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Contents

THE KEOKEO CAVE SYSTEM IN HAWAII

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Abstract

The Keokeo lava tube system lies within a lava flow that apparently originated in the Pu‘u o Keokeo vent on the Southwest Rift zone of Mauna Loa, on the Big Island of Hawaii. The lava flowed 1,500–3,000 years ago from the source near 2,200 m elevation all the way to the ocean, a distance of some 28 km. A large lava tube system has been discovered spanning most of the extent of the flow. The cave system is often braided into parallel branches, as well as being formed on up to four vertical layers. The system is sometimes segmented by ceiling collapse or lava sumps. As of this writing, 40.6 km of passage has been surveyed in segments ranging from 10 m to 4 km long. The deepest passages are readily distinguished because the lava downcut through a thick layer of ‘a‘ā, which is seen when the wall linings peel away. In places, there is evidence of downcutting through two ‘a‘ā layers. There are many white and orange crusts, frostwork, and coatings throughout the system, which could be the subject of a mineralogical investigation. Microbial mats are fairly common as well. Ohi‘a tree roots support a variety of cave-adapted species, including crickets, spiders, isopods, planthoppers, and moths. Two as-yet-undescribed species were recently found in the system. Other interesting resources in the system include bird and bat skeletons, and occasional native Hawaiian water collection and shelter sites.

1. Introduction

The Big Island in the U.S. state of Hawai‘i is home to the majority of major lava tube (pyroduct) systems (e.g., Kempe 2012) in the world. The second longest system in the world, the Kipuka Kanohina system, originates in the SW rift zone of Mauna Loa, within the Kahuku Unit of Hawaii Volcanoes National Park (HAVO), and passes under the Hawaiian Ocean View Estates (HOVE) and Kula Kai subdivisions, reaching almost to the ocean. Recently, another major system has been identified, also originating in the SW rift zone. The passages of the system are shown as the red lines in Figure 1. The system is formed in the Qk2 Mauna Loa flow which extends from the presumed source at Pu‘u o Keokeo (altitude of 2,200 m), all the way down to the ocean, some 28 km distant. The estimated age of the flow is 1,500 to 3,000 aBP (Sherrod et al. 2007).

2. Exploration History

Some of the lava tubes in the system were used by the original Polynesian settlers, arriving in the islands as long as 1000 years ago (cf. Wilmshurst et al. 2011). There is no evidence of such ancient occupation in the current survey.

In most of the 1800’s and 1900’s, the entire flow was on the property of the very large Kahuku Ranch. Ranch-hands and farm children sometimes visited the caves, although there is no written record of their underground activities. Above ground, initials and a date carved into the rock, along with the evidence of two empty bottles, tally with an account of George Jackson counting being present in 1868 near the source of the flow that year, at an elevation of about 1800 m. The upper portion of the Keokeo flow became part of Hawaii Volcanoes National Park (HAVO) in 2004. The lower portion was sold to private developers (Nani Kahuku Aina) in 2006, and the small parcel between these was acquired by The Nature Conservancy in 2015.

Systematic exploration of the Keokeo system began in 2011. Some entrances were found from satellite and aerial photos. The great majority of them were found on surface hikes, or by entering one entrance and coming out another one. To date, over 500 entrances have been identified. Of these, about two thirds have been explored and surveyed. For the entrances within HAVO, an initial reconnaissance of all of the passages accessible from a given entrance was made with a qualified archaeologist in order to determine if sensitive cultural resources were present.

To date, there have been about 250 field trips to the flow, of which roughly one fifth were to locate entrances, one fifth for archaeological reconnaissance, and the remainder for detailed mapping and photography. About 40.6 km of passage has been mapped in segments ranging from less than 10 m to over 4 km in length. The segments are usually separated by trenches formed by the collapse of the original tube. In other cases, especially where the gradient is low, the lava completely filled the passages when it cooled, making for lava sumps.

3. Geology

The geology of one of the longest segments of the system, Upper Kahuenaha Nui, was studied by Ingo Bauer as part of his Master’s thesis (Bauer 2011). The cave survey of this segment yielded a total length of 1,850 m, a total vertical extent of 55 m and an average slope of 5.7°. The cave features a main trunk that is up to 18 m wide and 11 m high. Its floor is in part formed by terminal ‘a‘ā. Above this trunk passage, there are numerous small to very small interconnected pahoehoe-floored passages. It was possible to study the cave formation process at the two entrance collapses (pukas in Hawaiian). The trunk passage appears to be formed by eroding an underlying ‘a‘ā rubble layer.

In places even the underlying ‘a‘ā core layer has been cut into. Above, a stack of seven superimposed pahoehoe flows with small meandering passages occurs, forming the primary roof of the cave. The lava flowing in this stack of sheets managed to combine into one flow, eroding the main trunk underneath. After cave formation first an ‘a‘ā flow and then a thin pahoehoe flow transgressed the area. The cave’s roof partly collapsed, not only exposing the transgressed ‘a‘ā, but also forming the two entrance pukas. This cave-forming mechanism is fundamentally different from the standard lava tube formation modes “inflation” and the “crusting-over of channels” (e.g. Kempe 2012).

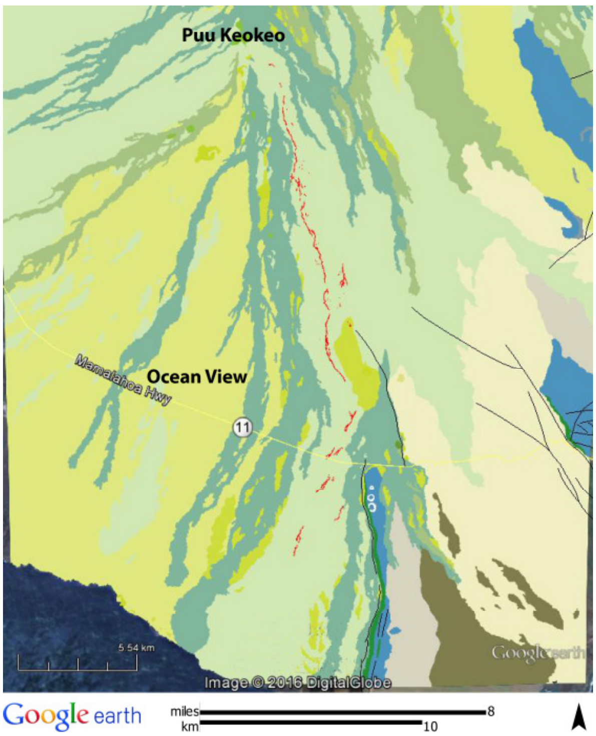

Figure 1. Geologic overview of the Keokeo flow on the south slope of Mauna Loa. The red lines show the approximate location of explored passages. The distance from the top to bottom of the figure is about 30 km, and north is up. The Keokeo flow is colored light green. Older flows are yellow and green, while modern flows are colored blue. The thin black lines indicte faults. Highway 11 crosses the figure from left to right just below the middle.

While detailed geologic studies have not been done in other segments of the system, the mode of down-cutting into an ‘a‘ā layer appears to persist throughout the main, lower level trunk passages. This is most often revealed by wall coatings, typically 0.2 to 1 m thick, that have peeled away, generally falling towards the center of the passage, and leaving a pile of exposed ‘a‘ā rubble behind. Often the ‘a‘ārubble is stained orange or red, due to formation of hematite by oxidation of the ferrous iron contained in the basaltic glassby. One of the more dramatic examples is shown in Figure 2.

Figure 2. Illustration of wall-lining peeling away to reveal a thick layer of red ‘a‘ā rubble behind. Bob South is the model. Photo by Peter and Ann Bosted.

Throughout the system, the larger entrances are often the best place to study the stratigraphy. Where there are clean ceiling collapses, it is sometimes possible to count the number of pahoehoe sheets and ‘a‘ā layers.

Figure 3. Stephan Kempe (in red) and Tim Scheffler above one of the largest entrance to the system. Photo by Peter and Ann Bosted.

