The Delissea Cave System lies in lava flow that originated high on the slopes of Hualalai volcano, on the island of Hawaii. Exploration and mapping began in 2003 with a majority of trips taken place over the last seven years. An abundance of cave entrances and passages have been found in the Pu'u Wa'awa'a ahupua'a flow.

The cave system ranges from 820 meters in elevation to over 2,200 meters in elevation, providing a large diversity of habitat for the native flora and fauna. This presentation will cover



*Veda Hackell below a deep skylight in the Ambigua section of the system. Photo by Peter Bosted.*

the exploration that has revealed a set of passages more complex than previously thought. The cave system length stands at 51 kilometers (31.6 miles) of surveyed passage of which over 32 kilometers (19.9 miles) are connected into one long and deep cave. The entrance pukas (pits) are host to a large and diverse population of native plants and trees, including the Delissea tree, which was thought to be extinct. Other plants which are rare in this dry 'Ohi'a forest environment include Ambigua and Hapuu. Biologists have found a wide variety of cave-adapted organisms. Many bird bones from now-extinct bird species have been studied, including a large Hawaiian goose which stood about two to three foot tall. In the steepest section of the cave, there are many extraordinary displays of colorful lava splatters. Examples of geological, mineralogical, paleontological, and biological resources will be illustrated through photographs that have been taken on this project.

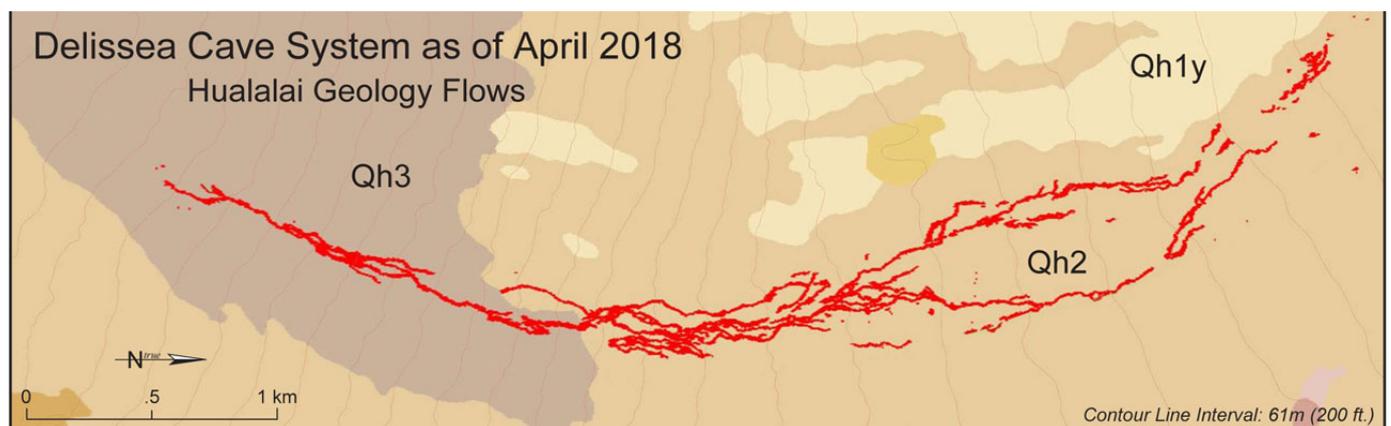
[As this goes to press, the length of the system has increased to 38.5 miles (62km), with the longest contiguous section 23.7 miles ~38Km long].



**Carol Vesely at the top of a lava fall in the Petrel section of the Delissea System. Photo by Peter Bosted.**



**Amazing splatter formations in the area known as the Spaghetti Factory. Photo by Peter Bosted.**



**Overlay of the cave system (as it was in early 2018) on a geologic map. The Qh2 flow has an estimated age of 1500-3000 b.p, while the Qh3 flow age range is 750-1500 b.p. The boundary of the Qh3 flow may be in error, as there is no indication in the cave of this younger flow invading the older system.**

## **The on-going saga to protect the Harmans Valley lava flow**

**John Brush**

Canberra Speleological Society Inc

Chairman, Commission on Volcanic Caves, International Union of Speleology

The Harmans Valley lava flow originated at the Mt Napier volcano in Western Victoria and flowed across the landscape in a pre-existing valley. At about 40,000 years old, the flow is one of the most recent in Australia. It is widely regarded as the best example in Australia of a lava flow constrained by a valley and for having one of the most intact and significant collections of young volcanic features. In addition, the flow contains the renowned Byaduk lava caves, has Aboriginal and early-European cultural heritage significance as well as dramatic landscape values.

The Mount Napier volcano and the upper part of the flow, containing many of the Byaduk caves, are protected within the Mount Napier State Park. However, for most of its length, the Harmans Valley flow is on privately-owned land where until recently, features on and in the flow - including caves, had been afforded very little if any protection, despite lobbying efforts over many years by concerned local residents, cavers, academic institutions and the local Aboriginal community.

In 2004 and again in 2015-16, sections of the flow were bulldozed, crushed and levelled to improve farming potential. Some surface features were obliterated and, as the most significant damage was in areas that are visible from a public viewing point, the landscape significance has diminished.

In October 2016, the Victorian State Government imposed an interim Significant Landscape Overlay (SLO) on those parts of the flow that lie on private land within the Southern Grampians Shire. This landscape protection control is due to expire on 31 October 2018. In March 2018, the Victorian Government held a public hearing to consider whether the SLO protection measure should be made permanent.

This paper reviews efforts to protect the flow and its important geological, landscape, ecological and cultural features and considers the likelihood of achieving effective permanent protection.

### **Introduction**

The Harmans Valley basalt lava flow in Western Victoria originated at Mt Napier and flowed down a pre-existing valley (Figure 1) for more than 20 kilometres in a westerly, then south-easterly direction. For most of this distance, the flow is located within the Southern Grampians Shire, but the last several kilometres fall within the Glenelg and Moine Shires and in these lower reaches, much of the flow is swamp covered, with little or no outcrop.

The renowned Byaduk lava caves occur within the flow and in addition, many surface features of the flow are still visible, including Tumuli, or lava blisters, lava lakes, levees and examples of a'a and pahoehoe lava surfaces. The flow is regarded by experts as the best preserved in Australia and is very important for education and research purposes. Much of what we know about the features of the flow comes from the work of Ken Grimes, a geologist, speleo and former member of the Commission on Volcanic Caves who passed away suddenly in 2016. The flow also has aboriginal and early-European cultural heritage significance as well as dramatic landscape values, which were also noted by Ken.

Mt Napier and the upper part of the flow, containing many of the Byaduk caves, are protected as they are within the boundaries of the Mt Napier State Park. However, most of the flow is on private property where, until recently, it had been afforded very little protection.



Figure 1. Major features of the Mt Napier State Park and Upper Harmans Valley.

In 2004 and again in 2015-16, some sections of the flow were bulldozed and levelled, an operation called rock crushing, to improve its farming potential. The rock crushing operations obliterated some surface features and, as the most significant damage has been in areas that are visible from a public viewing point (the Harmans Valley lookout), the landscape significance has been diminished.

### Geological setting

The Harmans Valley area lies within the Newer Volcanic Province (Figure 2), which covers an area of 25,000 Km<sup>2</sup> in Western Victoria and southeast South Australia (Cas, 2018). It comprises more than 400 eruption sites, extensive lava flows and scoria cones. The province has been active for around 8 million years, with the most recent eruption occurring at Mt Shank at the western edge of the province about 5000 years ago. Cas considers the province is still active and, as it is the only volcanic province in Australia that is still active, it is of national scientific significance.

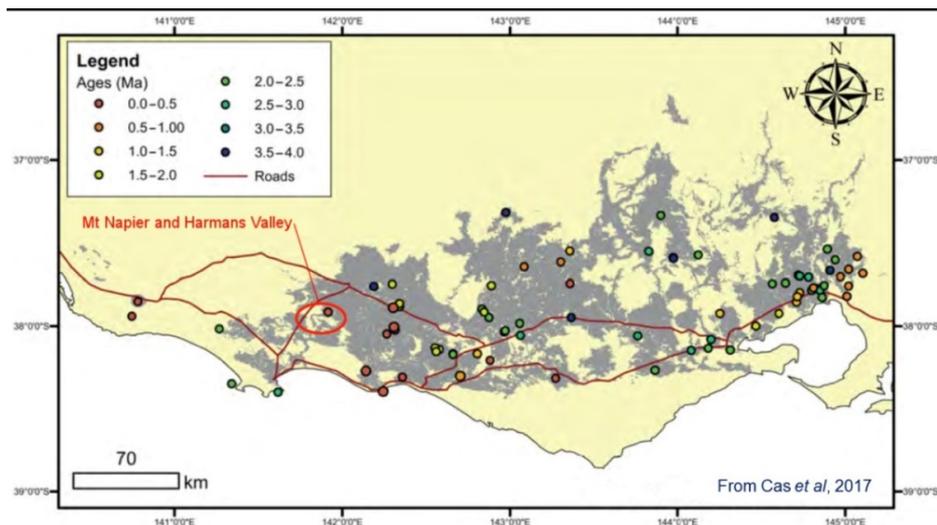


Figure 2. The Newer Volcanic Province of Western Victoria and southeast South Australia.

Mt Napier, the source of the Harmans Valley flow is close to the more recent end of the spectrum. Recent studies of Mt Napier and the Harmans Valley flow suggest an age of about 40,000 years (Cas, 2018). In geological terms, this is very young and explains why many surface features of the flow are still visible and why a range of dramatic lava cave features remain intact.

### **Features of the flow**

From a speleo perspective, the most important features of the Harmans Valley flow are the caves. As already noted, many of these are within the Mt Napier State Park. Caves have also been found in other parts of the flow but relatively little is known about them because of access constraints.

From a geological perspective, the most striking features are the tumuli, or lava blisters as they are sometimes called. These are steep-sided mounds of rock up to 10 metres high and 30 metres across that are thought to result from underlying pressure of lava forcing up the solidifying, but still plastic, surface of the flow. It is possible that steam, generated where the lava flows over wet or swampy areas, played a role in their formation. The tumuli are more common in areas where the lava flow is thin, such as near the edge of the flow and in side valleys. Tumuli occur in volcanic areas in other countries, but they are generally of a much smaller size than the ones found in Harmans Valley.

Other features of the flow include lava ridges, hummocky terrain (known locally as stony rises), lateral levees, lava canals and drained lava lakes, as well as smaller-scale features such as columnar jointing and pahoehoe and a'a surfaces. While these are common in volcanic areas, they are invaluable at the state and national level for education and research purposes as the Harman's valley flow is relatively intact, very young and readily accessible.

### **Rock removal and quarrying operations**

The first inhabitants of the area, ancestors of the Guditjmarra people, fashioned loose basalt boulders into shelters. Foundations of these structures can still be seen in the area.

Since the early days of European settlement, people have been continuing to modify the surface of the flow. At first, farmers improved the grazing value of their land by picking up loose rocks and using them to build dry stone walls. Later, farm tracks were pushed across the flow. As the rocky ground also proved to be a readily available source of material, rock was removed by the truckload for road construction works in the district. There are also several small quarries in the area where the aim was to dig beneath the basalt to access the underlying limestone, which was in demand for agricultural and construction purposes.

None of these small-scale operations had a major impact on either the important geological features of the flow or on the overall landscape vista, such as is visible from a public lookout beside the Hamilton-Port Fairy Road (Figure 3). Indeed, one of the valuable landscape attributes of the area is now considered to be the dry stone walls. They are also regarded as contributing to the cultural significance of the area.

In mid-2004, heavy machinery was used to break up and flatten the surface of the flow over a 15 hectare area. Surplus rock was pushed into several large heaps. Unfortunately, the damage was visible from the public lookout.



*Figure 3. Mt Napier and the Harmans Valley lava flow as it was in 1975, from the lookout beside the Hamilton-Port Fairy Road.*

In November 2015, after a change in landowners, the crushed area was re-worked and in July 2016, an additional 5 hectares to the east of the earlier work was worked over and the size of the rock heaps increased.

### **Attempts at protection**

In the 1990s the Victorian Division of the Geological Society of Australia assigned the Mt Napier volcano area, including the Harmans Valley flow, National significance as a Geological Heritage feature (Rosengren, 1994). It also assigned several individual listings, including international significance to the Wallacedale Tumuli and national significance to the Byaduk Caves. The current status of the listings is uncertain, but in any case they afforded no legal protection. In Victoria, there is no protection for geological sites unless they are on the National Heritage List (which does not include anything in the Harmans Valley area) or are within a National or State Park. This means protection for Mt Napier, for some of the Byaduk caves and other features within the Mt Napier State Park. However, for features on private land, protection is only possible by indirect means – that is, if the geological sites also happen to have other values that are covered by environmental, planning or Aboriginal heritage legislation.

At the time of the crushing work in mid-2004, there was a push for protection of significant geological features located on private land. Amid widespread local concerns about the rock crushing, the landowner agreed to halt work pending consideration of the issue by Southern Grampians Shire Council. The Council proposed seeking an Environmental Significance Overlay (ESO) under the Victorian *Planning and Environment Act 1987* for all areas of the flow on private land within the shire. In October 2004, the (then) Victorian Department of

Sustainability and the Environment (DSE) drew up a map of the proposed ESO over the area of the flow based on information provided by Ken Grimes. Unfortunately, the ESO was never gazetted.

In early to mid-2005, DSE appeared to have been more focussed on negotiating with the landowner to “offset” the damage caused to native vegetation during the rock crushing by undertaking plantings elsewhere on his property. Perhaps this was because DSE realised there was no basis for taking action for the destruction of geological features. It is not clear whether any agreement was reached with the landowner and there is no on-the-ground evidence of any planting ever taking place. Of course, from a geological perspective, planting in other areas of the flow had the potential to obscure the geology and landscape features.

In 2012, the (then) Department of Planning and Community Development completed a landscape assessment study in southwestern Victoria (*The South West Landscape Assessment Study*) in partnership with shire councils in the region. The aim of the study was to identify and assess key landscapes and make recommendations regarding their protection and management. The Harmans Valley, as viewed from the Harmans Valley lookout, was identified as being of state-level significance and proposed a Significant Landscape Overlay (SLO) for the area, noting rather poetically that:

“The view (from the lookout) is contained within the sweeping curve of the valley, with Mount Napier visible in the background. While other parts of the surrounding landscape are visible, the view cone describes the extent of the view that is dominated by the lava flow.

The open, cleared foreground and elevated position of the viewing location allows for excellent, uninterrupted views over the lava flow. There is a high contrast between the rough texture of the flow and the dark, scrubby bracken growing in its crevices, and the smooth, grassy slopes of the valley walls. The lava flow is a dramatic visual feature that twists across the middle ground. The central location of Mount Napier and the span of the landscape between it and the viewing location makes it easy to appreciate the distance that the river of lava travelled when the volcano was active. This is further highlighted by dark vegetation that frames the valley and directs the eye across the volcanic features”.

Despite this statement, there was no immediate action to implement the SLO.

The area visible from the lookout changed hands, and in November 2015, the new owner started to rework the area crushed in 2004. The works were soon halted after a stop-work order was issued by the Southern Grampians Council and the owner was asked to complete a Cultural Heritage Management Plan (CHMP) under the terms of the State *Aboriginal Heritage Act 2006*.

Early in 2016, the Victorian Government enacted the *Aboriginal Heritage Amendment Act 2016* which among other things, sought to clarify when a CHMP was required and also changed the nature of the CHMP from a guidance document to an approval one. The extent to which the landowner resolved the CHMP issues is not known, but in mid-2016 he recommenced works. On 8 July 2016, another stop-work order was issued under the Act. As was the case in 2004, there was a negative reaction in the local media. In response the

landowner noted there was no SLO over his land and that the real damage was done ten years earlier by someone else.

At about the same time, following representations to the Minister for Planning, an interim SLO was gazetted to cover all parts of the flow that were on private land within the Southern Grampians Shire. This basically meant there was a planning objective to maintain the landscape character and setting of the lava flow. The SLO was gazetted on 26 October 2016 with validity until 31 October 2018.

In 2017, the Southern Grampians Shire Council drafted a proposal for a permanent SLO in consultation with the Department of Environment, Land, Water and Planning (DELWP). In terms of the planning policy framework in Victoria, as set out in the *Planning and Environment Act 1987* (PEA), the shire council was the designated planning authority for the proposal. In October 2017, DELWP released a draft proposal for a permanent SLO for public comment and invited submissions to Council by 20 October 2017. Council received a total of 75 submissions, including one from the Commission on Volcanic Caves. Most of the submissions supported the SLO being made permanent.

DELWP established a planning panel to consider the submissions and in early March 2018, it convened a 2-day public hearing in Hamilton at which submitters were given the opportunity to speak. There were 18 presentations including by the Shire Council, representatives of the Gunditj Mirning Traditional Owners Aboriginal Corporation, academic institutions, community groups, landowners, the State Environment Department, geotourism organisations, the Australasian Cave and Karst Management Association Inc (ACKMA) and the IUS Commission on Volcanic Caves. A wide range of views was expressed in the hearing and during an associated field inspection (Figure 4). The hearing and outside discussions took place in a constructive and productive manner and a range of amendments proposed to the draft SLO addressed some of the concerns of landowners, most of whom did not support the SLO being made permanent, as well as those of the organisations seeking permanent protection of the flow who wanted specific restrictions on undertaking earthworks.



Figure 4. Field inspection of a rock crushed area during the public hearing, March 2018.

Perhaps the most significant amendment, which addressed a major concern of landowners, was to change the boundaries of the proposed SLO from a cadastral basis to the actual margins of the flow, plus a narrow (50 metre) buffer zone. The buffer zone was intended to cover potential errors in defining the margins of the flow as well as protecting the landscape setting of the flow in its valley. A buffer zone of 100 metres would have more adequately protected the landscape setting but there was little support for it. Changing the basis for defining the boundaries of the flow had the effect of removing some large parcels of land which had only very small sections of flow. It was also agreed there was little reason to include areas where the surface of the flow was completely covered with soil or wetland areas.

The Planning Panel submitted its report to the designated planning authority (the Shire Council) on 16 April 2018. The report was made available to the public about a month later. To a large extent, the report recommended what academics, field naturalists, ACKMA and the Commission on Volcanic Caves proposed at the Public Hearing. On 14 June, Council formally considered the report and voted unanimously to adopt the two most important recommendations of the Planning Panel report. It deferred consideration of a third recommendation that Council and DELWP develop a “plain English” guide to assist landowners through the application process for permits under the Planning and Environment Act.

Council will now advise the Victorian Minister for Planning of its decision and the permanent Significant Landscape Overlay will come into effect after a notice is placed in the Victorian Government Gazette.

## **Conclusion**

The vista of Harmans Valley lava flow as viewed from the Hamilton Port Fairy Road has changed significantly since I first saw it in 1975. Farm management tracks have been pushed across the rocky surface of the flow, vegetation has been killed off or removed and a 20 hectare area has been crunched, levelled and sown with pasture grasses. In addition, the growth of trees in softwood plantations has obscured the lower slopes of Mt Napier. The result is that the landscape values of the area have been significantly diminished and its value as an education and research tool may have been lessened.

Nevertheless, the flow remains the best preserved, dramatic and most readily observable flow in Australia. The flow also remains very important for Aboriginal and early European cultural heritage reasons. For these reasons, I am very pleased a Significant Landscape Overlay under the Victorian *Planning and Environment Act* will give legislated protection to the flow. However, as at 24 August 2018, the SLO has still not been gazetted and even after this happens, on-going vigilance will be required to ensure there is strict compliance.

## **Acknowledgements**

It is unlikely that I would have become involved in the Harmans Valley issue without Ian Lewis drawing my attention to recent developments in the Harmans Valley in October 2017. For this I am grateful.

I would especially like to thank Janeen Samuel for giving me access to Ken Grimes' emails, maps and papers on the Harmans Valley issue. Ken was working on the issue right up to the time of his sudden and tragic death in August 2016 and I wish to acknowledge Ken's long term commitment to raising public awareness of the importance of the Harmans Valley area and in documenting and seeking to protect its geological and cultural features as well as its landscape values.

I also acknowledge Emeritus Professors Ray Cas and Bernie Joyce in expanding my understanding of the Harmans Valley flow and the Newer Volcanic Province, through access to papers and stimulating discussions at Hamilton in March 2018.

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## Kanohina Cartography

Michael Sutton, Cave Conservancy of Hawai'i and Cave Research Foundation.

The braided maze of the Kipuka Kanohina Cave System, the second longest known lava cave, occupies a Mauna Loa flow of 750-1000 years b.p. situated on the south flank of the mountain. The earliest efforts to produce a map date from the late 60s and late 80s but nothing came of those attempts. Mapping really got started when Ric Elhardt and Rose Herrera opened the Kula Kai Caverns show cave in 1989 and with friends, began mapping their underground domain, including the neighboring Eli Cave. In 1999 a crew of National Speleological Society and Cave Research Foundation surveyors started mapping the many caves scattered around in the kipuka. The initial survey was primarily in Eli Cave and another large cave, Maelstrom. Late in 2000 Maelstrom was connected to Eli Cave by Joyce Hoffmaster via a tight squeeze. Soon after, Poha Cave was discovered by Don Coons and in November 2000, it was connected to Kula Kai. The following year, Poha was connected to Eli, integrating the four caves into one complex system. In 2001, New York based cavers discovered several entrances into the Cordwinder section, which connected to Maelstrom at several places. Later, Xanadu Cave, makai (down-flow) from Maelstrom, was connected to one branch of the latter via a dig.

The surveys of Eli and Maelstrom were plotted using the Compass cave survey software, but the earlier work preceded the advent of affordable computer drafting software. Maps of Kula Kai and Maelstrom were initially drafted in pencil on paper, and later transferred to Adobe Illustrator.

The Kanohina survey suffers from the problems with magnetic variability endemic to lava cave surveys. There is a nearly three degree difference in magnetic declination over the north-south extent of the system, and there are many localized variations. A normal protocol when running a large multi-year mapping program is to set up a compass calibration course, but this is of only limited use when the declination varies unpredictably over short distances. Localized variations result in foresight/ backsight discrepancies. This can be somewhat mitigated by keeping survey stations as far away from rock as practical, and the existence of numerous survey loops helps greatly, but the survey necessarily lacks the high precision of a typical limestone cave survey. The existence of numerous entrances has recently improved matters by using GPS locations, not dependent on the fickle magnetic field. However, this creates a serious practical problem in that the map already drafted no longer quite fits the survey line. A recent major revision of the survey net has therefore led to a great deal of cut and paste to wrestle the existing map onto the revised survey line. In recent years, a process known as round-tripping has become available. The entire map – survey line and passage detail – are imported together into the data reduction program and fitted to the revised survey. This should make further survey revisions easier to cope with.

The first and so far only completed map of the system is Bob Richards' 2003 award winning map of the Kula Kai section. Two further map sheets of about the same size as the Maelstrom sheet will be necessary to fully represent the existing system.



Figure 1: detail of the Maelstrom/ Cordwinder map.

**The History of Human Exploration and Occupation  
of the  
Lava Caves of the Zuni-Bandera Volcanic Field,  
New Mexico, USA**

By Harry Marinkis

In the high desert of New Mexico, in the Southwestern United States, is the Zuni-Bandera Volcanic Field (ZBVF) and hundreds of volcanoes, lava caves, and "ice caves." These caves have a rich history of occupation, exploitation, and exploration dating back almost 10,000 years. Native Americans have been using the caves for thousands of years. The caves attracted the attention of Europeans only about two centuries ago. Before then, the Spanish ignored the ZBVF and called the region "el malpais" - the badlands. During the past 100 years the caves narrowly avoided a nuclear blast, were bombed with high explosives, explored by rocket scientists, mined for guano and gravel, and finally protected as a National Monument. This is the history of the Zuni-Bandera lava caves.

# CIVIL DEFENSE CAVES OF HAWAII

by Peter Bosted

Hawai'i Speleological Survey

The Big Island of Hawaii is host to one of the greatest concentrations of large volcanic caves in the world. This was recognized in the 1960's when the State was mandated to identify shelters to be used in case of atomic war. While about half of the sites selected were hotels or other large buildings, the remaining sites were large lava tubes with enough room to hold hundreds of refugees. In some cases, these caves appear to have been well-known to local residents for many generations. Some of them may have been used in times of war in the pre-contact era. The civil defense authorities published lists of the cave locations in the local newspapers, placed yellow "atomic shelter" signs by the entrances, and in some case outfitted the caves with food, water, pit-toilets, and walls. In at least one case, school children were taken to the caves in emergency drill exercises. Members of the Hawaii Speleological Survey have used the lists to re-discover several of the caves that have largely been forgotten these days and fallen into neglect. Recent exploration of one of these has revealed a large and complex cave in the South Kona district with over ten km of passages. Maui Loa cave is not as long, but features huge passages, a scenic skylight and sunbeam, archeological artifacts, and an interesting pair of narrow labyrinth structures at each of the entrances. A labyrinth entrance is also found in Kalapana Cave of Refuge, with a second entrance overlooking the ocean on a vertical cliff-face. One of the entrances to Kazumura Cave, the longest lava tube in the world, was also a designated civil defense shelter.



***Tim and Janet Hughes with the remains of an old bed frame in a South Kona civil defense cave. Both photos by Peter Bosted***



***Glass water jugs, barrels that probably contained food, and stone walls.***

## **Early Explorers of the Modoc Lava Beds**

Bruce Rogers

Humans have roamed the Modoc Lava Beds for at least 5,000, perhaps as many as 11,000, years and most probably visited the caves in Medicine Lake Volcano during that time. Following the influx of white settlers in the 1820's-40's, visitors began exploring the "Beds." Local ranchers, especially Eugene Hopkins, stockmen, and settlers explored some of the more accessible and impressive caves, giving them descriptive and oftentimes whimsical names. In 1916, a newly settled four mill builder, Judd D. Howard, arrived, become enthralled with the area, and proceeded to explore the Lava Beds for nearly 25 years. He lobbied everyone he could and finally in 1925 Lava Beds National Monument was officially set aside. "JD" discovered, explored, and mapped many caves, giving many of them whimsical, classic, and local settlers and explorers names. Exploration lagged between about the early 1930's when the newly formed US Forest Service (USFS), then the Public Works Administration (PWA), and, finally the Civilian Conservation Corps (CCC) did about a decade of improvements in the Monument, including building cave trails and other facilities. A notable exception was during 1936, when Univ. California Berkeley's volcanologist Walter Glaeser spent more than a year locating and beginning mapping lava tubes with a shoe string budget (unfortunately due to a bureaucratic blunder, he was never paid for the work).

In about 1960 another local group, Spelunking Unlimited that was based in Klamath Falls, Oregon, began to explore and map caves. In 1964, the Park Service engaged newly graduated biologist Stewart Peck for a season and asked him to start mapping some of the approximately 300 lava tubes known caves; he managed to do about a dozen caves during his short season at the Monument. Modern organized cave studies started in 1972 when Dr. Aaron Waters of the USGS spent 4 years mapping the caves and wrote a lengthy paper on the geology of the area's spelean features. During the 1980's, NSS cavers began to realize the potential of the area and began exploring, mapping, and writing reports for the Park Service. Also in 1980 Dr. Julie Donnelly-Nolan, also from the USGS, located Waters' long lost paper and finally published it along with Waters and USGS geologist Bruce Rogers as USGS Bulletin 1673 in 1990. Since the late 1982 and early 1990's, the Park Service, San Francisco Bay Chapter, Shasta Area Grotto, and the Mother Lode Grotto of the National Speleological Society, Cave Research Foundation, and other groups pushed the known number of caves to about 600. That said, only about a quarter of the Monument itself has been systematically searched for lava tubes and much of the immediately surrounding US Forest Service land is virtually untouched. At present, continued exploration has located about 810 lava tubes are known from

within the Monument itself out of nearly 1600 in the surrounding counties.

A quarter million dollar Research Center was cooperatively planned by concerned caving community and the Park Service, financed largely by the caving community, and was opened in 2005 to all doing research and educational activities in the Klamath Basin.

# PELE'S SURPRISE

by Annie Bosted

Cave Conservancy of Hawaii and Hawaii Speleological Survey

The 2018 eruption of Kilauea on the island of Hawai'i from May 3 to August 5 is considered to be the largest eruption of that volcano in at least two centuries, in terms of both a higher volume and flow rate.

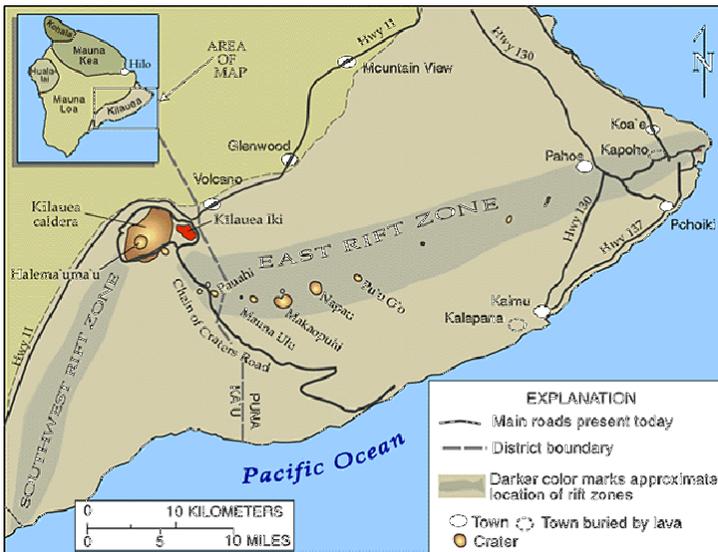
In this paper, I will draw on information supplied by the Hawai'i Volcano Observatory to illustrate changes in three areas of the volcano that were enormously affected by the eruption, namely the summit caldera, the Middle East Rift Zone (MERZ) and the Lower East Rift Zone (LERZ).

Lava erupted in the Lower East Rift Zone (LERZ), about 12 miles from the summit, in a residential subdivision

called Leilani Estates. In just a few months, the eruption spread about one cubic kilometer or more of molten rock over the lower Puna landscape, inundating homes, farms, businesses, roads, forests, shoreline and a lake. The eruption jolted the region with thousands of earthquakes (including Hawaii Island's largest in 43 years). The movement of lava from the summit to the LERZ resulted



***“A View From Above” shows the catastrophic force of a fast-moving lava flow from Hawai’i’s Kilauea volcano, seen here on May 19. The eruption destroyed nearly 700 homes and displaced thousands. PC: Bruce Omori—Paradise Helicopters/EPA-EFE/Shutterstock***



in 62 caldera collapse events at the summit, bringing the base of the crater to a level half way between the summit and sea level and leaving an enormous void.

Approximately a quarter of the amount of lava produced during the 35-year Pu'u O'o eruption in the MERZ was expelled in a matter of months in the LERZ. The voluminous activity was driven by several factors: a pressurized pre-eruption state at the summit and at the MERZ, and relative low elevation of the vents in the LERZ. This eruption again demonstrated a correlation between the magnitude of total co-ruptive summit deflation and vent elevation, with the greatest summit deflation coinciding with the lowest-elevation vents. Additionally, the summit collapses, which occurred as magma was drained from the reservoir, also could have driven magma to the vents.

This eruption was also famously destructive. The lava from 24 fissures covered 13.7 square miles, destroyed 716 homes, partially buried the Puna Geothermal Venture power plant, isolated 1,600 acres of farmland and caused damage by one estimate of more than \$800 million.

Over the four-month disaster, more than 2,000 residents were evacuated. The Hawaii Volcanoes National Park was closed, and the tourist industry was hard hit.



***With each large earthquake, ground shaking causes additional collapse within the Pu'u 'O'o crater, sending a plume of reddish-brown ash skyward. The size and vigor of a plume depends on the size of the earthquake and subsequent collapse. This roiling ash plume followed the magnitude-6.9 earthquake on May 4. Much of the rock within the crater is rust in color, which is a result of heavy alteration by acidic volcanic gases. When the rock is pulverized by a collapse event, the resulting ash plume is pink to reddish-brown ash plume. USGS photo by T. Neal.***

# The New Survey Result On Lava Cave System In Krongno Volcano Geopark, Dak Nong, Vietnam, In 2017-2018

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**Key words:** lava cave; lava lake; lava lining; endogenous entrance; sub-crustal lava cave.

**1. Introduction:** Recently, Vietnam is well-known as an emerging and leading country on lava cave in Southeast Asia and plays an important role not only in Asia but also in the world in the field of volcano geological heritage and volcano geopark as well.

The research on geological heritages, especially volcano geological heritage and lava cave in Krongno area and the vicinity, with the aim to establish Krongno Volcano Geopark (KVG) in Dak Nong province, The Central Highlands of Vietnam, has been started from 2007 by Dr. La The Phuc and his colleagues in the frame of a scientific project funded by UNESCO<sup>1)</sup>. Lava caves in the area have firstly been discovered during the implementation of this project. The discovery of the lava cave was immediately released to the world by the project's leaflets and Vietnamese news. Catching the news, the NPO Vulcano-Speleological Society (VSS) of Japan independently conducted a preliminary survey in 2012 and then conducted some joint surveys and studies between Vietnam and Japan from 2013 until 2015<sup>2-8)</sup>. In the first collaborative stage, as a result, 11 lava tube caves have been measured and one of them (C7) was registered as the longest lava tube cave in Southeast Asia of 1066.5m long. Containing a series of typical and marvelous lava interior formations, so in the KVG Dossier prepared by VNMN, the C7 cave is ranged as an international geological heritage.

The total length of the 11 lava caves measured in the first stage is 4832.5m long (Table 1; Fig.1).

In the second stage from 13th February to 25th 2017, as a contract work between Vietnam National Museum of Nature (VNMN) and VSS, in the frame of the project entitled “*Study and assessment of geological heritages, construction of the geopark in the Krongno area, Dak Nong province*” funded by Dak Nong province, 4 lavacave more have been surveyed and measured including: P8; P11; P20 and P1 + P2 with the length of 1940.7m. In this stage, the P8 and P20 have been measured therefore are considered as two deepest caves in KVG of 26m and 25m deep, respectively (Table 1; Fig.1)<sup>9)</sup>.

The third stage conducted by Vietnamese members for 5 lava caves: P3; P5; P10; PT06 and T1 with the length of 948.1m (Table 1; Fig.1)<sup>10)</sup>.

The discovery of archeologic stone wares etc. in P1/P2 cave and previously measured C61 cave and the biological aspects of the caves are an important human heritage for a volcanic cave Geopark<sup>10)</sup>. As the biological and archeological aspects of these caves are discussed in the other paper<sup>10)</sup>. So, in the paper, only the topology and the structure of the lava caves, those surveyed and measured in 2017-2018 (the second and the third stages) will be mentioned.