The cave passages often contain white, orange, and sometimes pink or green minerals. These most commonly occur as crusts or coatings on the ceiling, walls, and sometimes on the floor. There is a noticeable correlation of mineral coatings with high wind velocities near major entrances and constrictions where the Venturi effect makes for strong air flow. The relatively dry climate of the region likely stops the minerals from being dissolved, because they are much more common here than in the wet areas of Hawai‘i. Based on sampling in the nearby Kanohina system, most of the white minerals are probably calcite, gypsum or opal, although epsomite and mirabilite can be found. A typical medium-size passage with white, orange, and red coatings, and an ‘a‘ā floor over smooth linings, is shown in Fig. 4. In some areas, the minerals are in a frostwork-like morphology, as illustrated in Figure 5.

Figure 4. Ann Bosted in typical medium-sized passage with many mineral coatings. Photo by Peter and Ann Bosted.

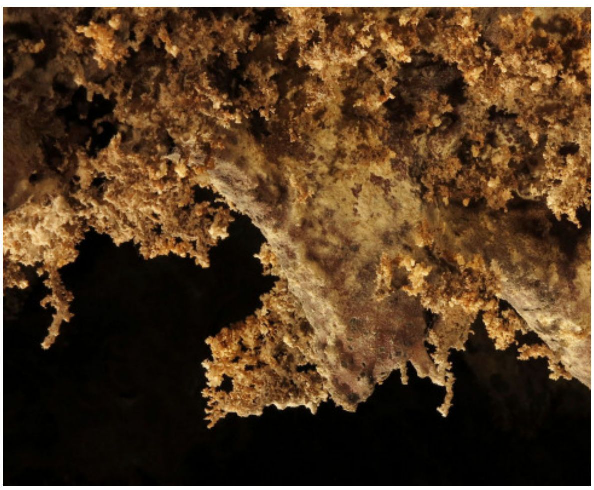

Figure 5. Delicate frostwork minerals on ceiling lava drips. Photo by Peter and Ann Bosted.

4. Biology

The Keokeo flow covers a large elevation range (from sea level to about 2,200 m), but the endemic Hawaiian Ohi‘a tree can be found throughout almost the entire range. This tree is very important to the cave biology, because it is adapted to putting its roots down into lava tubes, often going right through to the floor below. Some of the roots are well over 10 m long and bundles up to 30 cm in diameter occur. An example of thick forest of Ohi‘a tree roots is shown in Figure 6.

The tree roots are an important source of nutrition and water for a host of cave-adapted species. Including crickets, millipedes, spiders, isopods, moths, and planthoppers. The very rare thread-legged doodle bug was observed in one location, as well as two as-yet-unidentified species.

Another important source of the cave biology is the large number of goats that use the caves as night-time shelters.

Figure 6. A thick forest of ohi'a tree roots. Photo by Peter and Ann Bosted.

They supply nutrition by their excrements and the degradation of their dead bodies. The goats are generally found at lower elevations. At higher elevations, the most common mammal bones are Mouflon (a form of wild sheep), cattle, occasional horses, rats, and mongooses. A typical passage with an ungulate skull is shown in Fig. 7.

Figure 7. Typical passage with mouflon skull in the foreground. Photo by Peter and Ann Bosted.

Well-preserved fossil bird bones are also sometimes found, especially in deep passages far from entrances, where they are protected from weathering. Some of these may be from now-extinct species. A systematic study has not been done yet, however. One of the best-preserved examples is shown in Figure 8. This is most likely the head of one of the petrel varieties. In one remote cave location, over a dozen Hawaiian hoary bat skeletons were found very recently.

Microbial mats are found throughout the system. None have been studied as of this writing.

Figure 8. Fossil bird head. Photo by Peter and Ann Bosted.

Finally, the deep entrances provide a haven for certain rare and endangered plants. The moister climate is a boon to the Hapu'u (tree fern). Large Koa trees can also be found in deep pukas where the steep sides have excluded cattle, which would otherwise eat and trample the young trees. An example of abundant native vegetation in a skylight puka is shown in Figure 9.

Figure 9. An overhanging skylight with native vegetation. Photo by Peter and Ann Bosted.

5. Prospects

With about 200 or more entrances to investigate, clearly more work is needed just to finish the exploration, mapping, and photo-documentation of the Keokeo system. Meanwhile, there are many opportunities for detailed studies of the geology, biology (both macro and micro), extinct birds, and archeology. Combined with refined dating techniques such as paleo-magnetic measurements, it may be possible to determine how many different flow episodes were involved in forming the Keokeo System, and over what time period. Potential investigators would need to obtain a permit from the National Park Service or other land owners.

Acknowledgments

Thanks to the numerous cavers who helped with mapping and photography, especially Ann Bosted, Bob South, Ingo Bauer, Don Coons, Gary Whitby, Jenny Whitby, Bob Richards, and Carol Vesely. We thank the National Park Service for their strong support.

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Robotically Based Detection of Proposed Universal Microbial Biosignatures For Lavatubes on Earth and Extraterrestrial Targets

P.J. Boston [1, 2] (and a cast of thousands…)

Unique microbial patterns (aka "biovermiculations") and other biotextures and biominerals may be indicative of present or past microbial communities in caves and other extreme habitats. Since 2007, we have been mathematically modeling such patterns, studying them in nature, and attempting to simulate them in the laboratory. The work is now mature enough to have taught us some important lessons about how such features are established, and continue to change as physical, chemical, and biological circumstances continually shift. Although such biopatterns occur in a wide variety of cave types, and even some surface environments, their occurrences in basaltic lavatubes is often particularly striking and thus, provide an exceptional example for extended study. We will present a visual trip through the various morphologies and scaling factors to be found in lavatube biovermiculations and a summary of our findings of 8+ years of research to date.

The direct application of our findings to the detection, identification, and characterization of such features in caves and other habitats on Earth is being explored using robotic platforms under development for planetary exploration (Figure 1). We will present results of integrated science-on-robot trials in New Mexico lavatubes during September 2015. The latest cutting edge robotic concepts for access to subsurface and other challenging terrains will also be briefly reviewed, time permitting.

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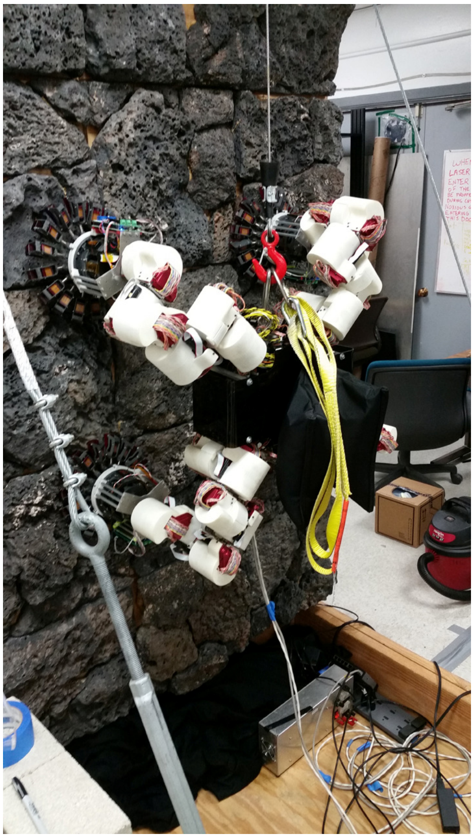

Figure 1: Prototype of the LEMUR robot under development at the Jet Propulsion Laboratory Rock Wall Test Facility. A version of this robot was recently tested in lavatubes at El Malpais National Monument, in Grants, New Mexico. LEMUR possesses unique footpads fitted with Microspines™ that grip rock using a series of circular arrays of sharp hooks, thus enabling secure clinging across a wide span of relative surface roughness conditions. The project goal is to integrate a variety of scientific instruments with such robots for access to lavatubes on Earth that may be inaccessible due to size, thermal characteristics, or gases poisonous to human investigators and to develop such capabilities for application to extraterrestrial mission targets including Mars and lunar lavatubes, and possibly cryogenic volcanic cavities on icy Solar System bodies. Image courtesy of A. Parness, NASA-JPL.

INSIGHTS INTO SPELEOTHEMS FROM LAVA TUBES OF THE GALAPAGOS ISLANDS (ECUADOR): MINERALOGY AND BIOGENICITY

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Abstract

Different types of hard and soft speleothems (stalactites, stalagmites, columns, crusts, flowstones, micro-gours and botryoidal coralloids) have been observed throughout lava tubes in the Galapagos archipelago, Ecuador. Three lava tubes were studied in this work: Gallardo and Royal Palm volcanic caves (Santa Cruz Island) and Sucre Cave (Isabela Island). The studied speleothems were mainly formed by opal, calcite and clay minerals, including plagioclase and pyroxenes from the basaltic host rock. Rarely, iron oxides, gypsum were found in some speleothems, which were interpreted as alteration products of the primary volcanic materials. Field emission scanning electron microscopy revealed abundant filamentous

bacteria, and reticulated filaments similar to those recently observed in others lava tubes around the world. These filaments are associated with EPS and mineral deposits rich in Si, Ca or Fe. The identified minerals and the evidence of biosignatures suggest a biological contribution to speleothem development within Gallardo, Royal Palm and Sucre lava tubes.

Introduction

Lava tubes have been considered of little mineralogical interest until recently (Hill and Forti 1997; Forti 2005). However, studies on speleothems from volcanic caves are currently receiving more attention. Detailed mineralogical and geochemical analyses have been performed in lava tubes around the world over the last 20 years (Hill and Forti 1997; Forti 2005; Daza and Bustillo 2012, 2014; Miller et al. 2014a, 2015).

Volcanic caves host an especially interesting variety of mineral-utilizing microorganisms and mineralized microbial structures, which may be recognized as biosignatures (Miller et al. 2014a; Garcia-Sanchez et al. 2015). Many of these biosignatures have been found in speleothems of volcanic caves from Australia (Webb and Finlayson 1987), the Azores archipelago (Bustillo et al. 2010; De los Rios et al. 2011; Northup et al. 2011; Daza et al. 2014), United States (Boston et al. 2001; White et al. 2010; Northup et al. 2011), and Easter Island (Miller et al. 2014a, 2015), among others. Most of these authors report opal and ochre speleothems similar to those described in the present work.

In general, primary cave minerals are formed at the same time as lava tube formation and in the first stages of lava cooling (White, 2010). Secondary cave mineral deposits, or speleothems, may result from the leaching of materials by meteoric seepage water and mineralized with the aid of microbial activity (Northup et al. 2011). Studies on the mineralogy of lava tubes from Galapagos Islands are very scarce. Gallardo and Toulkeridis (2008) reported gypsum and calcite as the main minerals in speleothems from Gallardo Cave on Santa Cruz Island. Forti and Calaforra (2014) carried out a general description of Galapagos lava tubes in a sampling survey conducted during the 16th International Symposium of Vulcanospeleology, corroborating the previous results. An earlier study performed on the siliceous speleothems of Galapagos lava tubes revealed enigmatic reticulated filaments (mainly rich in Si) associated with other microbial cells and filamentous bacteria (Miller et al. 2014b).

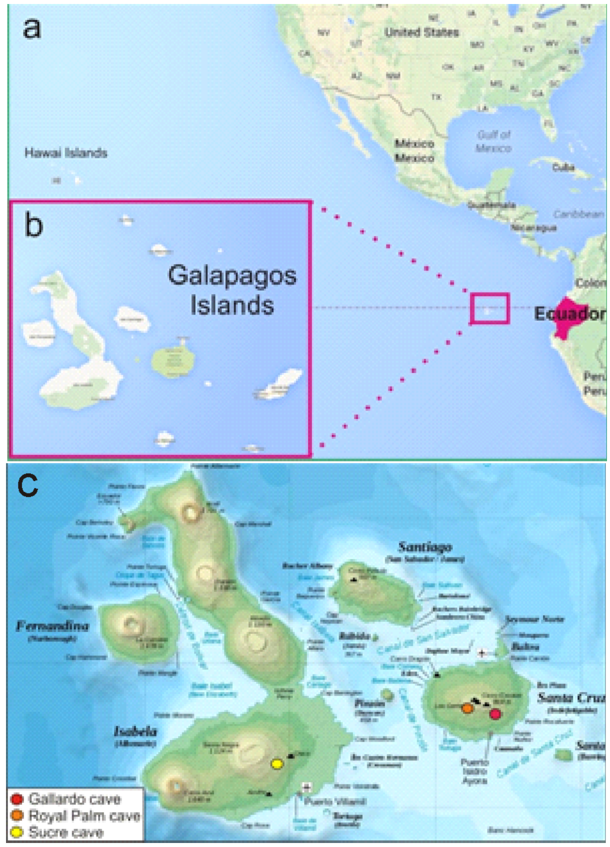

Figure 1.
a) Location of the Galapagos Islands, about 1000 km offshore from Ecuador; b) Detail of the Galapagos Archipelago. Google maps image. c) Location of the studied volcanic caves: Gallardo and Royal Palm lava tubes on Santa Cruz Island and Sucre lava tube on Isabela Island.

The aim of the present work is to advance in the mineralogy and microbe-mineral interactions of speleothems from lava tubes of the Galapagos Archipelago (Santa Cruz and Isabela Islands).

Geological Setting

The Galapagos Islands are situated within the equatorial zone, about 1000 km west from the Ecuador coast, in the eastern Pacific Ocean (Fig. 1a). The Galapagos microplate is at the junction of three oceanic plates: the Pacific, Cocos and Nazca plates, which are moving away from each other. Galapagos is located just east of the East Pacific Rise and south of the Galapagos Spreading Center (Gallardo and Toulkeridis 2008).