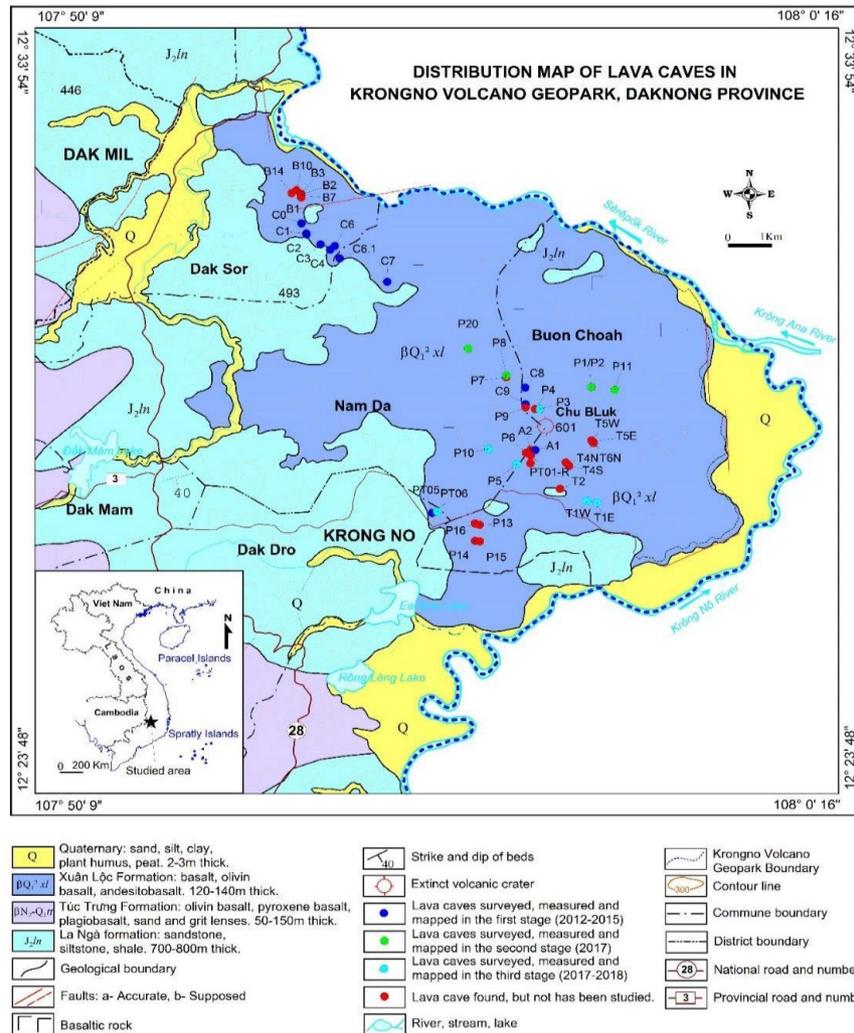


Fig.1. Distribution map of lava caves in Krongno Volcano Geopark, Dak Nong province, Vietnam.

**Table 1. List of 20 lava caves surveyed and mapped in Krongno Volcano Geopark, Dak Nong, Vietnam up until March 2018<sup>1-10)</sup>**

N <sup>o</sup>	ID	Location	Longitude	Latitude	Length (m)	Depth (m)	Entrance type
The lava caves surveyed, measured and mapped in the first stage (2012 – 2015)							
1	C0	Dak Sor	107° 53' 32.87"	12° 31' 18.69"	475.5	14.9	combined
2	C1	Dak Sor	107° 53' 34.35"	12° 31' 11.00"	402.0	3.5-4.5	secondary
3	C2	Dak Sor	107° 53' 35.39"	12° 31' 10.04"			secondary
4	C3	Dak Sor	107° 53' 47.24"	12° 31' 2.35"	716.3	7.3	secondary
5	C4	Dak Sor	107° 53' 52.28"	12° 30' 57.91"	251.5	9-10	secondary
6	C6	Dak Sor	107° 53' 57.02"	12° 31' 0.91"	180.3	4.3	secondary
7	C6.1	Nam Da	107° 53' 59.76"	12° 30' 51.23"	293.7	4.6	secondary
8	C7	Nam Da	107° 54' 35.12"	12° 30' 32.47"	1066.5	15-20	combined

9	C8	Buon Choa'h	107° 56' 19.20"	12° 29' 8.53"	791.0	23.8	secondary
10	C9	Buon Choa'h	107° 56' 20.03"	12° 28' 55.59"	217.0	22.6	combined
11	A1	Buon Choa'h	107° 56' 28.73"	12° 28' 19.67"	438.7	10	combined
<i>Total length of 11 caves surveyed, measured and mapped in the first stage:</i>					<b>4832.5 (m)</b>		
The lava caves surveyed, measured and mapped in the second stage (2017)							
12	P1, P2	Buon Choa'h	107° 57' 10.14"	12° 29' 8.57"	530.5	15-18	secondary
13	P8	Nam Da	107° 56' 5.74"	12° 29' 18.07"	344.1	26	primary
14	P11	Buon Choa'h	107° 57' 28.24"	12° 29' 5.97"	498.1	7-9	secondary
15	P20	Nam Da	107° 55' 37.67"	12° 29' 39.58"	568.0	25	primary
<i>Total length of 4 caves surveyed, measured and mapped in the second stage:</i>					<b>1940.7 (m)</b>		
The lava caves surveyed, measured and mapped in the third stage (2017 - 2018)							
16	P3	Buon Choa'h	107° 56' 32.87"	12° 28' 51.52"	81.0	5	secondary
17	P5	Buon Choa'h	107° 56' 13.01"	12° 28' 8.86"	204	4.2	secondary
18	P10E P10W	Nam Da	107° 55' 54.22" 107° 55' 52.45"	12° 28' 20.06" 12° 28' 20.82"	160	4.5	secondary
19	PT06	Dak Dro	107° 55' 16.68"	12°27'28.62"	200	5	secondary
20	T1	Buon Choa'h	107° 56' 59.80"	12° 27' 42.69"	303.1	16	combined
<i>Total length of 5 caves surveyed, measured and mapped in the third stage:</i>					<b>948.1 (m)</b>		
<i>Total length of 20 lava caves surveyed and mapped in the 3 stages:</i>					<b>7721.3 (m)</b>		

**2. The caves surveyed, measured and mapped in the second stage:** They include the following caves: P1/P2, P8, P11 and P20.

**[Cave P1/P2]** The P1/P2 location is shown in Fig.1, and the structural map and its features are shown in Fig.2 and photo-1~photo-6. The cave is located 1.450m northeastern of the Chu B'Luk volcano. It is a compound cave in which the caves of P1, P2 overlap each other. This is a close subsurface lava cave with a total extension distance of 530.5m. P1/P2 cave was formed from lava flows originated from Chu B'Luk volcano in the southwest. Lava flows forming the P1/P2 cave occurred in various/episodic phases, in which later lava flows altered, and cause instability to, the previously formed structure of

the cave, even collapsed the ceiling in some place and created the secondary entrance and skylights of this cave system.

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P1/P2 cave has thin and unstable ceiling layers, which make it dangerously easy to collapse and the geoheritage to be destroyed.

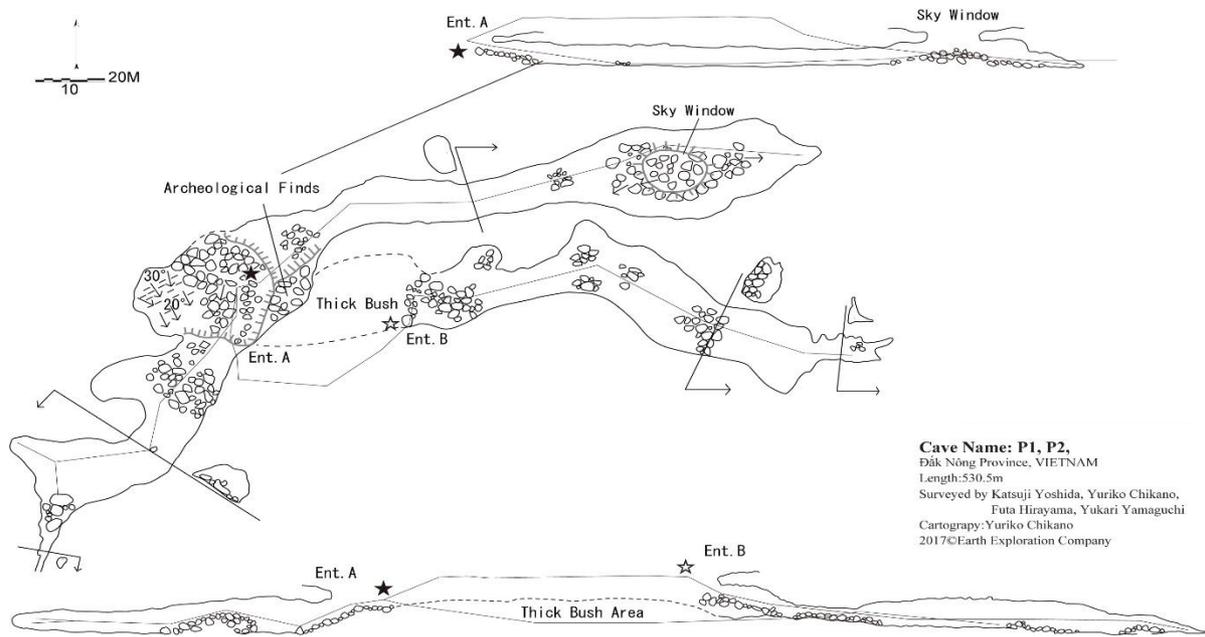
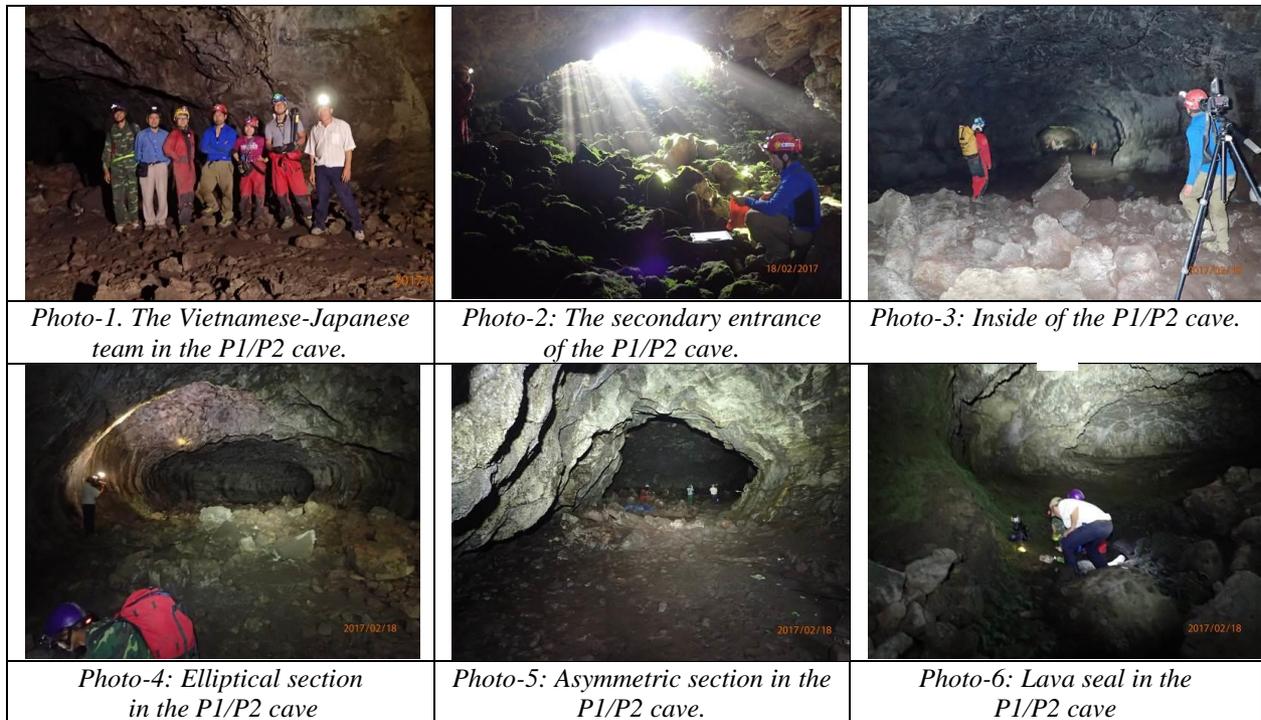


Fig.2. Structural map of the P1/P2 lava cave.



**[Cave P8]** The overall cave shape is shown in Fig.3. This is a lava tube cave with a total extension distance of 344.1m and 26m in depth with a vent hole. The cave is 1,556 m northwest to the Chu B'Luk crater (Fig.1) and was created from a high-temperature lava flow, gas rich, low

viscosity, ran along a quite deep valley. Hence, the cave ceiling layer is quite thick and has very large fluctuation: most anticipated thickness can be up to over 20m in upstream area and ultra thin, only about a few dozen centimeters at the cupolar in the downstream of the cave.

The P8 cave entrance is a typical primary type, formed due to the busting lava gas. Therefore, the P8 entrance is quite round and deep vertical to 26m as mentioned above. In fact, it is also a skylight (vertical opening of vent hole) of the P8 cave.

Photo-7 to Photo-15 show some features inside of the P8 lava cave. Stalactites and stalagmites in the cave could be considered probably as calcium carbonate or silicate, so they need to be studied more in details in the future.

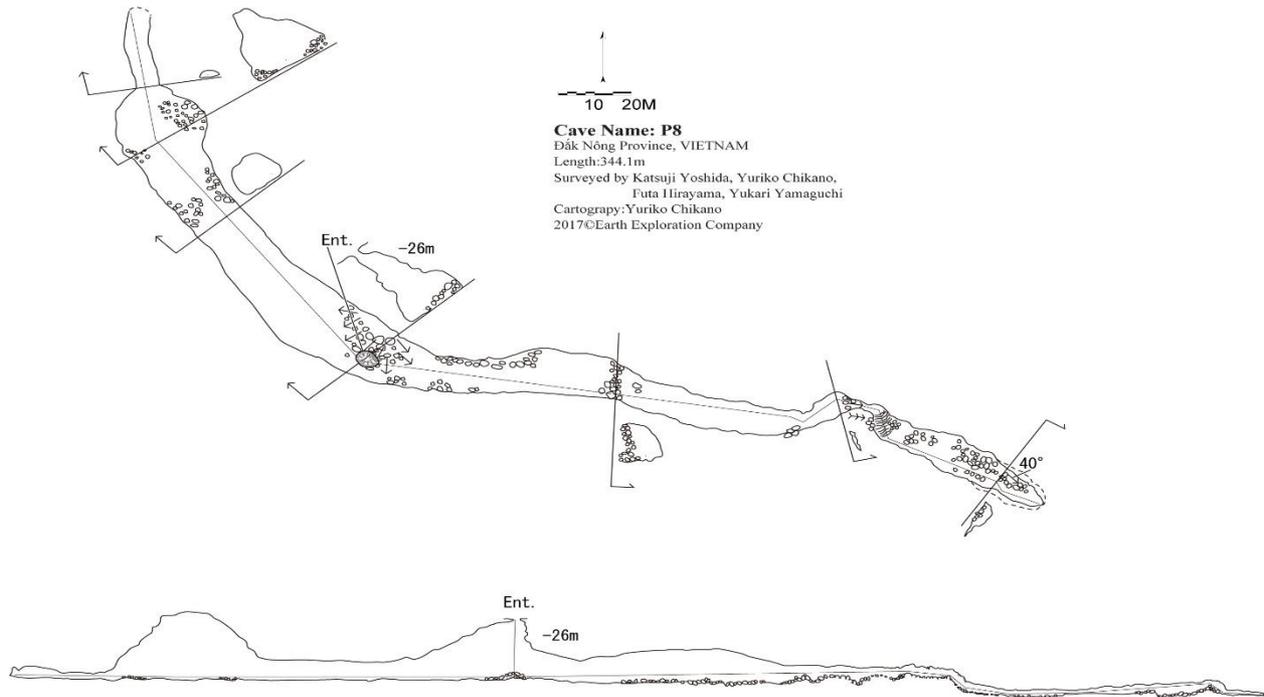


Fig.3. Structural map of the P8 lava cave.

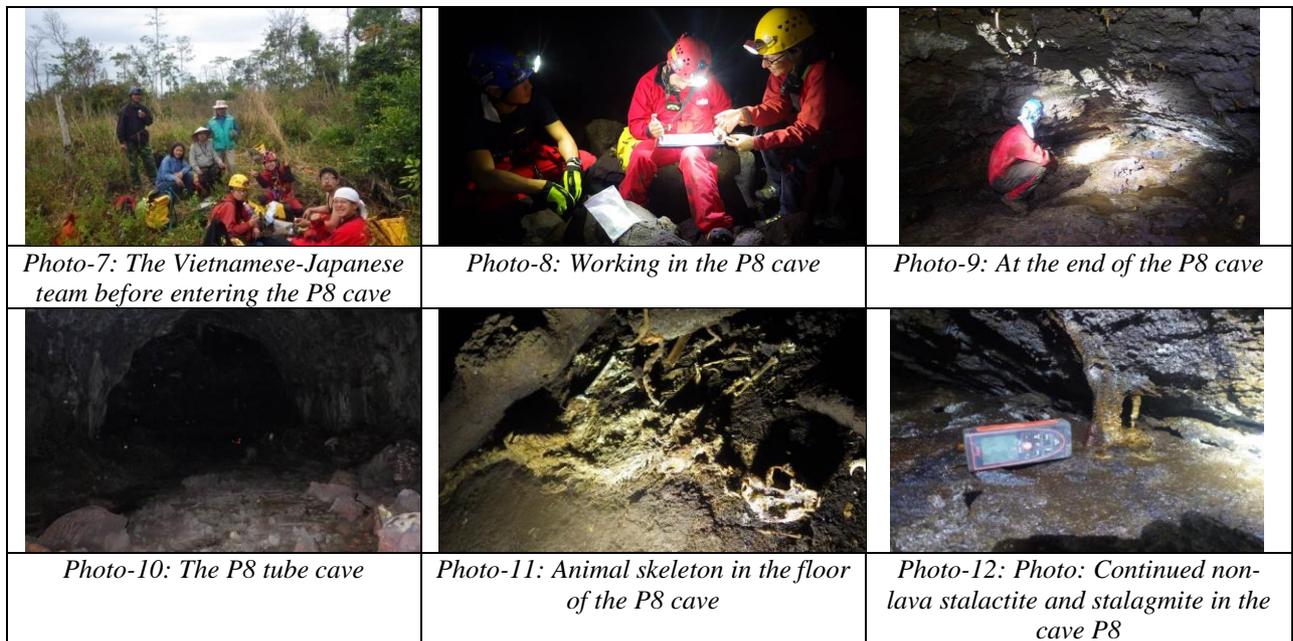




Photo-13: Inside of the P8 cave



Photo-14: Endogenous entrance in P8 cave



Photo-15: Secondary stalagmite in P8 cave

**[Cave P11]** The overall cave shape is shown in Fig.4. This is a lava tube cave with a total extension distance of 498.1 m.