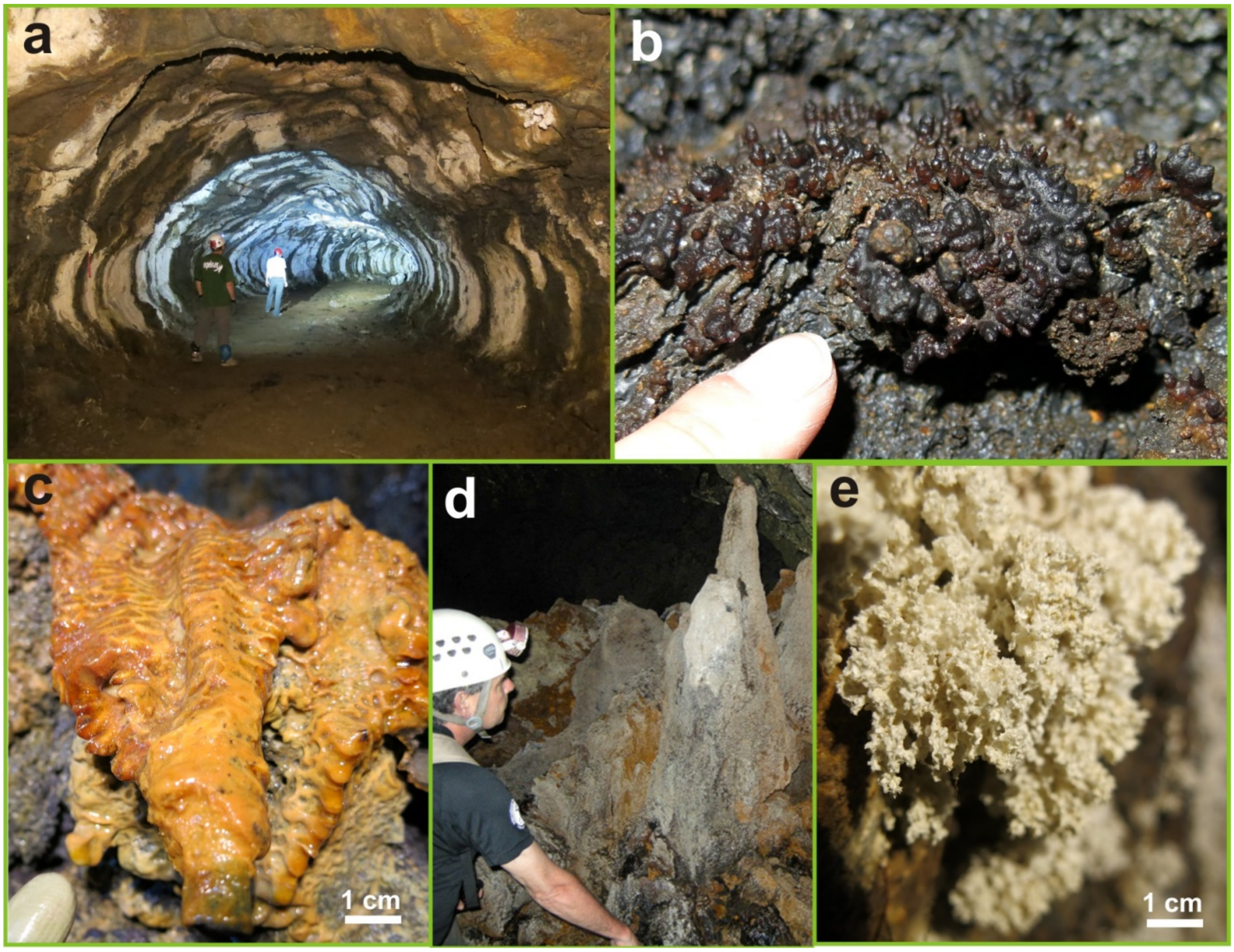

Figure 2.

Field images of speleothems from Galapagos lava tubes: a) General view of Bellavista lava tube (Gallardo Cave); b) Brownish small coralloids on the walls of Love tunnel (Gallardo Cave); c) Reddish stalactite on walls of Royal Palm lava tube; d) Big stalagmites near the entrance of Royal Palm Cave; e) Moonmilk on the walls of Bellavista lava tube (Gallardo Cave).

All islands of the Galapagos Archipelago are of volcanic origin: there are 7 islands with an area >100 km^2 (Isabela, Santa Cruz, Fernandina, Santiago, San Cristobal, Floreana and Marchena) (Fig. 1b), 12 islands (Pinta, Española, Baltra, Santa Fe, Pinzón, Genovesa, Rábida, Wolf, Darwin, Seymour North, Tortuga and Bartolomé) ranging from 60 to 1 km^2, as well as 42 small barren islands and 26 rocks, of only a few square meters (Gallardo and Toulkeridis 2008). All of these islands are still active, making it one of the most volcanically active places on earth (Gallardo and Toulkeridis 2008).

Three volcanic caves from Galapagos were sampled for this preliminary study, corresponding to two lava tubes (Gallardo and Royal Palm caves) on Santa Cruz Island, and one lava tube (Sucre Cave) from Isabela Island (Fig. 1c). All of them are hosted in basaltic lava flows (pahoehoe type) (Gallardo and Toulkeridis 2008).

Gallardo Cave is also known as "Bellavista Cave" and locally known as "Amor" or Love Tunnel depending on the cave section. It is located in the eastern part of the island, near Bellavista town and 6.8 km north of Puerto Ayora. The cave is a lava tube 2250 m long up to 9.8 m maximum height and 17.8 m maximum width. It is interrupted by six ceiling collapses and the first km is usually used as a tourist trail.

Royal Palm Cave is located in the western part of Santa Cruz Island, near Santa Rosa village and close to the Miconia Highland Forest, adjacent to the Galapagos National Park of Santa Cruz. This lava tube is 600 m long, with a mean of 5-15 m height and 2-10 m width. It is managed by the Royal Palm Hotel for touristic use.

Sucre lava tube is one of the longest tubes known on Isabela Island; the cave is also accessed by an ecotourism trail approximately 480 m long. It is located in an agricultural/forest zone, approximately 14 km from Puerto Villamil (Fig. 1c).

Different types of speleothems have been reported on the walls, ceilings and occasionally on the floor of these lava tubes (Fig. 2a). They comprise small coralloids (Fig. 2b), stalactites (Fig. 2c), stalagmites (Fig. 2d), columns, powdery crusts, botryoidal speleothems, flowstones, gours and moonmilk (Fig. 2e) with colorations from whitish and greyish to ochre, brownish and reddish. In many cases, the speleothems are still growing in response to specific physical and chemical processes within the cave, which are influenced by the extremely humid microclimate of the Galapagos Islands.

Materials and Methods

Different types of speleothems from the two parts of the Gallardo Cave (Santa Cruz Island) were studied: (i) fragments of coralloids, small powdery crusts and botryoidal speleothems from Love Tunnel, and (ii) white moonmilk and coralloids from the Bellavista lava tube. Ochre stalactites, stalagmites, columns, and beige and greyish small coralloids were collected in Royal Palm Cave (Santa Cruz Island). Small stalactites, thin powdery crust and coralloids from Sucre Cave (Isabela Island) were also selected for analysis.

The mineralogical characterization of the speleothems (19 samples) was performed by X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), micro-Raman spectroscopy and a Gandolfi camera.

XRD was carried out using a Philips PW1710 diffractometer with a Cu anode (CuKα, λ=0.154 nm). Infrared spectra were recorded on a Perkin Elmer Spectrum 100 FTIR-ATR spectrometer in reflectance mode. Micro-Raman spectroscopy analyses were conducted using a Laser Research Electro-Optics (REO). The spectrometer used was a KOSI HoloSpec f/1.8i model made by Kaiser, covering a spectral range in Raman displacement of 0–3800 cm^{-1} and a spectral resolution of 5 cm^{-1}, and the CCD was a DV420A-OE-130 model from Andor (1024×256 pixels). Microanalyses up to 40 μm diameter spots were undertaken with a Nikon Eclipse E600 microscope using 50x magnification. Some speleothem samples were also analyzed using a Gandolfi camera (40 kV tube and 20 mA, radiation CuKa, λ = 1.5418 Å, with Ni filter). The internal structure and morphological characteristics of the speleothems were examined by scanning electron microscopy (SEM Philips XL40) coupled to an energy dispersive X-ray spectroscopy microprobe (EDS-EDAX 9900). Field Emission Scanning Electron Microscopy (FESEM) was also carried out using a Jeol JSM-7001F microscope equipped with an Oxford EDS detector.

Results and Discussion

Mineralogy

Powder XRD analyses of the speleothems from Gallardo lava tube showed patterns corresponding mainly to amorphous silicate, calcite and clay minerals (nontorsite, sepiolite, illite). XDR patterns were similar for speleothems from both sections of the cave (Love Tunnel and Bellavista lava tube). Noteworthy was the identification of iron oxides (hematite) in one stalactite from Love Tunnel.

The moonmilk deposits from Bellavista lava tube were mainly formed by calcite, with small amounts of montmorillonite, organic compounds and clay minerals as accessory minerals, as revealed by FTIR, micro-Raman and Gandolfi camera. However, the speleothems from Royal Palm Cave were mainly composed of iron oxides (including goethite and hematite), with some calcite, clay minerals and plagioclase; the latter are derived from the host basalts.

Speleothems from Sucre lava tube showed the same minerals as those found in samples from Gallardo Cave. Gypsum was also detected by XRD in a speleothem from this cave.

Hydroxyapatite was detected by all techniques in two speleothems from Royal Palm and Sucre caves. Their origin might be linked to the remains of bones of small dead animals (birds?).

Most samples comprised amorphous substances difficult to identify by XRD. For this reason, FTIR, Raman spectroscopy and Galdonfi camera were used. These analyses revealed that the amorphous silicate, mainly detected in speleothems from Love Tunnel, were composed of opal. Montmorillonite, organic compounds and amorphous carbon were detected by FTIR and micro-Raman in samples from Bellavista lava tube.

SEM Observations

FESEM images showed several inorganic and organic structures on the speleothem samples. Coralloid speleothems were generally of siliceous composition,

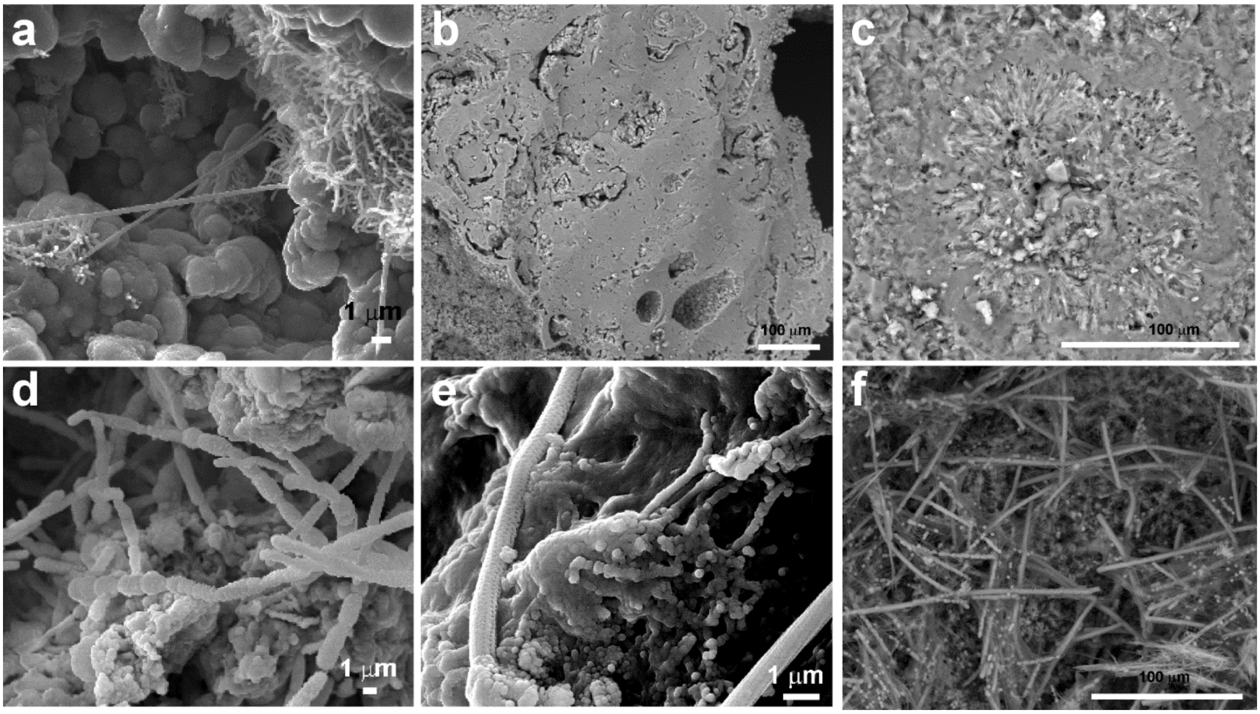

Figure 3.
FESEM images of speleothems from Galapagos lava tubes. a) Coralloid speleothems depicting opal microspheres from Royal Palm Cave. b) etch pits or microboring (arrows) produced by microbial cells on the mineral surfaces of coralloids from Love Tunnel (Gallardo Cave). c) Acicular calcite crystals in a coralloid; d) Actinobacteria-like structures from Love Tunnel (Gallardo Cave); e) Detail of a reticulated filament on a siliceous coralloid from Bellavista lava tube (Gallardo Cave); f) Large amounts of filamentous bacteria associated with EPS in moonmilk deposits from Royal Palm Cave.

depicting botryoidal aggregates formed by opal microspheres (Fig. 3a). Imprints and etch pits or microboring produced by bacteria were also observed on the mineral surfaces (Fig. 3b). In addition, filiform coralloids were sometimes found on siliceous coralloids with acicular structures formed by calcite crystals (Fig. 3c).

In general, the siliceous speleothems observed by FESEM showed abundant microbial structures, including actinobacteria-like cells (Fig. 3d), filamentous bacteria and reticulated filaments associated with extracellular polymeric substances (EPS) (Fig. 3e). These fibrous structures consist of long filaments with mineralized sheaths rich in Si, Ca, and Fe, as detected by EDS microanalyses (Fig. 3e).

Reticulated filaments similar to those observed in this study, have been also reported in speleothems collected from lava tubes in the Canary Islands (Spain), Easter Island (Chile) and Cape Verde Islands (Melim et al. 2008; Miller et al. 2014a,b), as well as in a granite springwater tunnel in Porto, Portugal (Miller et al. 2012) and limestone caves (Melim et al. 2008). Most of these reticulated filaments have been characterized as mineralized filaments with hexagonal and diamond-shaped chambers resembling honeycomb structures).
Occasionally, needle-shape calcite fibers associated with microbial cells were observed in Gallardo Cave samples (specifically on speleothems from Bellavista lava tube; Fig. 3f). These microbial cells were also found in close association with EPS, evidencing geomicrobiological interactions.

The formation of siliceous speleothems reported in many studies has been interpreted as having been mediated by microbes (Aubretch et al. 2008, 2012; Daza and Bustillo 2014; Forti 2005; Miller et al. 2014a; Urbani et al. 2005; Vidal Romaní et al. 2010; Willems et al. 2012). Their mineralogy has been mainly described as opal A, and the presence of microbial structures and EPS associated with opal microspheres indicating their biogenic origin (Aubretch et al. 2008; Miller et al. 2014a).

Conclusions

Several types of speleothems such as stalactites, stalagmites, columns, powder and crusts, botryoidal speleothems, flowstones, small coralloids and soft and hard micro-gours have been found in Gallardo, Royal Palm (Santa Cruz Island) and Sucre (Isabela Island) lava tubes. Most of these speleothems are composed of opal, calcite and clay minerals. Plagioclase and pyroxenes appear as secondary minerals of the host rock (basalt). Calcite is present in a small proportion of samples, and is interpreted as representing the most recent speleothemic stage in these caves. Gypsum was detected in a single sample, whereas iron oxides, including hematite and goethite were identified in several. These minerals are considered alteration products of the primary volcanic materials. Hydroxyapatite is the main mineral in two samples, whose origin might be linked to the decay of bones of small dead animals. Associated with this varied mineralogy, different filamentous bacteria were observed in almost all the studied speleothems, though reticulated filaments were found particularly on siliceous speleothems. The Galapagos Islands and their lava tubes seem to be a unique site for future geomicrobiological studies to gain a deeper and more accurate understanding of the biogenicity of these speleothems and the relationship between silica/opal/carbonate precipitation and microbial activity.

Acknowledgements

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SEARCHING FOR LAVA TUBE CAVES – A RAPID METHOD

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Abstract

Searching for lava tube caves by traditional means can involve challenges and limitations such as (a) hiking, which can take a lengthy amount of time, and can, on occasion, be formidable due to the nature of some of the terrain that is encountered, and (b) aerial spotting with either an airplane or helicopter, which can be very costly, and may require prior planning/scheduling. In the case of an airplane, attempts to observe potential caves can be difficult due to the higher elevation of the plane. Use of a helicopter can also be somewhat problematic. Also, with these aerial approaches it would not be possible to truly closely observe, nor enter, a pit or collapse for further assessment.

We offer an alternative to the above approaches with the use of a drone and a mounted high resolution video camera. Such a technique and equipment is also not cost prohibitive, nor requires extensive planning and scheduling. With the available movements of the drone and the mounted camera, essentially all directional axes can be achieved for successful viewing. In this presentation we will demonstrate, with video examples, the rapid use of the drone in a search for lava tube caves on the Big Island. Once collapses/pits or suspected leads have been spotted, actual exploration can commence.

Introduction

Traditional approaches in narrowing the search for caves rely on an understanding of geography and geology, coupled with sound research. This can then be followed by ridgewalking or hiking the terrain to attempt to discover a cave. With limestone-based caves, aerial techniques are also helpful, but may not necessarily discern cave entrances, as such entrances are not always visible from overhead, and can also be obscured by extensive vegetation.