P11 Cave is located 1,853m in the northeast of Chu B'Luk volcano, near the east of the P1/P2 cave. The P11 cave mainly developed from northwest to southeast; although its middle section bended towards the sub-latitudinal direction, possibly due to impacts from the paleo-terrains. This part has collapsed and created two entrances facing each other: East and West (Fig.4).

Due to the fact that the P11's cave chamber is fairly wide with appealing dome-shaped ceiling (elliptic cross section), and a flat floor, the name proposed was "Krongno Hall Cave" to allude to its fancy (Figure 5, 6). So the P11 cave has great potential for geo-tourism thanks to its many inherent values. Photo-16 to Photo-24 show some typical features of the P11 lava cave. There are two types of stalactites in this cave: primary and secondary origin with unique drapery (flag) type. Stalactites are considered probably as calcium carbonate or silicate.

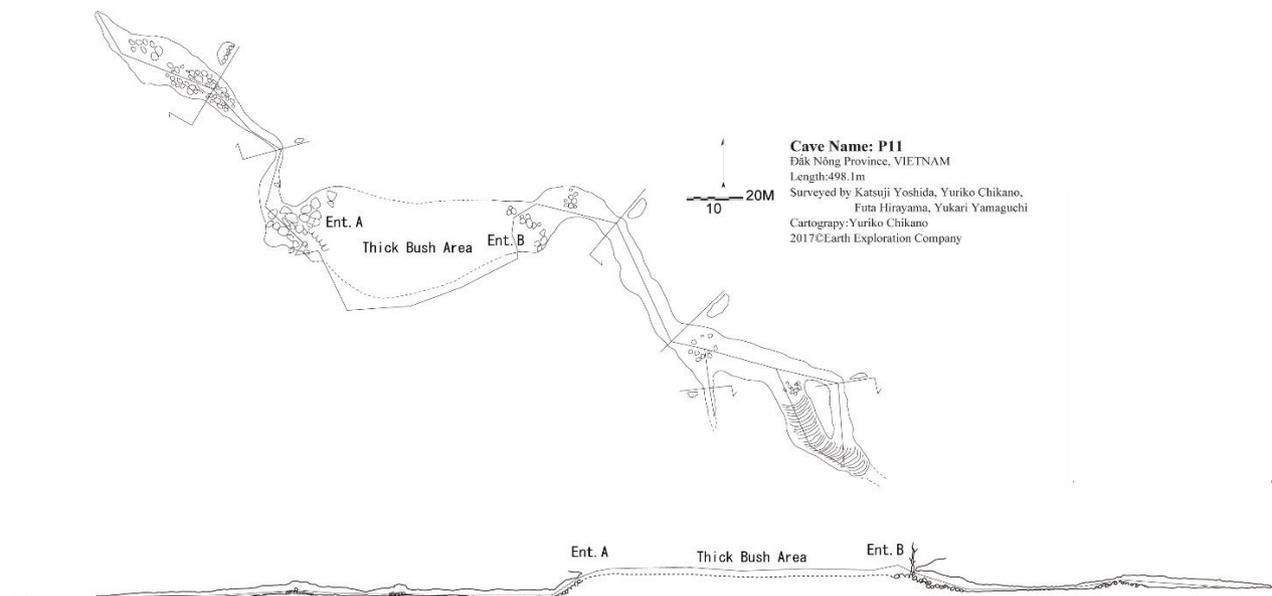


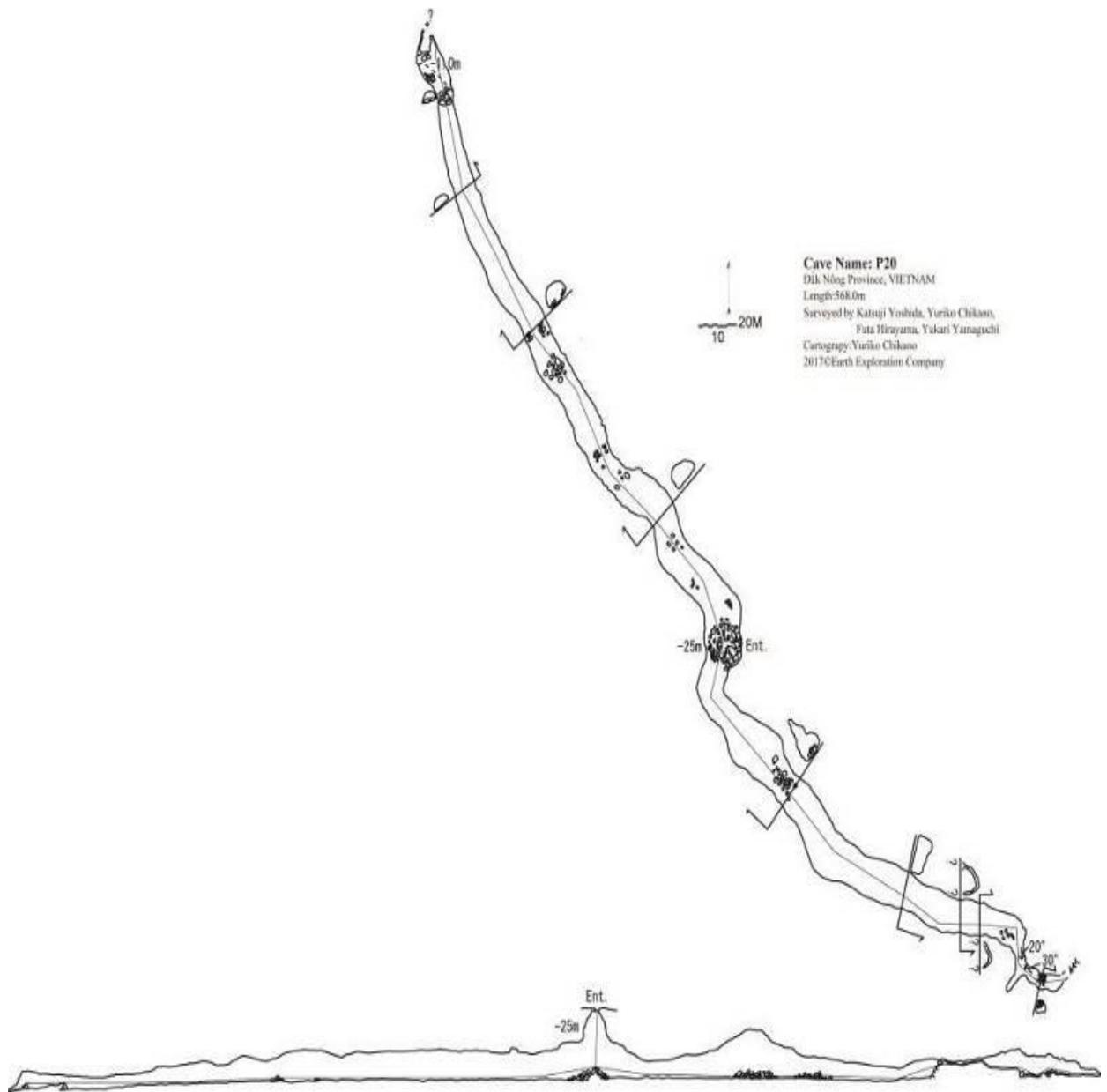
Fig.4. Structural map of the P11 cave.

		
Photo-16. Krongno Hall - The main chamber of the P11 cave	Photo-17. Lava levee in P11 lava cave	Photo-18. Lava flow direction in the floor of the P11 lava cave
		
Photo-19. Semi-rounded lava linings in the P11 lava cave	Photo-20. Lava flows drained at the end of the P11 lava cave	Photo-21. Primary stalactites on the ceiling of the P11 lava cave
		
Photo-22. Upstream of the P11 lava cave	Photo-23. Drapery non-lava stalactites in the P11 lava cave	Photo-24. Primary stalactites on the P11 lava cave's wall

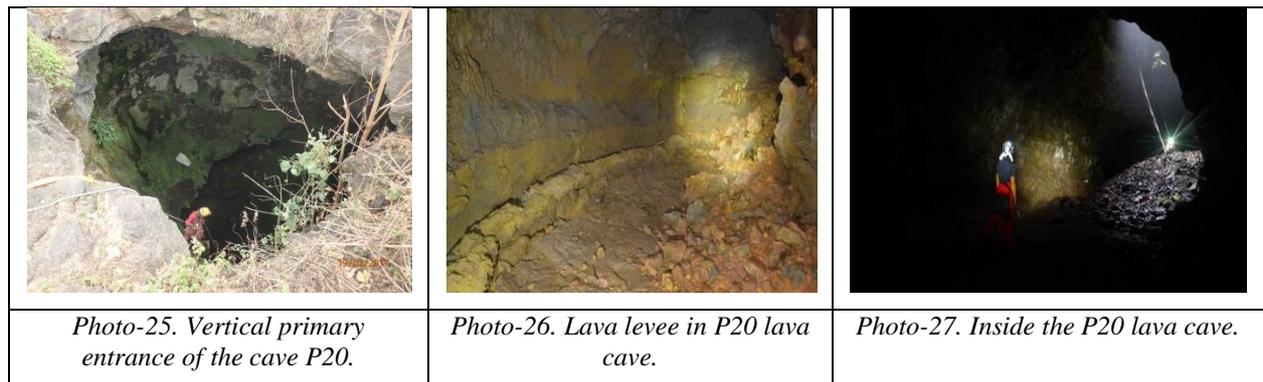
**[Cave P20]** The overall cave shape is shown in Fig.5. This is a lava tube cave with a total extension distance of 568.0 m. The P20 interior features will be illustrated in photo-25 to photo-31.

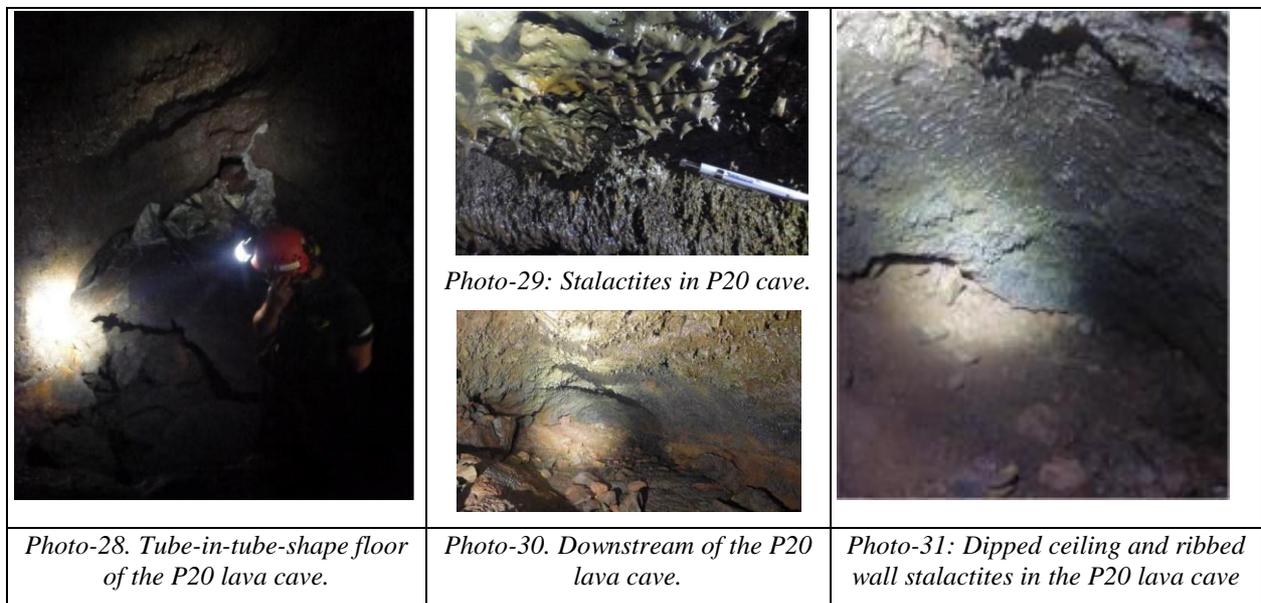
The P20 cave is located 2,602m from the Chu B'Luk crater to the northwest, just south of the C7 cave, on the same axis (Fig.1). Due to being formed from a large lava flow, the P20 has a very thick cover and up to > 15m. The ceiling cover is basically thick and relatively stable, although some sections of the cavern are still in the ceiling, leaving the products to collapse on the cave floor.

Similar to the P8 store, the P20 store is also of primary origin as it is formed by the discharge of lava from a chamber of high pressure gas in a lava tube. P20 cave is a volcanic cave formed from a lava flows flowing in the valley of paleo-terrain should have large thickness, with the direction of stable development from the Southeast to the Northwest. The width of the cave from upstream to downstream remained relatively stable, average from 12m-15m. Most of the lava formations in the P20 cave are re-melted and "enameled" by the high temperature of the late lava flows.



*Fig.5. Structural map of the P20 cave.*





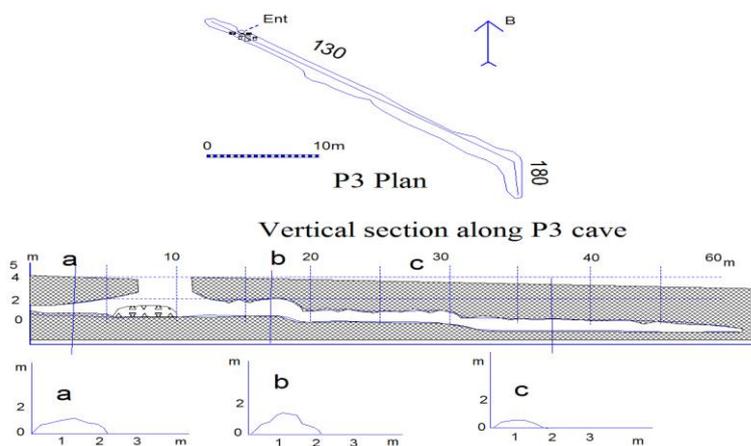
**[Cave P3]** P3 lava cave is quite close to Chu B'Luk volcano, just 473 m in the north-northwest (Fig.1). The P3 interior features will be illustrated in photo-32 to photo-37.

This is a cave with a less complex formation and structure than other caves, which reflects the lava flow with large energy, rich in gas. Originally, the lava flow in the straight direction toward the crater, then it changed direction aligning with a trench (NW-SE direction) of the paleo-terrain. P3 has many sections with roof collapse that created breakdowns, which make going in and out rather difficult.

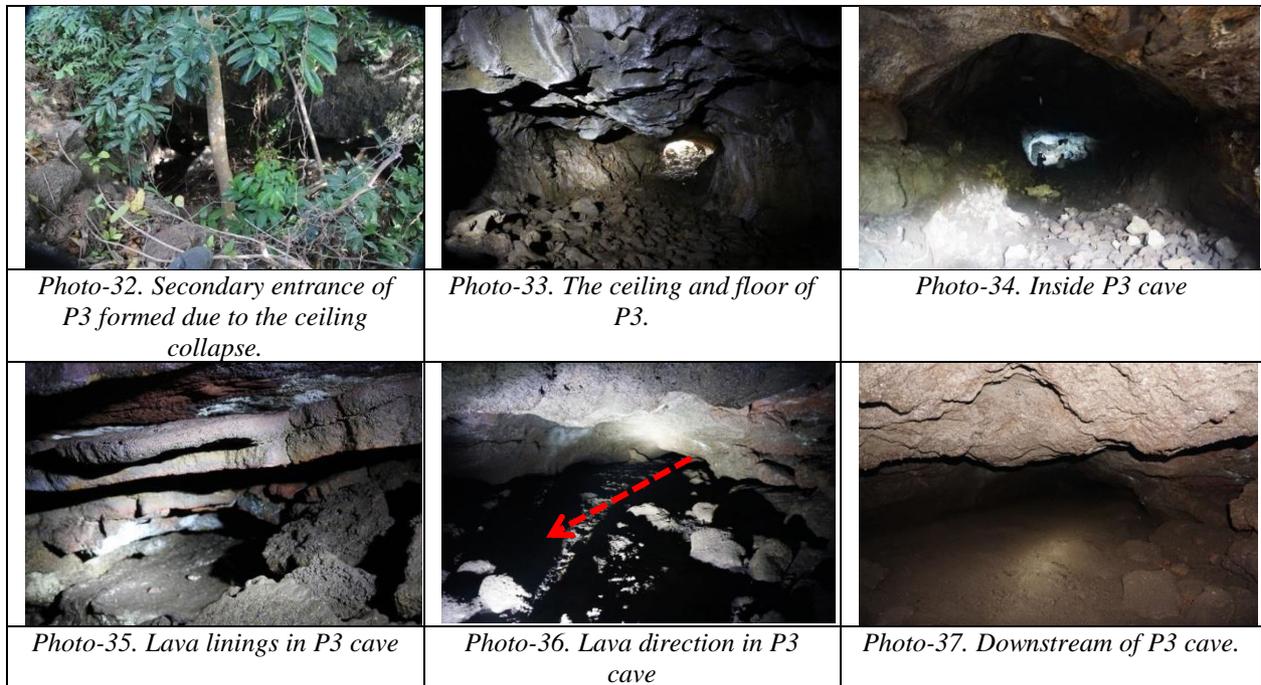
Cave P3 has a single and relatively circular entrance formed by roof collapse.