In the case of lava tubes, the nature of the terrain on lava fields can, at times, be very challenging when hiking, and cave entrances/collapses can prove to be very difficult to see at ground level. Aerial techniques for the discovery of new lave tube caves, and the location of existing caves, are possible with the use of aircraft such as airplanes and helicopters. However, these aircraft have their limitations in terms of (1) detailed logistics - the need for advanced planning, scheduling, location of the aircraft, and the availability of a pilot, and (2) the very significant cost involved for a pilot and aircraft. We offer an alternative to the above approaches with the use of a drone and a mounted high resolution video camera. Such a technique and its equipment is (1) portable, (2) not cost prohibitive, and (3) does not require extensive planning and scheduling. With the available movements of the drone and the mounted camera, essentially all directional axes can be achieved for successful viewing.

To demonstrate the use of a drone for the location, and initial assessment of a lava tube entrance/collapse, we undertook this activity on two different days on the Big Island of Hawaii.

Equipment and Specifications

The equipment and their specifications, used in the drone searches, are described below. It is also important to note that this equipment is portable and can be effectively carried in backpacks into the field.

Equipment

DJI Phantom 2 Quadcopter Drone

Quadcopter Remote Control

GoPro Hero 3+ Camera, with 1080p Video

Tripod Monitor

Key Specifications

The key specifications of the Quadcopter involve (1) a flight time of 12 to 15 minutes with the onboard battery, (2) a top speed of approximately 40 mph (64 kph), (3) a maximum range of at least 2 miles (3.2 km), and (4) a working elevation/altitude near ground level to several hundred feet (or much higher – but not encouraged for reasons due to regulations). When in flight, the quadcopter can be remotely directed to rotate to the left or right, and can move vertically up to higher elevations or down near ground level. The mounted camera can pivot up or down. The quadcopter can easily hover over a specific area of interest. With the available movements of the drone and the mounted camera, essentially all directional axes can be achieved for successful viewing.

Monitor Details

The stationary monitor is mounted on a tripod and remains at the base of operations, while the quadcopter flight is controlled by remote control. During flight, the base monitor's display shows the operator what the quadcopter-mounted camera is recording in real-time, and also includes flight data information on (a) distance, (b) elevation, (c) vertical and horizontal speed, (d) the azimuth from the home point (where it first took off), and (e) the battery life of the drone. The monitor is also capable of tracking the GPS location of the quadcopter, but the GPS option was not included with our drone. It should be noted that the drone is controlled remotely by line-of-sight. That is, the drone must be able to communicate with the base operator without obstructions in the field.

Photographs of Equipment

Figure 1: Quadcopter Drone with Mounted GoPro Camera on Platform

Figure 2: Greg Chavdarian with Quadcopter Hand-Held Remote Control and Full Display Monitor on Tripod

Discussion and Results

First Searches and Demonstrations – April 2015

To demonstrate how rapidly a drone can locate a cave, we chose to work in a region known to have a number of caves, or potential caves. In April of 2015 we traveled into the saddle of the Big Island (between Mauna Kea and Mauna Loa) at an elevation of approximately the 8,000 ft (over 2,400 m) and higher. In this region, there are massive lava fields, and a number of known and suspected lava tubes. Having arrived at our base location by vehicle, we quickly set up the equipment near the side of the road.   This specific locale was chosen since Crystal Cave is nearby, and had been visited by one of us (C.C.) five years earlier. However, it was not known if there were additional collapses present in this vicinity. The drone was flown in the general direction of Crystal Cave while high definition video was recorded with the onboard camera. The goal was to look for any entrance collapses, including the entrance to Crystal Cave. With this first flight, the Crystal Cave entrance was quickly located. During the flight, it also became obvious in the video, that Crystal Cave was part of a specific and lengthy lava flow. It is important to note that past (historical) eruptions and flows can be easily differentiated by drones. Unknown to either of us was the possibility of further collapses, which could indicate potentially additional lava tubes within this flow. The drone was therefore flown farther along and above this flow, and we surprisingly found several additional collapses, most in a linear pattern. This could open up the opportunity to explore the collapses beyond Crystal Cave to determine whether there are (a) more lava tubes, and (b) are some or all of these linearly placed entrance collapses part of a larger lava tube. As the drone flew over the collapses, we were able to direct the drone lower and much closer to a specific collapse in order to observe finer details. This first drone flight demonstrated several advantages in the search for caves.

After a successful demonstration with the first drone flight, we then traveled to another locale nearby, where it was known that some modestly deep pits existed that would require a short rappel to explore them. The plan was to find the first pit with the drone, and then demonstrate another advantage of the drone – the ability to remotely direct a camera-mounted drone down into a pit for further exploration/assessment. As part of the 2010 trip to this area by one of us (C.C.), part of our team actually rapelled into the pit closest to the road. (This pit is also noteworthy for the intriguing lava balls lying on the surface nearby.) On this day, we planned to demonstrate an alternative to a rappel. Our second drone flight of the day – from a base location by the road - quickly located this pit. After we hiked to the pit, the drone was then directed down into the pit to demonstrate that video recordings inside a pit could be obtained. The drone was controlled by line-of-sight from an operator standing on the edge of the pit. Due to the angle of the sun, the bottom of the pit was partially shrouded in shadow, but the drone camera did manage to still provide a closer view of a substantial part of the bottom. It should be noted that it is possible to optionally attach an on-board lighting system to the drone for illumination, although we did not have that feature on our specific drone. The demonstration was successful. To show the descent of the drone into the pit and its ascent from a different perspective, we also recorded video with a separate camera held by one of us standing at the lip of the pit. The advantage with the use of this technology is that this technique could assist cavers in determining if there were additional passages in the bottom of a pit, or interesting features, without the necessity of having to rappel into every pit that they encounter. In this fashion, a caver could then make a more informed (and more rapid) decision as to whether or not to physically rappel into a pit for further exploration. As long as line-of-sight is maintained with the operator and the drone, and the pit is wide enough to safely fly the drone, this novel approach will work. We then flew the drone well beyond this first pit in the search for more collapses or pits. One of us (C. C.) was aware of an additional pit beyond the first one (based on the 2010 trip). The drone quickly found this very large and relatively deep pit, while we remained at the base location by the road. The drone hovered over it and took additional video. The drone was then sent even further, and to our pleasant surprise, we discovered a third substantial pit that we were not aware of. Thus, within a matter of minutes, we were able to successfully locate and record three large lava pits. We also demonstrated the ability to lower a drone with camera into a pit to afford additional evaluation of the pit. The video recordings that were obtained are included for presentation at the Symposium.

Second Searches and Demonstrations – October 2015

We returned to another locale off of Saddle Road on the Big Island at an elevation of 5,700 ft (over 1,700 m) under an overcast and somewhat foggy day in October of 2015. This would provide another good test of the drone and camera facing more challenging weather conditions. We parked our vehicle off-road (4WD vehicle) and near the path that would take a hiker to the well-known, undeveloped Emesine Cave, over 2 miles away. Since Emesine Cave was in this area, we wanted to see if the entrance collapses of other caves were also present, and could be spotted in a timely manner. The terrain here was much more rugged than that in the Saddle area during our April 2015 trip. In addition to the tough, undulating lava terrain in this region, there were some areas with partial vegetation, and places with extensive vegetation (even forest-like), which would make hunting for cave entrances more challenging. We knew that our drone would barely have the range (and battery life) to actually reach Emesine Cave and return, so we decided to instead simply search for potential lava tube leads in this general area. We chose to undertake three flights on the same day, one to the east of Emesine, one to the west, and one to the south (and all of them south of Saddle Road).

The same base location was used for all three searches. The first flight to the east revealed rugged lava terrain, with some significant vegetation, and variable fog overhead. However, the conditions were still conducive to detecting some leads. The drone and camera finally picked up a potential lead partially obscured in a somewhat forested area. In this case, further exploration would require a hike to the lead to determine the extent of the find, however, the mission was accomplished. The flight to the west was similar in terms of rugged terrain, but very sparse in vegetation, which made it easier to spot possible leads. In this case, an intriguing lead was indeed found. The drone and camera were repositioned above the lead/entrance and re-oriented to provide various views. If this lead was to be further pursued, the next step would likely have involved a hike to this location for further evaluation. The final search was directed to the south, and along the hiking trail to Emesine Cave. However, the drone did not travel as far as Emesine's location due to the range of its battery. This last search traveled over terrain with and without significant vegetation (forest-like areas), but along the Emesine hiking trail. Although no lead was observed during this third and final search, and no large collapses/entrances were observed on this day of overall searching, two potential leads were nonetheless observed and recorded. This aerial search technique again successfully demonstrated the ability to cover extensive swaths of land in an expeditious manner, and discover potential leads. These video recordings are included for presentation at the Symposium.