Overall development direction of P3: Besides the short section of the cave of 5m running in the sub-longitudinal direction; the rest of P3 developed in linear towards the southeast - northwest  $310^{\circ}$ (Fig.6).

P3 has relatively flat floor that is lower in the upstream in the southeast and gradually higher in the northwest, concave ceiling. These created 2 high level distinctive from each other, where lever 1 is the lower section in the SE (Fig.6).



*Fig.6. Structural map of P3 lava cave.*

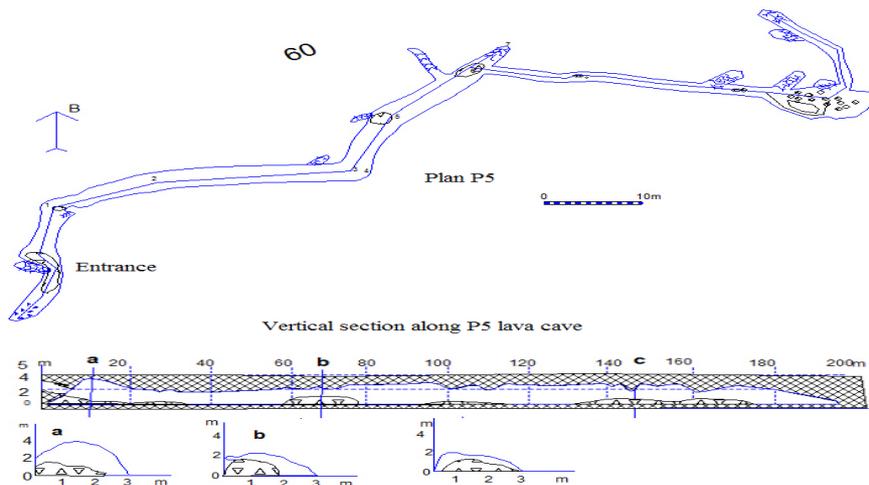


**[Cave P5]** Cave P5 is located about 1.080m to the southwest of Chu B'Luk crater (Fig.1). It developed quite zigzag due to the paleo-terrain, where the lava flows were controlled (Fig.7).

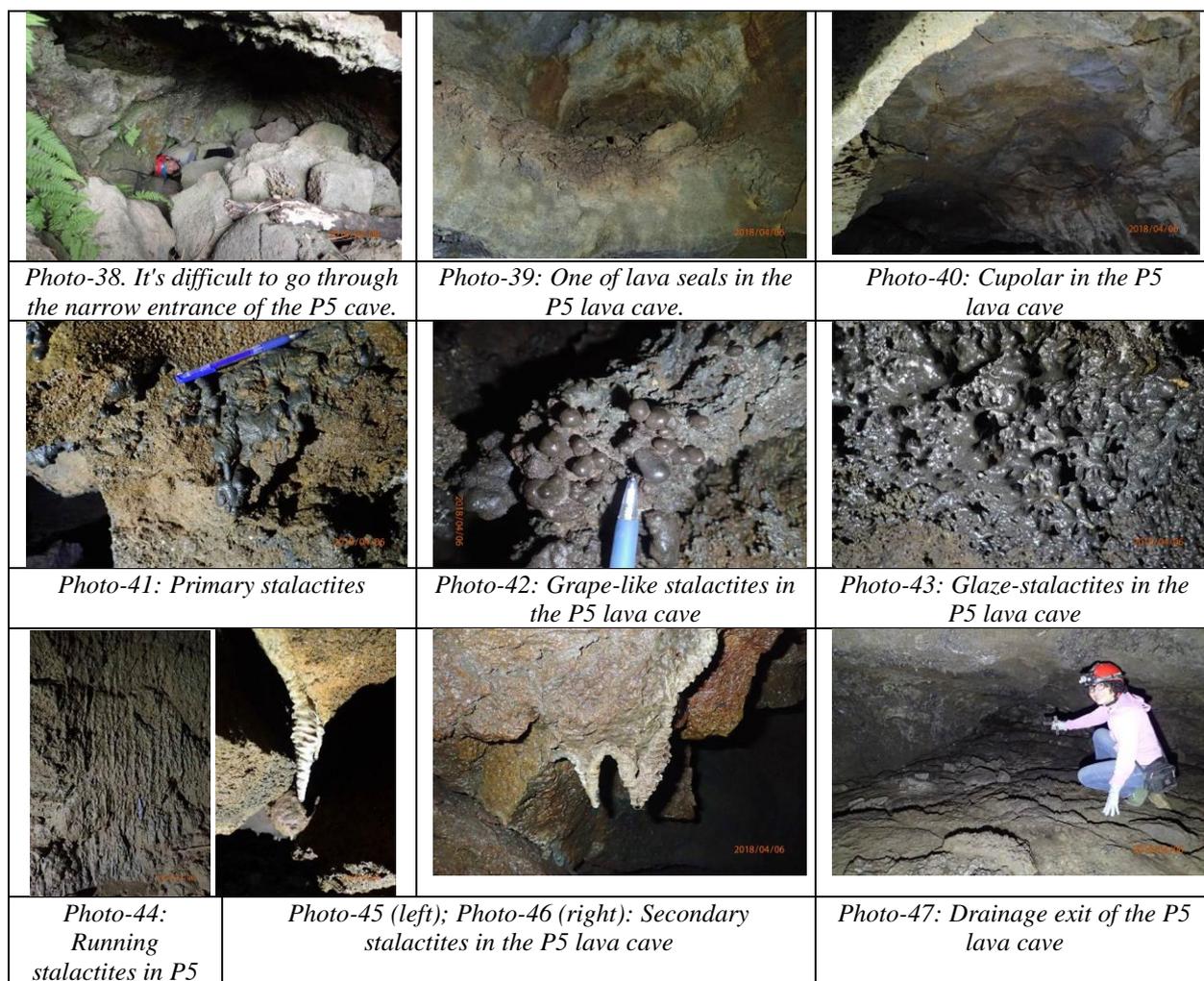
There are many seals developed in the cave, where late lava flows run into the main tube through lava skylights, then those windows were

sealed. The only sole mixed entrance is in the Southwest downstream of P5 lava cave.

The P5 interior features will be illustrated in photo-38 to photo-47.



*Fig.7. Structural map of the P5 cave.*



**[Cave P10]** P10 is located 1,310m northwest of Chu B'Luk volcano (Fig.1). Cave P10 is a subcrustal, shallow, extend in sub-latitudinal linear, and non-stratified (Fig.8). The P10 interior features will be illustrated in photo-48 to photo-57.

The cave has two entrances of secondary origin, as they are formed from roof collapse in the middle of the cave: East entrance facing west and West entrance facing east. These two entrances are formed from a cave ceiling collapse about 10m wide near the upstream of the cave, dividing

the cave into two branches: east branch and west branch.

Cave P10 is the only surveyed cave in KVG that turns out to be subcrustal lava cave, with a different mechanism of formation from other caves.

P10 is a shallow, semi-submerged cave with a roof cover from 1m to 1.5m.

The P10 is subcrustal lava cave, small in size, formed by the gas pressure in the lava flow that pushes the hard shell above it. Some authors

(Stevenson, 1999; Ken G. Grimes, 2002; Gadányi P, 2010) explained that the mechanism of this cave formation was due to the high pressure in the

lava tube which raised the hard shell up to form a cave, (blister or inflation).

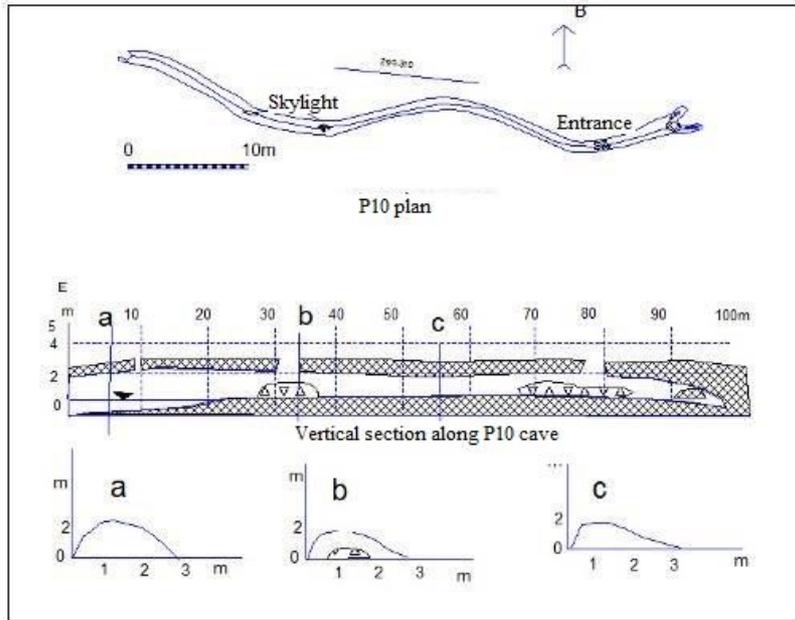


Fig.8. Structural map of P10 cave.



Photo-48: The P10 lava cave looks like the Tunnel of General Christian de Castries in Dien Bien Phu Battle on the fairly flat basaltic terrain in Nam Da commune.



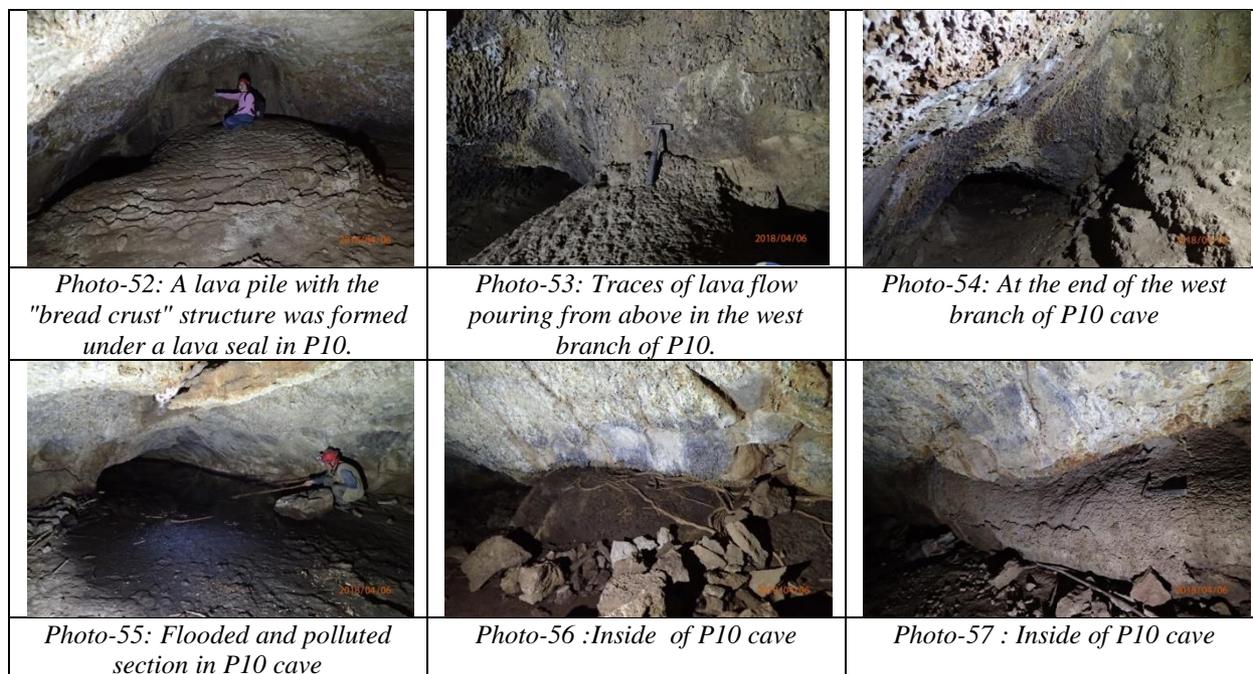
Photo-49: Pahoehoe is trace of the latest lava flow in the roof of P10.



Photo-50: Skylight due to collapse in P10 lava cave

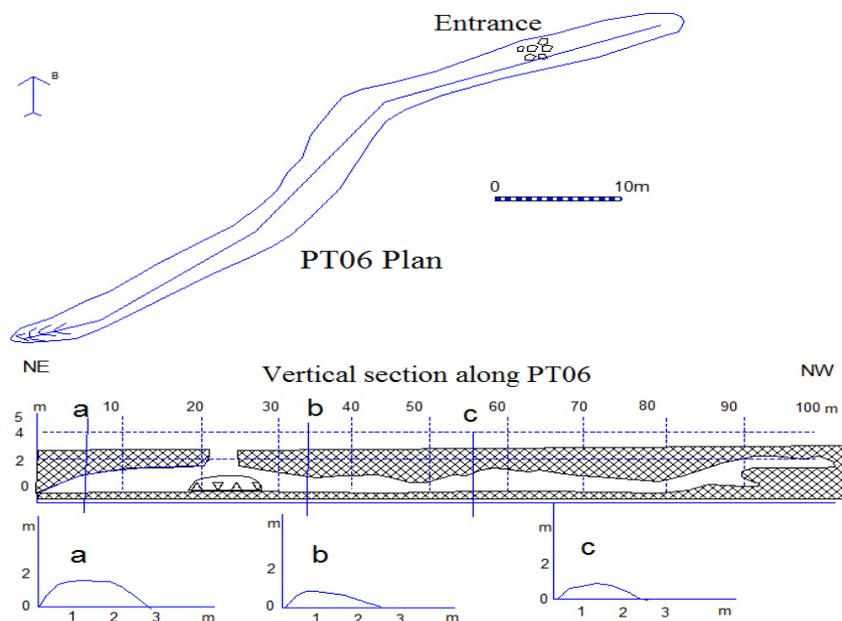


Photo-51: Crack along the P10 ceiling



**[Cave PT06]:** The PT06 is located 3,240m northwest of Chu B'Luk volcano (Fig.1). The cave is formed from lava flowing from the Chu B'Luck volcano in the northeast to the southwest with a fairly flat trough on the paleo terrain. This

cave has a mechanism of formation as well as a simple cave structure with traces of overflow on the surface of paleo terrain. PT06 floor is composed of products that are very messy, rugged and difficult to go.



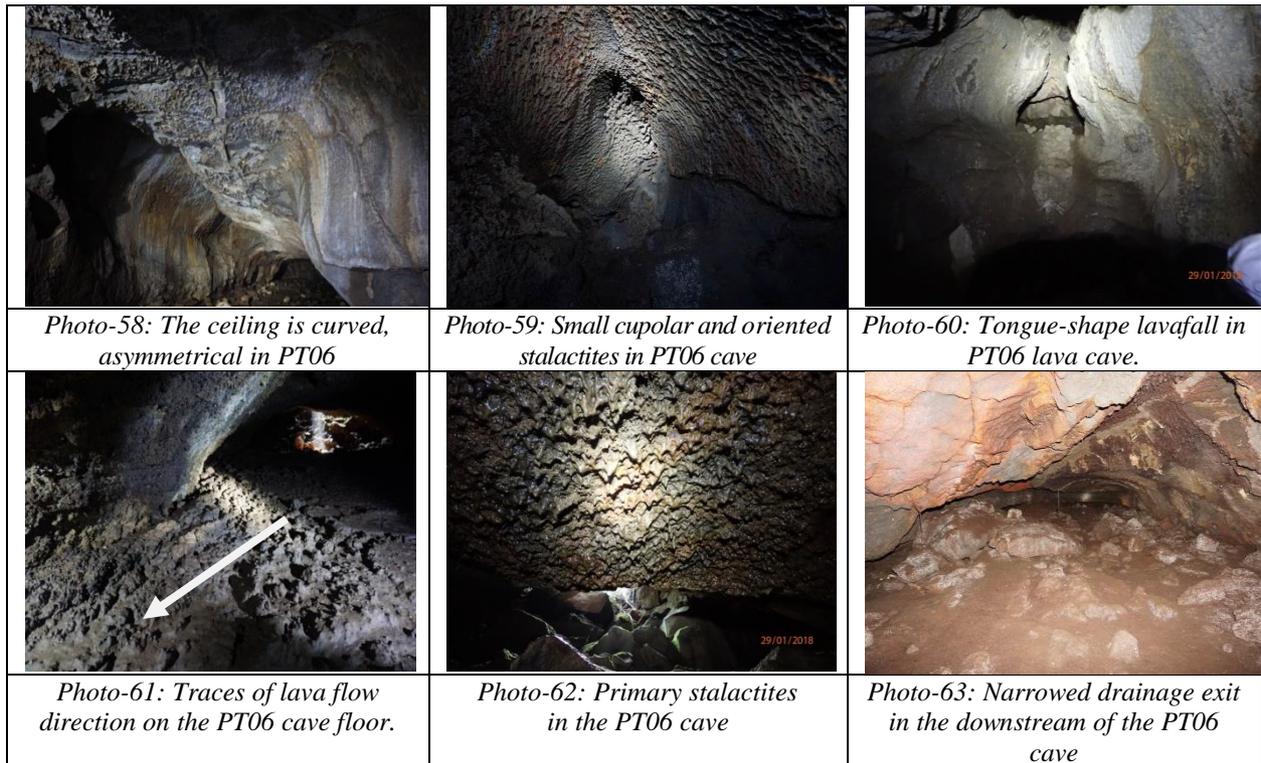
*Fig.9. Structural map of PT06.*

With the length of 193,0m, PT06 has only one entrance located northeast of the cave. PT06's entrance is a secondary entrance, formed by the process of cave ceiling, narrow entrance cave entrance.

Lava flows originating from Chu B'Luk volcano in the northeast flowing to the southwest, and clinging to the valley of paleo-terrain (NW-TN direction) on the basis of simple terrain, creating a simple lava cave (Fig.9).

Lava flows of the next eruption phase also have low viscosity flowing into the cave area, creeping into the cracks as well as various layers of lava that make up the pahoehoe structure. On the ceiling of PT06 developed some oval shaped cupolars. These cupolars are the result of the gas accumulation of the lava flow during cave formation.

The PT06 interior features will be illustrated in photo-58 to photo-63.



**[Cave T1]:** T1 cave is located 1,830m south-east of Chu B'Luk volcano (Fig.1). The cave direction develops from northwest to southeast. With the length of 303.1m and two secondary entrances, T1 cave is one of the very complex structure caves bearing many unique interior lava formations. The T1 interior features will be illustrated in photo-64 to photo-72.

The mechanism of formation of the T1 cave is very complex, as the basalt lava flows of Chu

B'Luk volcano from the northwest run to the southeast and cling to a valley of paleo terrains with an undirected direction. The T1 cave with thick cover. Interior formation in the cave has many unique formations on the regional level, such as: pahoehoe and A'a lava, lava flow, lava waterfall, lava window, lava seal, lava lake, pipe-shape linings, primary and secondary stalactites, pillow-shape lava considered unique geological heritages in the region as well as in the world.

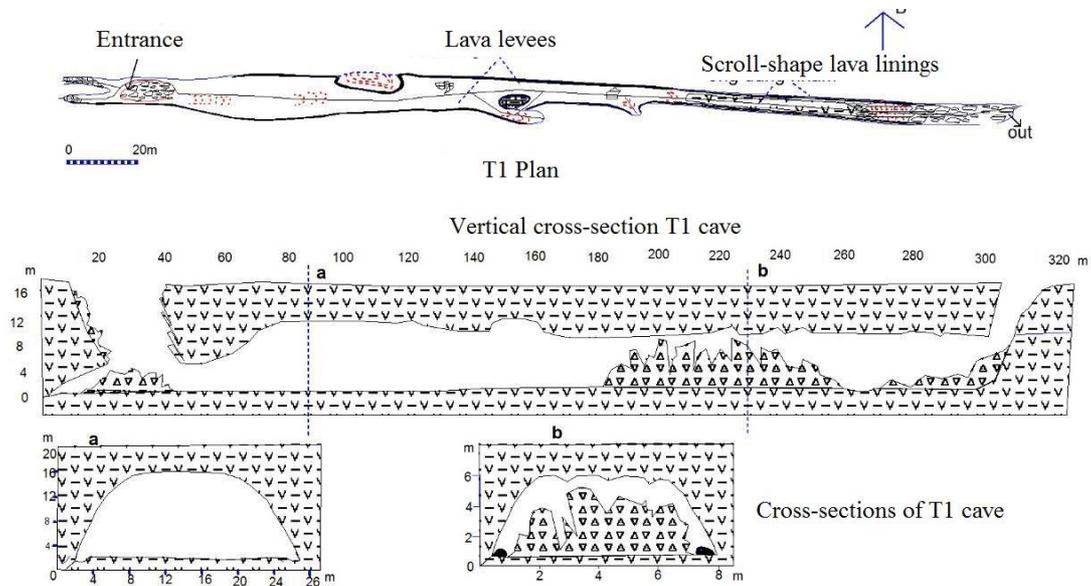


Fig.10. Structural map of the T1 lava cave.

<p>Photo-64: Western entrance of Cave T1, viewed from inside</p>	<p>Photo-65: The gas holes with some cm deep in T1 lava cave linings</p>	<p>Photo-66: A big cupolar in T1 cave</p>
<p>Photo-67: Seal-shape lava pile in the foot of a lava seal in T1 cave</p>	<p>Photo-68: Secondary stalactite in the T1 lava cave.</p>	<p>Photo-69: Lava lake in T1 cave</p>
<p>Photo-70: Pipe-shape lava linings in T1 cave</p>	<p>Photo-71: Pillow-shape lava in the T1 cave</p>	<p>Photo-72: Secondary stalactite in T1 cave</p>

### 3. Concluding remarks and future work:

According to results of the 2017-2018 surveys, there are many new discoveries on the KVG lava caves:

- Besides lava formations with their endogenous genesis such as dipped and ribbed lava, tube-in-tube shape structure, pipe-shape linings, pillow-shape lava, etc., of molten lava on the ceiling, wall and floor, we have also discovered other non-lava formations (secondary genesis): secondary stalactite/stalagmite; drapery-shape stalactite, rose-shape stalactite etc.
- Besides almost ordinary lava tube caves those are lower than topography surface, we have surveyed, measured and mapped P10 lava cave as an only subcrustal lava cave of KVG.
- Many archaeological relics have been found in some KVG lava caves opening a new chapter for prehistoric archaeology and Anthropology in Vietnam and Southeast Asia as well.
- Further observation and analysis will be required by experts or specialists. Further investigation and exploration will be continued and planned without artificial environmental destruction damage, even though research excavation will be required for archaeology.
- Both natural and cultural values in the KVG lava caves contributed the most important content in the KVG's Dossier, that planed will be submitted UNESCO in November 2018.

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# Lava Caves, Lava Formations And Biological And Archaeological Values Firstly Discovered In Krongno Volcano Geopark, Dak Nong, Vietnam

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**Key words:** lava cave, lava formation, lava tree mold, Krongno Volcano Geopark.

**Abstract:** The lava caves or volcanic caves have been discovered in Dak Nong Province since 2007, in the frame of a scientific project sponsored by UNESCO. They now become the key geological heritage of Krongno Volcano Geopark (KVG), Dak Nong, Vietnam. The results of the collaborative surveys and studies between Vietnam geologists and the NPO Vulcano Speleological Society, Japan from 2012 to March 2018 have discovered a total of 45 caves, in which detailed mapping for 20 caves with the length of 7721.3m, including confirmation of endogenous origin for the lava cave system. Up to now, the lava caves in KVG have been studied and recognized heritage values on the three fields: geological, biological and cultural-archaeological as well.

Speleothem/lava cave formations in the lava caves in KVG are considered as valuable and unique geoheritages for geotourism development. They play an important role to interpretate/explain the formation mechanism of the lava cave system there. Therefore, studying speleothem/lava cave formations in lava caves in KVG are considered as important task of the Vietnamese and Japanese scientists. Some initial studying results on the lava tube caves, their typical and unique speleothem/lava cave formations, biological and archaeological values will be presented in the paper.

(The paper was conducted under the financial support to: the science and technology project entitled “Study and assessment of geological heritages, construction of the geopark in the Krongno area, Dak Nong province” provided by Dak Nong province and the National Science and Technology project “Survey and study of volcanic cave heritages with the aim to construct on-site conservation museums in the Central Highlands, taken Krongno Volcano Geopark, Dak Nong province as an example (2017-2020)”, coded TN17/T06 within the Tay Nguyen Program 2016-2020 period).

## 1. Introduction<sup>1)</sup>:

Krongno Volcano Geopark (KVG) is located in the northern part of Dak Nong province, The Central Highlands of Vietnam and based on the main geological heritages related to the volcanic activities in the late Cenozoic stage. Up to now, five volcanoes have been discovered in KVG. However, Chu B’Luk is only one that produced lava cave system in

the eastern part of the geopark. The lava cave system has been known after discovery of La The Phuc and colleagues in the frame of the project “Survey, study of geological heritages with the aim of establishing geopark and protect environment in the Trinh Nu waterfall area, Cu Jut district, Dak Nong province”, (2007-2008) funded by the Vietnam National Commission for UNESCO<sup>1)</sup>. Since then,

lava caves become object of scientists, especially geologists.

## 2. Geological setting<sup>2~5</sup>:

KVG is located in the southern part of The Central Highlands of Vietnam (Fig.1), which is strongly affected by the collision of three major tectonic plates, namely the Eurasia, Indo-Australian, and Pacific. KVG and its adjacent area have a very complicated geological development history. *Before the Cambrian, this was* in the Kon Tum terrane/uplift. This is one of the Precambrian-continental reefs in the Phanerozoic. Geological formations, which are still preserved and exposed on the surface of KVG and its adjacent area, are authentic evidence reflecting the history of KVG development, including (mainly) four stages:



Figure 1. KVG on the map of Asia.

Period 1 - Mountain forming from the Permian to the Triassic period, forming the Truong Son orogenic belt, along with the S-type batholith granitoid whose zircon age (TIMS) was about 260-245 million years.

Period 2 - The passive continental margin in the Early - Middle Jurassic, forming terrigenous sedimentary rocks of Dray Linh ( $J_1dl$ ), La Nga ( $J_2ln$ ) and Ea Sup ( $J_2es$ ) formations.

Period 3 - The active continental margin with the presence of Dinh Quan ( $\delta-\gamma\delta-\gamma J_3dq$ ), Deo Ca ( $\gamma\delta K dc$ ) and Ca Na ( $\gamma K_2cn$ ) formations.

Period 4 - Planation and basaltic eruptions of continental diffusion. The stage of Paleogene ((Paleocene-Oligocene) began with the erosion and abrasion which created plain terrains (300-400m, 500-800m, 1,400-1,600m) commonly observed in many places in the Central Highlands, as well as the Indochina. This was followed by the formation of Tertiary basins, the operation of the East Sea, the left sliding in the NW-SE sections. In the Neogene-Quaternary period, the dominant mechanism was mass heat-subsidence, the movement of vicissitudes, where basaltic eruptions occurred strongly throughout the Central Highlands, as well as Indochina. KVG was forcibly raised in block domes and under the influence of west-to-east tension. Those eruptions started from 16.5 mya (where the bottom of the South China Sea stopped its extension) and stopped 199,000 years ago. Two geological units in this period are Tuc Trung ( $\beta N_2-Q_1 tt$ ) and Xuan Loc ( $\beta Q_1^2 xl$ ) formations consist of basaltic rocks. Lava caves in Krongno area were formed in basaltic rock of Xuan Loc formation with the age of 689,000-199,000 years, erupted from Chu B'Luk volcano in the NE of KVG (Fig.2).

## 3. Methodology:

In term of geology and speleology, in order to discover and survey volcanic caves effectively, a series of methods and techniques are chosen, including: Inheritance data method; Remote Sensing image interpretation method; Sociological investigation method; Investigation, field survey, sample and literature collection method; K/Ar sample analytical method; Statistical classification method; Professional discussion method; Information technology method; Surveying and mapping lava cave and Current methodology.

However, there are four methods considered as most important and decisive, and briefly described as follows:

- Remote Sensing image interpretation method:

Analyzing satellite and aerial images to interpret and discover entrance of lava caves. Furthermore, the drone images are very effective in discovering lava caves, especially in dry season, when the plant cover almost disappear out of the surface. In dry season, entrances of lava cave may be discovered by scattered and outstanding green dots on the yellowish-grey colour background of basaltic rocks in the images.

- Surveying and mapping lava cave method: Objectives of the cave surveying is to know the lava tube cave distribution, each direction relative to the eruption point (crater) by measuring the lava tube cave position and length in the KVG area and to know the structure of each lava tube cave by measuring the height width, slope angle and observing the inner structure of wall, ceiling and floor. The used instruments are for cave entrance location: GPS, for height, width and length inside the cave: laser distance measuring instrument, for slope angle of cave floor: inclination meter, for cave turning angle: protractor, for observation of the shape of the inner wall surface floor surface measurement by using calipers.

- K/Ar dating isotopic analytical method: This method is based on measurement of the product of the radioactive decay of an isotope of potassium (K) into argon (Ar). Potassium is a common element found in many rocks, including basaltic rocks. In basalts, the decay product  $^{40}\text{Ar}$  is able to escape the liquid (molten) rock, but starts to accumulate when the rock solidifies (recrystallizes). So the K-Ar dating isotopic analytical method is considered as an effective method for basaltic rocks in the studying area.

- Current methodology: Based on the study of

current geological processes, such as volcanic eruptions and the formation of lava caves, those are taking place at present, for example the volcanic processes in Hawaii, to interpret/explain similar processes happened in the geological past. The formation mechanism of many lava formations in lava cave has been interpreted by using the method.

In term of biology and archaeology, speciality methodologies has been used to meet the detailed requirements of those fields. They will be mentioned in another separate academic papers.

#### **4. Lava caves in KVG<sup>6~14</sup>):**

As mentioned above, all lava caves in Krongno area were formed in lava flows closely related to the eruption of Chu B'Luk volcano. Among 45 lava caves have been discovered in KVG, there are 20 caves have been measured, comprehensively surveyed/researched and mapped as of March 2018 (Fig.2; Table 1). Of course, we only mention the caves having entrances large enough for an adult to go through, but not to mention the others having much smaller, inaccessible entrances. Lengths of these caves vary from 81m to 1066.5m, reaching the record length of SE Asian volcanic caves (6). Volcanic caves scatter irregularly in different directions surrounding the Chu B'Luk volcano, reaching the farthest distance of 15km northwest from the volcano (labelled as B), in Dak Sor commune. The volcanic caves normally aggregate as belt-formed, reflecting the lava flow direction of the eruption of Chu B'Luk volcano.

In term of the groundwater level, the volcanic caves are divided into two types, dry and wet caves. The dry caves are above the current groundwater level, while the wet type is below the groundwater level, normally soaked with the water. The study up to date is mostly concentrated on the dry caves having entrances exposed to the surface. Those

underground water level have not yet been explored and studied on all three scientific

fields, including geological, biological diversity, and cultural heritage as well.

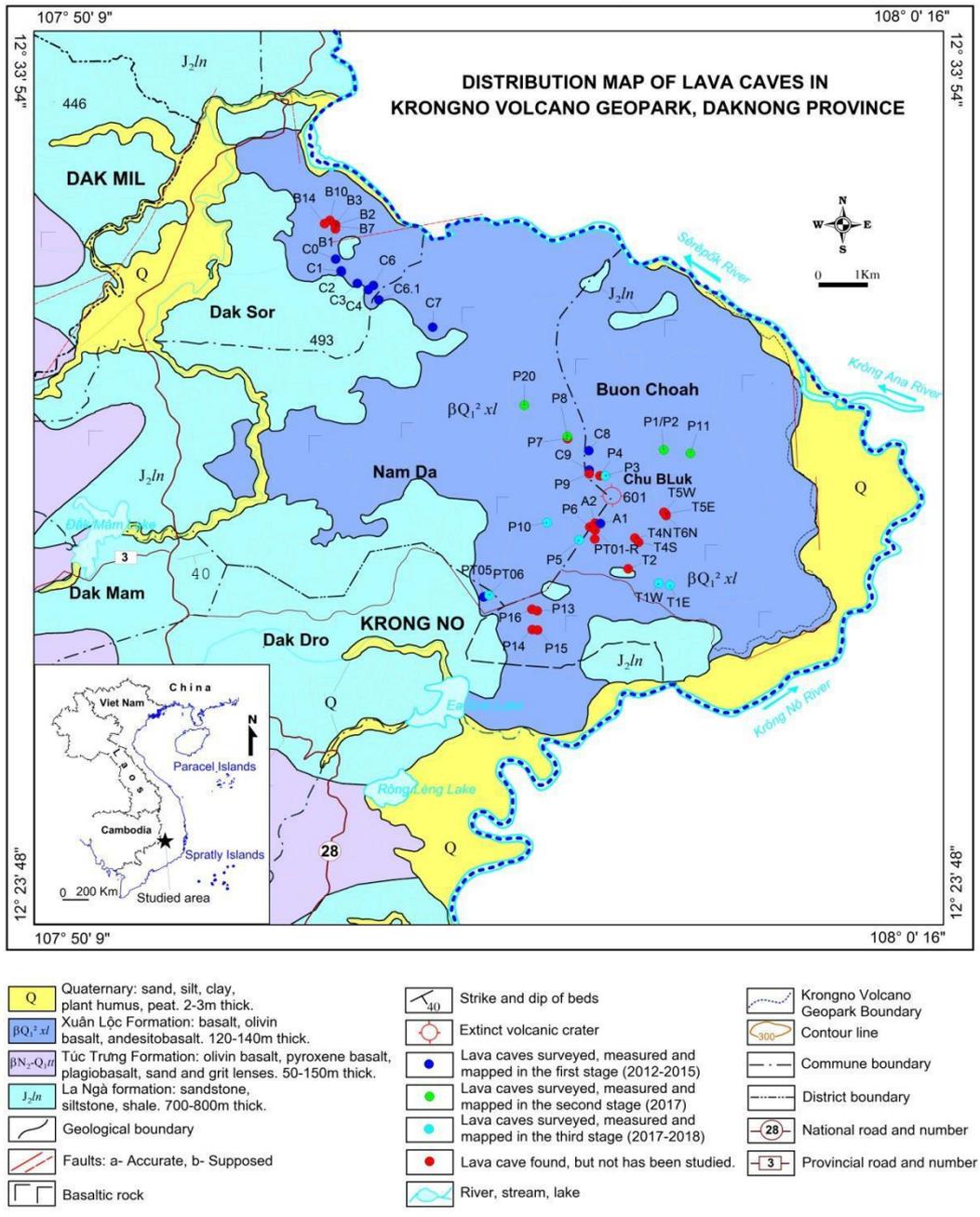


Fig.2. Distribution map of lava caves in Krongno Volcano Geopark, Dak Nong, Vietnam.