Conclusion

In this presentation we have successfully demonstrated the use of a remote-controlled quadcopter drone with a high-resolution video camera in the search for lava tube caves/entrances (collapses). The components – drone, camera, monitor, controller, and tripod – can be carried in backpacks into the field. The technique affords rapid and effective searches at a nominal cost, compared to other aerial techniques.

In general, the use of such drones is becoming a world-wide phenomenon. However, to date, this technique has not as yet been in common use, in the caving community, in the search for caves. Because of the nature of the topography on the Big Island of Hawaii, the use of drones is well-suited to the discovery and assessment of possible cave entrances. Once such collapses/pits or suspected leads have been spotted, actual exploration can commence.

In the February 2015 Vulcanospeleology Symposium, we will demonstrate, with video recordings of the two days of exploration, the use of this aerial technique – a drone with a high-resolution video camera - in the search for lava tube caves.

Bárðarbunga Eruption. The effectiveness of observation of the eruption from a commercial aircraft compared with observation by a consumer grade drone.

Phil Collett

In the early 2000s I had been on a Shepton Mallet Caving Club – Bournemouth University expedition to locate and explore caves in the flows produced by the 1783 Laki eruption. As the Bárðarbunga eruption in the Holuhraun was a similar type of eruption, I was keen to see it. As it was next to impossible to get the permits required to visit by car, a flight was the only option.

DJI flew Phantom drone close enough to the eruption to melt the camera, so I found close up images very interesting, as I could better understand what I had seen at Laki.

CAVE EXPLORATION WITHIN THE GREAT CRACK OF KILAUEA VOLCANO

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The Big Island of Hawai`i is currently formed by the mass of five large volcanoes. The Kohala Range to the north is the oldest and has not erupted in recent geologic times. Mauna Kea is the tallest at 13,796 feet in elevation. It last erupted shortly after the most recent ice age, but has not erupted in historic times. Mauna Loa (Long Mountain) is the largest, stretching from Hilo on the east to Kona on the west and south to Ka Lae, the southernmost point of the island. The high point on the caldera rim to this massive structure reaches 13,677 above sea level. The base of the island formation plunges to more than 16,000 feet below sea level. Hualalai rises to 8,271 feet above the Kona coast. Kilauea perches on the southern flank of Mauna Loa at an elevation of just over 4,000 feet. It is the smallest of the volcanoes, but also the most active in historic times, erupting nearly continuously for the past forty years. The last three volcanoes in this list have all erupted in historic times and are expected to do so again. A sixth active volcano, Loihi, is actively growing beneath the ocean just to the south of Ka Lae.

The staff at Hawai`i Volcanoes Observatory (HVO) are actively monitoring all of these mountains in an effort to better understand their formation and hopefully better predict when and where the next eruptions will occur. One of their most promising techniques has been to closely follow the expansion and contraction of each mountain mass as lava plumes rise up from the deep mantle of the planet. These upward rising flows of magma originate tens of kilometers beneath the surface and exert enough pressure to actually enlarge the overall volume of an entire mountain core. Once the plume erupts to the surface, pressure is released and the mountain responds with a deflation episode. It shrinks in volume.

In order to accommodate these massive changes in volume, each mountain develops a set of three linear cracks that radiate outward from the summit caldera. They are normally arranged equidistance from one another, so that 120 degrees of arc separate one from the next. This highly regular pattern is believed to be related to the original crystal structure of the basalt. The same “three way split” can be seen on a smaller scale in tumulus formations that pop up on the surface of current day pahoe`hoe flows. In most cases two of these fault zones are dominant, while the third is often very subtle or sometimes buried beneath an adjacent mountain. The last stage eruption events of the more ancient mountains usually blanket the entire surface with deep ash deposits. On these mountains, the original fault zone areas are buried and no longer visible.

On current day maps and air photos, these active Rift Zones are clearly recognizable on the most active volcanoes. Mauna Loa has dominant features extending to the southwest and northeast. Kilauea has prominent rift zones to the southwest and east. The summit craters of Hualalai are developed along rift zones that extend to both the northwest and southeast. Most of the larger flows on the Big Island for the past 200 years have erupted along these zones. The Northeast Rift Zone of Mauna Loa has been actively depositing many of the longest lava flows on the island throughout historic times. Most erupt high on the mountain, flow down toward the saddle to Mauna Kea and then turn east toward Hilo. Some have even reached the city limits. Major events have been observed in 1842, 1855, 1881, 1935 and 1984. These eruptions are generally characterized by long duration events that often flow for months with a preference to deposit Pahoehoe lava rather than A`a. The Southwest Rift Zone has been equally active with major eruptions in 1887, 1907, 1919, 1926 and 1950. Eruptions along this active fault line generally spring out at elevations from 6,000 to 8,000 feet. Most reach the coastline below in record times ranging from three hours to eight days. Flowing at this volume and speed, they normally form open channels with fast moving material that deposits predominantly A`a lava. The single longest and largest flow on the island broke out at an elevation just above 11,000 feet on Mauna Loa in 1859. This flow is believed to be associated with a rather poorly defined Northwest Rift Zone. It reached the ocean approximately 47 miles from the eruption site in less than one week, depositing primarily A`a along the way. The event then shifted to a slower flowing regime and laid down a ribbon of Pahoehoe just adjacent to the original tongue. This more sedate episode eventually reached the ocean, as well and continued to flow for nearly four months.

Hualalai Volcano has erupted only once in historic times with flow events that originated off the Northwest Rift Zone and flowed to the sea in 1801.

The geologists at Hawai`i Volcanoes Observatory have been monitoring lava flows on the Big Island for more than a century now. Their current facility, built in 1912 is perched on the rim of Kilauea Caldera. Monitoring the movement of subterranean magma upward beneath the caldera of Kilauea Volcano has long been their primary focus. Visitors to the Volcano in the 1800's often describe a "boiling inferno" or "Hades own hell" across the floor of Kilauea Caldera. Most of the activity during this century seems to have been centered beneath the mountain summit. Beginning in the twentieth century, things began to change. Flows broke out along the higher elevations of the Southwest Rift Zone as early as 1920 and persisted through the 1974. Large events also occurred along the lower Eastern Rift Zone in 1955 and 1960. During the early 1970's a major shift occurred toward the higher elevations of the East Rift Zone and eruptions have been more or less continuous in this area for the past 40 plus years. Major eruption sites include Mauna Ulu, Kupa`ianaha, and Pu`u O`o.

So finally we arrive at the primary focus of this paper, the lower extent of the Southwest Rift Zone on Kilauea Volcano. Beginning at roughly 2,300 feet in elevation, this section of the Rift is quite unlike any other on the island. Faulting activity here has consolidated into a feature named The Great Crack. It is just that, a single large crack that runs unbroken for more than 10 miles before finally reaching the coastline. Averaging 30 to 60 feet in diameter and roughly the same in depth, it is easily visible on Google Earth images and stands out as a prominent feature for any aircraft flying over the area. Most of the floor of this open crack is littered with breakdown, but there are occasional gaps where cave entrances and pit craters lead to greater depths within the Great Crack System. A master thesis by Chris Okubo has located more than twenty of these voids. Most require vertical climbing equipment to enter. A small group of dedicated cavers has been working to explore at least a few of these underground systems.