**Table 1. List of KVG lava caves**

List of 20 volcanic caves surveyed and mapped							
N <sup>o</sup>	ID	Location	Longitude	Latitude	Length (m)	Depth(m)	Entrance type
1	C0	Dak Sor	107° 53' 32.87"	12° 31' 18.69"	475.5	14.9	combined
2	C1	Dak Sor	107° 53' 34.35"	12° 31' 11.00"	402.0	3.5-4.5	secondary
3	C2	Dak Sor	107° 53' 35.39"	12° 31' 10.04"			secondary
4	C3	Dak Sor	107° 53' 47.24"	12° 31' 2.35"			716.3
5	C4	Dak Sor	107° 53' 52.28"	12° 30' 57.91"	251.5	9-10	secondary
6	C6	Dak Sor	107° 53' 57.02"	12° 31' 0.91"	180.3	4.3	secondary
7	C6.1	Nam Da	107° 53' 59.76"	12° 30' 51.23"	293.7	4.6	secondary
8	C7	Nam Da	107° 54' 35.12"	12° 30' 32.47"	1066.5	15-20	combined
9	C8	Buon Choa'h	107° 56' 19.20"	12° 29' 8.53"	791.0	23.8	secondary
10	C9	Buon Choa'h	107° 56' 20.03"	12° 28' 55.59"	217.0	22.6	combined
11	P1, P2	Buon Choa'h	107° 57' 10.14"	12° 29' 8.57"	530.5	15-18	secondary
12	P8	Nam Da	107° 56' 5.74"	12° 29' 18.07"	344.1	26	primary
13	P11	Buon Choa'h	107° 57' 28.24"	12° 29' 5.97"	498.1	7-9	secondary
14	P20	Nam Da	107° 55' 37.67"	12° 29' 39.58"	568.0	25	primary
15	A1	Buon Choa'h	107° 56' 28.73"	12° 28' 19.67"	438.7	10	combined
16	P3	Buon Choa'h	107° 56' 32.87"	12° 28' 51.52"	81.0	5	secondary
17	P5 (PT07)	Buon Choa'h	107° 56' 13.01"	12° 28' 8.86"	204	4.2	secondary
18	P10E P10W	Nam Da	107° 55' 54.22"	12° 28' 20.06"	160	4.5	secondary
			107° 55' 52.45"	12° 28' 20.82"			
19	PT06	Dak Dro	107° 55' 16.68"	12° 27' 28.62"	200	5	secondary
20	T1W	Buon Choa'h	107° 57' 6.264"	12° 27' 39.02"	303.1	16	combined
Total length of 20 volcanic caves surveyed and mapped					<b>7721.3</b>		
List of 25 volcanic caves discovered, not detailed surveyed and mapped							
21	A2	Buon Choa'h	107° 56' 24.22"	12° 28' 19.96"			
22	PT01-R	Buon Choa'h	107° 56' 23.52"	12° 28' 15.38"			
23	PT05	Dak Dro	107° 55' 7.99"	12° 27' 31.50"			
24	T1E	Buon Choa'h	107° 57' 7.44"	12° 27' 41.51"			
25	B1	Dak Sor	107° 53' 32.72"	12° 31' 35.34"			
26	B7	Dak Sor	107° 53' 32.82"	12° 31' 40.68"			
27	B2	Dak Sor	107° 53' 32.30"	12° 31' 41.65"			
28	B3	Dak Sor	107° 53' 30.32"	12° 31' 41.71"			
29	B10	Dak Sor	107° 53' 28.05"	12° 31' 44.91"			
30	B14	Dak Sor	107° 53' 22.64"	12° 31' 42.49"			
31	P4	Buon Choa'h	107° 56' 26.64"	12° 28' 51.57"			
32	P6	Buon Choa'h	107° 56' 27.20"	12° 28' 17.57"			
33	P7	Nam Da	107° 56' 5.84"	12° 29' 16.87"			
34	P9	Buon Choa'h	107° 56' 21.40"	12° 28' 53.09"			
35	P13	Buon Choa'h	107° 55' 42.94"	12° 27' 21.57"			
36	P14	Buon Choa'h	107° 55' 42.54"	12° 27' 8.97"			
37	P15	Buon Choa'h	107° 55' 46.04"	12° 27' 8.67"			
38	P16	Buon Choa'h	107° 55' 42.44"	12° 27' 22.77"			
39	T2	Buon Choa'h	107° 56' 39.54"	12° 27' 52.67"			
40	T3	Buon Choa'h	107° 56' 17.24"	12° 28' 12.97"			
41	T4N	Buon Choa'h	107° 56' 44.24"	12° 28' 13.27"			
42	T4S	Buon Choa'h	107° 56' 46.55"	12° 28' 10.47"			
43	T5W	Buon Choa'h	107° 57' 4.14"	12° 28' 30.37"			
44	T5E	Buon Choa'h	107° 57' 5.04"	12° 28' 29.27"			
45	T6N	Buon Choa'h	107° 57' 5.54"	12° 28' 28.17"			

interpretation of topographic map, Flycam images in combination with the field survey documentation reveal a number of negative topographic relieves (tunnel-shaped), having

diameters varying between 10m and 15m and depths ranging from 3m to 20m, aligned linearly. Subsided holes are filled with disorderly aligned basaltic boulders, indicating wall or ceiling collapse. Other

holes contain elastically deformed basalt fragments, produced by initial volcanic eruption. Whether the holes are collapsed cave roofs, forming secondary cave entrances now being buried, or small-scaled volcanic craters of the Chu B'Luk volcanic system. needed further detailed investigation.

### 5. Lava formations in lava caves in KVG<sup>13~14</sup>:

Many lava formations have been identified in KVG lava caves. They are reliable evidences for the endogenous origin of lava cave system in the area, reflect the

properties of the lava flows, the cave formation process as well as their origin. A variety of lava formations have been mentioned, such as: primary and secondary entrances, flooring and branching features of the cave, lava levee, lava shelves, traces of lava on the cave floor and cave wall, lining, lava ball, lava window and seals, lava waterfall, skylight, lava lakes, lava pillows, pahoehoe and clinker floors, primary and secondary stalactites, lava glaze, lava tree molds, ect.(Fig.3~Fig.34 ).



Fig.3 Multi-generations stalactites in C6.1. Photo: Luong Thi Tuat.



Fig.4 Saw-blade stalactites in C0 cave. Photo: Luong Thi Tuat.



Fig.5 Shark teeth stalactites in C0 cave. Photo: La The Phuc.



Fig.6 Primary stalactites in C0. Photo: Nguyen Thanh Tung.



Fig.7 Parallel tube structure of A1 cave. Photo: Luong Thi Tuat.



Fig.8 Linga-shape lava in C6'. Photo: Luong Thi Tuat.



Fig.9 Lava seal in C2 cave. Photo: La The Phuc.



Fig.10 Level marks in C7 cave. Photo: Luong Thi Tuat.



Fig.11 Thin lava linings in C8 cave. Photo: Luong Thi Tuat.



Fig.12 Thick lava linings in C9 cave. Photo: Bui Van Thom.



Fig.13 Skylight in C7 cave. Photo: Neo Thanh.



Fig.14 Skylight in C8 cave. Photo: Luong Thi Tuat.



Fig.15 Exiguous tube in the upper C7 lava cave. Photo: Luong Thi Tuat.



Fig.16 Lava glaze in the C7 cave wall. Photo: Luong Thi Tuat.



Fig.17 Smooth surface & lava ball in C7. Photo: Suzuki Kazutoshi.



Fig.18 Scallope ceiling and charcoal in C8 cave. Photo: Luong Thi Tuat.

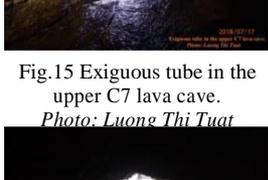


Fig.19 Lava window in A1 cave. Photo: Luong Thi Tuat.



Fig.20 Lava window in C2 cave. Photo: La The Phuc.



Fig.21 Ship-bow structure in C2 cave. Photo: Luong Thi Tuat.



Fig.22 Grape stalactites in P5 lava cave. Photo: Luong Thi Tuat.



Fig.23 Lava lake in T1 cave.  
Photo: Luong Thi Tuat.



Fig.24 Pillow-shape lava in T1 cave. Photo: Luong Thi Tuat.



Fig.25 Tube-in-tube in C7 cave. Photo: Luong Thi Tuat.



Fig.26 Primary stalactites in C3. Photo: Tsutomu Honda.



Fig.27 Lava shelf in C7 cave. Photo: Suzuki Kazutoshi.



Fig.28 Lava tree mold in C2 cave. Photo: Luong Thi Tuat.



Fig.29 Lava tree mold in C3 cave. Photo: Tsutomu Honda.



Fig.30 Lava tree mold in C4 cave (at least 4.9m). Photo: Luong Thi Tuat.



Fig.31 Ropy lava in C7(left). Photo: Nguyen Thanh Tung); Lava levee in C6' (right); Photo: Luong Thi Tuat.



Fig.32 Lava fall in P5 cave (left) Photo: Luong Thi Tuat. Secondary stalactite (right) Photo: Yuriko Chikano.



Fig.33 Ropy and levee lava in the C7 upper-stream. Photo: Luong Thi Tuat.



Fig.34 Scroll-shape linings and pillow-shape lava in T1 cave. Photo: La The Phuc.

Fig.3~Fig.34. Illustration images for lava cave formations in KVG lava caves.

Source: VNMN and VSS.

## 6. Biodiversity in KVG's lava caves<sup>8~13</sup>;

Some unique cavern animal species have been seen in KVG lava caves, consist of bat, snake, scorpion, snail, frog, ect. (Fig.35~

Fig.42). Also, several species are expecting to be endemic and new species for science. Of course, they all need to be studied more detailed in the future (Fig.43~Fig.57).



Fig.35 Bat in C6.1 lava cave. Photo: Luong Thi Tuat.



Fig.36 Bat in C4 lava cave. Photo: La The Phuc.



Fig.37 Snake (*Bungarus candidus*) in C7 cave. Photo: Yoshida Katsuji.



Fig.38 Black scorpion (*Heterometrus laoticus*?) in C7 cave. Photo: Luong Thi Tuat.



Fig.39 Snail in C7 cave. Photo: Yoshida Katsuji.



Fig.40 Other snail species in C7 cave. Photo: Yoshida Katsuji.



Fig.41 Frog in C9 lava cave. Photo: Luong Thi Tuat.



Fig.42 Frog in C7 cave. Photo: Yoshida Katsuji.

Fig.35÷Fig.42: Some different animals have been found in KVG lava caves.



Fig.43 *Laponia sp.*

Fig.44: *Thelcticopis sp.*

Fig.45: *Coelotes sp.*

Fig.46: *Gnaphosa sp.*

Fig.47: *Trombidioidea sp.*

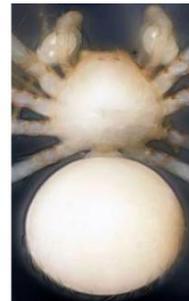


Fig.48: *Pholcus sp.*

Fig.49: *Belisanna sp.*

Fig.50: *Khorata sp.*

Fig.51: *Leptoneta sp.*

Fig.52: *Tyrannochthonius sp.*



Fig.53: *Anapistula sp.*

Fig.54: *Telema sp.*

Fig.55: *Tetrablemma sp.*

Fig.56: *Opilionida sp.*

Fig.57: *Lagynochthonius sp.*

Fig.43~Fig.57 : Some different animals have been found in KVK lava caves and are expecting to be endemic and new species for science (*source: the VNMN's biologists group*).

### 7. Archaeological value in KVG lava cave<sup>15~17)</sup>

- Before 2017, many archaeological relics have been found in KVG area. They all are open-air ones, none of cave relics has been found.

- In 2017, the first lava cave relics have been discovered in a series of lava caves in KVG. - According to the decision 52/QĐ-BVHTTDL dated 09/01/2018 of the Ministry of Culture, Sports and Tourism, Vietnam National Museum of Nature and Department of Culture, Sports and Tourism of Dak Nong province in collaboration with Vietnamese

archaeologists have finished the first excavation stage in C6' and C6.1 lava caves. Results of the excavation have found many important evidences of prehistoric people living in lava cave in the Middle Neolithic (7,000-5,000years BP) to the Late Neolithic and Early Metal Age (5,000-4,000 years BP) (Fig.60). Besides tens of thousands relics of stone tools, animal bones snail shells, mussel shells, ceramic broken pieces, brass arrows, (Fig. 58; 64; 65; 66; 68; 69), etc. Archaeologists have identified 3 prehistoric human skeletons (Figures 59; 61; 62; 63) in three separate tombs (Figure 58) and many bone pieces of at

least ten other human individuals (Fig.67) in the excavation pit in C6.1 cave. Obtaining the studying results in the C6.1 excavation pit, first time in Southeast Asia and over the world, archaeological relics and prehistoric human skeletons have been found in lava cave. On September 18th, VNMM have released

preliminary results of the excavation in the C6.1 cave, marked a huge milestones in Anthropology, Archaeology in Vietnam, Southeast Asia and the world as well: Prehistoric Archaeology in lava cave.



Fig.58. Archaeological excavation pit in the C6.1 cave.



Fig.59. The skull of a little girl in the C6.1 cave excavation pit (M2).



Fig.60. Results of the 14C dating in the C6.1 excavation pit.



Fig.61 The human skeleton M2 revealed in the C6.1 excavation pit.



Fig.62 The human skeleton M2 revealed in the C6.1 excavation



Fig.63 The human skeleton M3 revealed in the C6.1 excavation



Fig.64. Stone axes tools in the C6.1 lava cave



Fig.65. Sea snail shell jewelry in the C6.1 pit



Fig.66. Broken ceramic relics in the C6.1 excavation pit

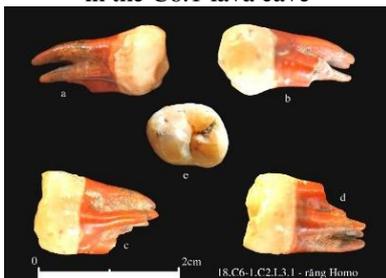


Fig.67. Teeth of prehistoric man in the C6.1 excavation pit



Fig.68. Snail shells in the C6.1 excavation pit



Fig.69. Mussel shells in the C6.1 excavation pit

Fig.58~Fig.69. Archaeological relics in the C6.1 cave archaeological pit, in KVG, Dak Nong, Vietnam

Source: VNMM.

## 8. Conclusions:

Three lava caves C7, T1 and C6.1 in KVG's lava cave system have proposed ranking as international heritages in KVG Dossier. Lava caves in KVG have been studied and recognized on both natural heritage (geological and biological) and cultural (archaeological) values. Thanks to the unique scientific multi-values, lava caves have become the most important heritage of the geopark. Therefore, they play important role as pillar heritage in the KVG Dossier, that plan to be submitted to UNESCO in November 2018<sup>13)</sup>.

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# Hydrodynamic aspects of lava tube caves in the Krongno area, Dak Nong province, The Central Highlands, Vietnam

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## Abstract

From 2012 to 2015, the joint team of the Vietnam National Museum of Nature (VNMN) belonging to the Vietnam Academy of Science and Technology (VAST) and NPO Vulcano-Speleological Society of Japan carried out a survey for volcanic caves in the lava flow from the Chu B'Luk volcano located in Krongno district, Dak Nong province, The Central Highlands of Vietnam.

As a result of the survey, the joint team explored 18 lava tube caves, among which 11 lava tube caves were measured and mapped. The inner wall (ribbed wall) and ceiling (lava stalactite) observation of lava tube cave, together with the measurement of the height and slope angle for some caves are carried out.

By using two hydrodynamic models for these observations, two physical properties for lava yield strength and surface tension were estimated from these results.

From lava tube cave height and slope angle, the flow in the lava tube is modeled by Bingham fluid flowing in the inclined cylindrical pipe with gravity potential. Then, the condition of the cave formation is formulated and this formulation was applied to estimate the yield strength in the studied area. Gravity, lava density, slope angle and cave height are the decisive parameters that determine the Bingham yield strength of lava. For lava tube Cave C2, the estimated yield strength is  $2.3 \times 10^4$  dyne/cm<sup>2</sup>, which shows a reasonable value as yield strength of basaltic lava.

From ceiling and wall surface observation, the role of surface tension of lava on the formation of lava stalactite or ribbed wall is analyzed by a hydrodynamic instability model of lava boundary layer attached to the ceiling or side wall. The surface tension 560~990 dyne/cm estimated from this model for Cave C3 and Cave B14, shows a reasonable value as surface tension of basaltic lava.

## 1. Introduction

The Chu B'Luk volcano is located in Krongno district, Dak Nong province, The Central Highlands of Vietnam (Fig.1). It is one of the continental volcanoes that blew a large amount of soft lava having a silicic acid weight fraction of 48.3 to 52.4% <sup>(1)</sup>. The Vietnam National Museum of Nature (VNMN), and the NPO Vulcano-Speleological Society conducted a joint survey of the lava tube cave in the lava flow ranging from the Chu B'Luk crater to the Dray Sap Waterfall area from 2012 to 2015 <sup>(2~9)</sup>. As a result, 18 lava tube caves were discovered and surveyed, and 11 caves of which were measured and mapped, and the total extended distance was 4832.5 m at the time of January

2015. The location of the lava caves including lava caves recently surveyed (20 caves in sum total up to now at 2018)<sup>(10)</sup>, are also shown in Fig.1.

Fig.2 shows a typical measurement result for the lava tube cave for Cave C2.

We present findings obtained on the physical properties (yield strength and surface tension) of lava deduced by cave geometry and internal observation.

## 2. Hydrodynamic models of Bingham fluid flow for lava tubes

A considered schematic for lava tube flow is indicated on Fig.3 where  $H=2R$  is tube diameter (or tube height),  $R$  is radius of the lava tube, and  $\alpha$  is slope angle of the lava tube.

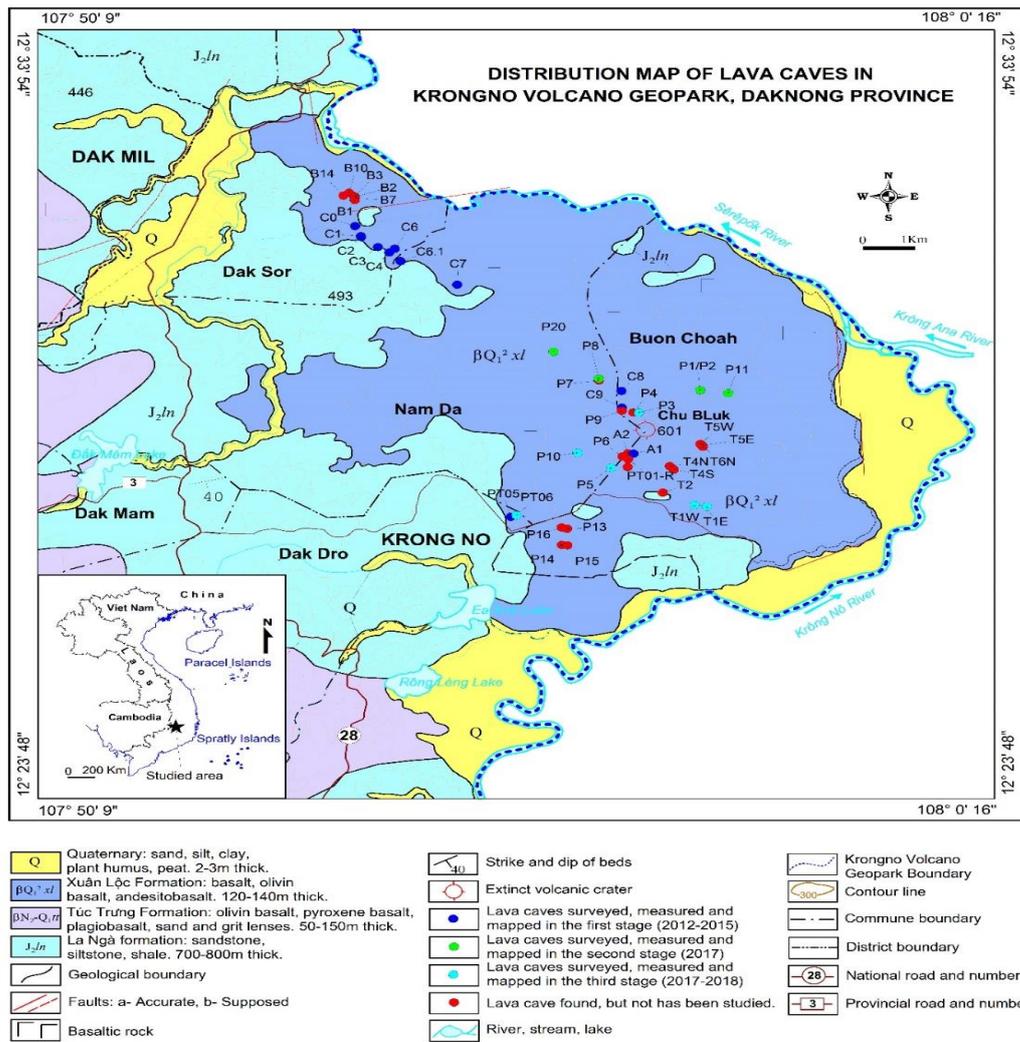


Fig.1 Distribution map of lava caves in Krongno Volcano Geopark, Dak Nong province, Vietnam

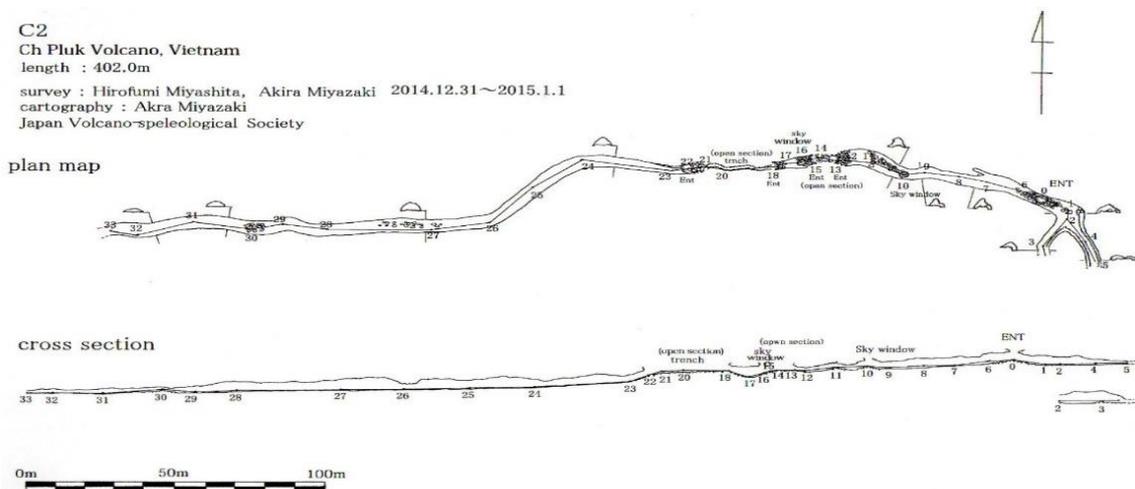


Fig.2 Horizontal and vertical cross section of lava tube Cave C2

Fig.3 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 gravity<sup>(11,12)</sup>. After the termination of eruption (drain back of magma), a hollow is formed in the tube producing a “lava tube cave” in which the lava in the tube could be drained out by the gravity (free flow). The hydrodynamic model for lava tubes with the flow speed distribution in the tube is shown in Fig.4.

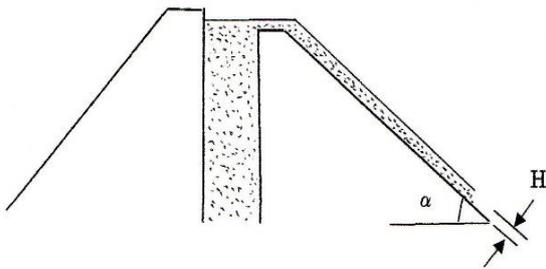


Fig.3 Schematic of lava tube flow

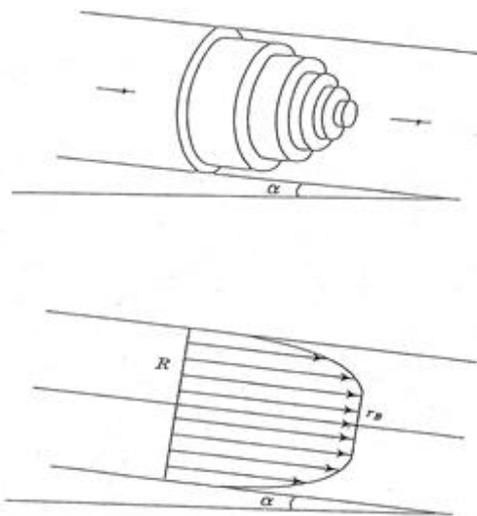


Fig.4 The flow speed distribution in the tube

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

$$\text{For } \tau_w = (\rho g \sin \alpha)R/2 > f_B$$

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

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

$$\text{For } \tau_w = (\rho g \sin \alpha)R/2 < f_B$$

$$u = 0$$

Here,  $\tau_w$  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,  $\eta_B$  is Bingham viscosity,  $g$  is the gravity force and  $\rho$  is lava density. Critical condition for lava tube cave formation is: for  $H = 2R$ ,  $H = 4f_B / (\rho g \sin \alpha)$ , then,  $f_B = H(\rho g \sin \alpha) / 4$

### 3. Bingham yield strength estimated from lava tube cave height

Lots of lava tube caves are found between Chu B’Luk volcano and Dray Sap Waterfall in a straight line distance of about 9 km. Among them, the lava tube cave C2 is used as a typical lava tube cave. The cavern height  $H$  of the C2 cave (Fig.2) is about 10 m, the total length is 402.2m and the elevation difference between upper and lower extremities is 15 m, so the inclination angle is  $\alpha = 2.1$  degrees.

Fig.5 and Fig.6 show the inside of the cave C2. From this cavern height and inclination angle  $\alpha$ , we can estimate the Bingham yield value of lava. Bingham yield value  $f_B = H(\rho g \sin \alpha) / 4 = 2.3 \times 10^4$  dyne/cm<sup>2</sup> is obtained with  $\rho = 2.5$  g/cm<sup>3</sup>. Here,  $g$  is the gravitational acceleration. This value means relatively fluid lava like Kilauea volcano and Piton de la Fournaise.



Fig.5 Inside of C2



Fig.6 Inside of C2

#### 4. Hydrodynamic instability model and estimate of surface tension from lava stalactite and ribbed wall

Fig.7,8,9. show a general feature of the inside of lava tube cave. Lava stalactites are positioned periodically on the surface of the ceiling wall or side wall. From the periodical pitch of the stalactites, we can obtain the surface tension of the lava<sup>(13,14)</sup>. The pitch will be the critical wave length of the occurrence of instability of thin liquid film attached on the surface of the ceiling of the lava tube cave as shown in Fig.10. The pitch  $P$  is shown as:  $P=2\pi(\gamma/g\rho)^{1/2}$ , where  $\gamma$  is surface tension of liquid  $\rho$  is density of liquid,  $g$  is gravity acceleration. From the pitch of lava stalactites on the roof surface, the surface tension of lava  $\gamma= P^2 g\rho /4\pi^2$  is determined. If there is a superposition of the lateral and vertical surface flow, the ribbed wall will appear and keep the same pitch as that of lava stalactite. As for the surface tension calculated from the pitch of lava stalactites on the roof surface of Cave C3 or ribbed wall of Cave B14 ( $P=3$  to  $4\text{cm}$ ) (see Fig.11 and Fig.12), the surface tension of lava was determined as  $560\sim 990$  dyne/cm. The estimated surface tension matches with the experimental results by melting the lava in the

Laboratory<sup>(15)</sup>. It is considered that it is a reasonable value as basaltic lava.



Fig.7 Inside of Cave P20

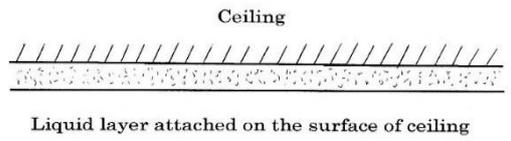


Fig.8 Roof of Cave C3

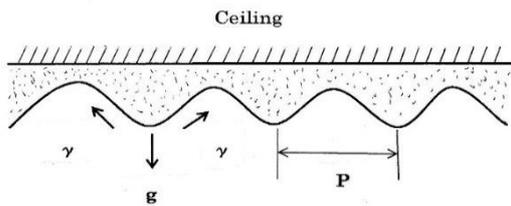


Fig.9 Inside of Cave B14

**Instability of liquid layer attached on the ceiling**



**(A) Initial stable state of liquid layer**



**(B) Onset of instability of liquid layer**

Fig.10 Schematic of the onset of instability of liquid film attached on the ceiling



Fig.11 Lava stalactite of the ceiling of Cave C3

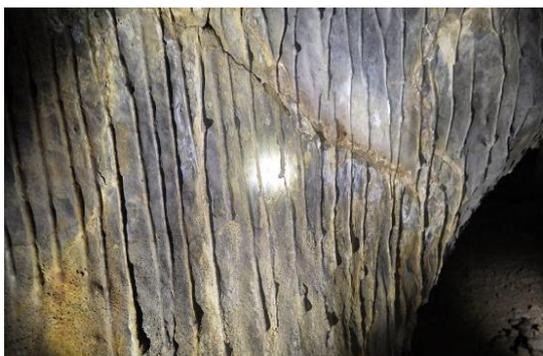


Fig.12 Ribbed wall of Cave B14

**5.Summary:**

The following two table show findings of hydrodynamic aspects obtained on the physical properties (yield strength and surface tension) of lava by cave geometry and internal structure observation.

Table1 Yield strength of lava flow of Chu B’luk Volcano

Item relating to yield strength	Numerical
Length of lava tube cave C2	402.2 m
Height of lava tube cave:H	10m
difference in elevation between upper and lower extremities	15m
Slope angle $\alpha$ of the cave C2(Inclination of the Cave C2)	2.1 degree
Yield strength: $f_b = H(\rho g \sin \alpha) / 4$ , $\rho: 2.5 \text{ g/cm}^3$ , $g: 980 \text{ cm/sec}^2$	$2.3 \times 10^4$ dyne/cm <sup>2</sup>

Table2 Surface tension of lava flow of Chu B’Luk Volcano

Item related to surface tension	Numerical
Pich of lava stalactite of ceiling:Cave C3 and ribbed wall of Cave B14	3~4cm
Surface tension: $\gamma = P^2 g \rho / 4 \pi^2$ , $\rho: 2.5 \text{ g/cm}^3$ , $g: 980 \text{ cm/sec}^2$	560 to 990 dyne/cm

These physical values of lava flow of Chu B’Luk volcano(elevation: 601m) are reasonable value as basaltic lava.

This lava of high fluidity is similar to that of Kilauea volcano and Piton de la Fournaise.

The drilling survey results shows that lava flow thickness is 120~140m.This suggest that the eruption of lava flow from Chu B’Luk volcano was like a flood.

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# Principal Pyroduct Processes

by

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## Abstract

The exploration of lava caves has made tremendous progress in the last thirty years, not the least fueled by the biannual meetings of the Commission on Volcanic Caves. Lava caves are certainly the third, if not the second, most important cave type by number and total length on Earth (after caves in carbonate rocks and likely before caves in sulfate rocks). Among the many lava caves, or more generally formulated, caves in volcanic rocks, we find different types, secondary or primary in origin. Secondary caves occur along sea shores, along the banks of rivers, along tectonic fissures or in between talus. These caves can be quite large. In Hawai'i we found a 1 km long and 100 m deep cave cut into layers of lava and paleosol strata by a creek, similar in appearance to an alpine epigenic carbonate rock cave including numerous water falls, plunge pools, scallops, a siphon and an impressive phreatic loop (Kukaiiau Cave).

Among the primary cavities we find a series of strange cave types, such as tree casts, even the cast of a diceratherium, hollow intrusions, vents, lava bubbles, pressure ridge caves, or separations in between pāhoehoe sheets. The most common cave type, though, is the post-eruptional conduit that permits molten lava to flow subterraneously for long distances, allowing shield volcanoes to cover large areas with surface slopes of a few degrees only. These caves, colloquially called "tubes" are neither tubular in shape nor are they normally filled by lava when active. Titus Coan, an educated missionary, was the first who reported seeing an active lava conduit on Mauna Loa in 1843. He saw the lava flowing in an open space - a river of molten fire - and coined the term "pyroduct" in analogy to "aqueduct" (the covered, free-flowing water conduits the Romans built to supply water to their cities). Older terms have priority in science, specifically if they do not convey misconceptions.

For almost a hundred years after Coan not much happened in pyroduct-research (apart from the fact that Olafsen had described the origin of pyroducts more or less correctly already in 1774-75 in Iceland) until Tom Jaggar named a newly investigated cave on Kilauea “Thurston Lava Tube”.

The interior inspection of pyroducts and their survey has shown that they not only vary in cross-section between different conduits but also internally. Factor 10 cross-section area changes within the same duct are not uncommon. This tells us that such caves cannot have been filled to their top with lava, but that (apart from the smallest sections functioning as valves) much of the final cave was an underground canyon with a lava river flowing at its bottom. The change in passage cross-section is owed to erosion, downward (for example by lava falls), sideward (by undercutting and collapse of walls) and upward (by ceiling collapse). That pyroducts in fact erode downward was shown beyond doubt when we discovered Pahala ash outcrops in the walls of Earthquake Cave/Kilauea in 1991.

In textbooks (except for Lockwood & Hazlett, 2010), “lava tubes” are described as “over-crusting channels”. Both the recent observations of the ongoing eruption on Kilauea by the colleagues of the Hawaiian Volcano Observatory and the analysis of roof structure of pyroducts, show that the “over-crusting” hypothesis seems to be a rare case, while the majority of analyzed cases is formed by “inflation”. This involves uplift of the primary lava sheet by consecutive later sheets injected from below. The hottest and topographically lowest flow thread forms the later pyroduct.

Three general types of pyroduct cases can be discerned:

- (1) The single-trunked conduit. It originates from one lava flow; the resulting cave may drain early braids but eventually the flow concentrates in one trunk passage.
- (2) The double-trunked case. It involves conduits active in parallel and influencing each other.
- (3) The superimposed-trunked case. It is the most complex pattern, where conduits are superimposed on each other by an increase in erupted lava volume. Here pyroducts cross each other, all active at the same time and drained top to bottom. This causes the most complex cave pattern.

Internally many processes act to alter the cave's appearance. Ceiling collapse may open skylights through which cold air can enter causing the freezing of internal septa (secondary ceilings). This results in the separation of the passage into two (or more) levels. After the activity and during cooling further collapses occur, either opening more skylights or littering the floor of the cave with blocks. During activity, when hot gas fills the upper part of the cave, part of the ceiling can be melted, causing the ceiling to look like a honeycomb. Also, hot air draft can form lava ripples. Furthermore, a score of different rock speleothems may be observed in pyroducts, owing their existence to a variety of transient conditions.