The Great Crack has been mentioned in many past publications by various geologists including Don Swanson from Hawai`i Volcanoes Observatory. Bill Haliday recognized the potential for caves to be developed within this fault system quite some time ago. They first introduced the author to the area in August of 2001. Our first trip was somewhat limited by the amount of gear that we packed along. Since no one had actually ever entered the cave entrances that were known to exist along the length of the crack, we didn't bring along much rope. One short hand line was about it. As we entered the cave opening that they had chosen for this original trip, it very quickly became obvious that these were caves of a very different sort. The horizontal cave entrance to this first Great Crack feature was substantial. A talus slope descended into an opening easily large enough to accommodate a two lane highway. The only problem was the house sized boulder that was lodged precariously between ceiling and floor. It was clearly out of sync with the angle of repose of the surrounding smaller sized breakdown matrix and looked as though it had no more than minimal contact where one tip end of the rock touched the ceiling. This theme of large boulders with little visible support was to hold true throughout our exploration of the Great Crack Caves.

With little rope and only small hand lights, we were not able to explore any distance into the cave, but did establish that there was a sizable horizontal passage that ended after only 150 feet. We did also establish that a small hole along the left hand wall was easily enterable into a deep vertical drop that blew a great deal of air. It was intriguing and certainly offered promise of more exciting exploration to come.

The next trip to the cave was on the 23rd of February, 2001 when Ric Elhard, Cindy Heazlit and the author returned with a full kit of vertical gear and more than 450 feet of rope. They managed to descend 85 feet to a second level of the cave that directly underlies the large upper passage explored on the initial trip. This pitch was followed immediately by a 20 feet up climb and then a 120 rapel into an even larger third level. This horizontal run lasted for a few hundred feet and then pinched down to yet another drop. Rigging their last small diameter line, they were elated to discover the largest passage yet at a depth of just over 400 feet below the surface. This horizontal run doubled back directly beneath the three upper level segments of the cave, four distinct levels stacked one on top of the other. This lowest level of the cave was also the largest averaging more than 30 feet in diameter with vertical walls that ascended straight up into darkness. The cave was definitely more of a crack than a tube, but thick wall coatings indicated that it has also carried large volumes of lava at various times in the past. A few collapsed sections revealed that at least four different flow events had passed through the crack system. Samples collected on this trip were turned over to Don Swanson at HVO. He was able to confirm that they were identical in composition to the 1823 flow which first rises to the surface several miles beyond this point along the crack system.

The entire cave is developed along vertical tectonic openings that were later occupied by large volumes of flowing magma. Floors throughout the cave are littered with highly unstable breakdown. The one point of solid bed rock seen in the entire cave occurred at the deepest point reached during the exploration. Ceilings exhibit clear flow features and filled dikes of basalt. They are believed to be formed as the surface of each subsequent flow event cooled on contact to the open air above. Pitches that allow egress to each level of exploration were most likely formed by collapse of thin shelled areas in this false floor. A similar process is often visible in lava tubes, forming characteristic "tube in tube" development.

A third trip on January 12, 2002 was needed to complete the exploration and finish up survey work to complete the map that accompanies this article. The author and Ric Elhard lead this final trip and entered the cave along with Warren Hollinger, Penelope Pooler, Andrew and Eli Dubois. A final 85 feet ascend was climbed and rigged, surveys and photos were collected and the final terminus of the cave was reached. Total surveyed length was 2,320 feet. Maximum depth below the surface was established at 600 feet. The entire cave underlies roughly 1,000 linear feet along the Great Crack System with four distinct layers developed one on top of the other.

Thus ended our exploration into the first cave surveyed along The Great Crack. Things took a very interesting turn in December of 2005. Our next adventure into this fascinating new underworld started out as a very pleasant surprise. Don Swanson had been approached by a cinematography company named Pangolin Pictures. They were filming on the Big Island and were especially interested in documenting features along The Great Crack. The author and Ric Elhard accompanied them on a surface reconnaissance to the area, and they were very keen to do a segment on underground exploration into this unusual underground environment. The idea was to film an ongoing exploration into a new cave beneath the crack. They would also provide helicopter support to overfly the length of the rift zone and pick out the best potential site to film. The helicopter would also ferry all the gear and personnel to and from the location.

Filming this original exploration turned out to be one of the more frustrating elements of the entire project. The long day was spent taking one step forward and two back in order to make sure that the cameras caught every possible angle of the event. We did manage to finally bottom one pitch that day and confirm that the cave did continue down a much larger and deeper second drop. No survey or sampling occurred on this trip, but we did manage to take a number of nice photos of the Great Crack from the air and the filming was finally featured by the PBS broadcasting system as a segment of their feature *"Violent Hawai`i"*.

On December 28, 2005, we managed to return to the cave on foot without the helicopter or filming crew in tow. The author, Ric Elhard, Jack Vose, Kendall Whiting, Brian Killingbeck, Jeff Moore, Andy Porter, and Allen Cressler all invested what turned out to be a fine day of exploration, survey and photography. This cave turned out to be somewhat shorter than the first with 1,590 feet of survey accumulated. A maximum depth of 518 feet was recorded. This feature is developed along roughly 600 linear feet of the Great Crack fault.

This second cave system exhibited many strong parallels to the first. Both are composed of four distinct levels, each one formed directly above the next. The lowest level of each cave is also the largest and longest. Passage cross sections normally feature tall canyons rather than oval tubes. Flow features are prominent on the walls, especially in the lower levels of the cave. Floors are entirely composed of very friable breakdown, usually stacked at angle of repose and very treacherous to negotiate. Ceilings exhibit strong flow features and filled dikes. A clear pattern of formation is beginning to develop as we explore more of these underground features.

A third prominent feature of the Great Crack has long been known. This cave lies somewhat offset to the main fault feature, but is believed to be formed by the same processes. Wood Valley Pit Crater is a large open air feature that drops 150 feet directly into a large subterranean chamber. From here it descends through a second small breakdown filled chamber and seemingly ends there. A hardy few have managed to squirm on down through the breakdown floor and squeeze into a well developed lowermost level of the cave. From here the route doubles back directly under the entrance chamber along a well developed linear crack system that is quite a lot smaller than the lowermost levels of the Great Crack Caves, but does still exhibit clear flow features from the lava that coursed through at some time in the past.

Exploration of this cave was first begun by a British Expedition back in the 70's. HSS members have visited the cave many times since then, including a trip to host National Geographic photographers. A team of Swiss cavers lead by Geral Fauvre recently completed a very accurate and detailed map. The author is attempting to include at copy of this illustration with this article.

In summation: Rift Zone development within the volcanoes of the Big Island of Hawai`i have long been known to be primary routes for the movement of magma beneath these massive mountains. The famed "curtains of fire" that erupt along these dominant fault lines are normally the opening event of each new eruption. Monitoring of these events has been documented by the Hawai`i Volcano Observatory for many decades. For the first time, members of the caving community have also been able to physically enter into this fascinating and highly dynamic underground environment. Their documentation is beginning to form a much more detailed understanding of how these elements function.

EXPLORATION of EMESINE CAVE and THE 1880-81 FLOWS OF MAUNA LOA VOLCANO

by

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On May 1, 1880 an eruption of lava began in Moku`aweoweo, the summit crater of Mauna Loa on the Big Island of Hawai`i. The flow of lava is believed to have lasted for only a few days and was not easily visible at most locals on the island. In and of itself, this was not a noteworthy event. Small eruptions of this type are more or less the norm for Mauna Loa. Most residents of the island paid little attention. Volcanologists today realize that these events are important indicators of bigger things to come on Mauna Loa, the Long Mountain.

On November 5, 1880 a second eruption began at an elevation of 11,000 feet along the Northeast Rift Zone of the mountain, roughly one mile above Pu`u Ula`ula. The National Park Service maintains a cabin at Red Hill along their summit trail in this area today. This second episode of the eruption sent high fountains of lava into the air as the magma found a path to the surface through narrow cracks and faults along the Rift Zone area. Though still a long ways away, this pyroclastic spectacle was clearly visible from Hilo and most of the eastern half of the island.

The high fountains continued for two weeks, pumping out massive amounts of lava and creating flows down each flank of the ridgeline. To the north the flow quickly raced down into the Saddle country between Mauna Loa and Mauna Kea. To the south a second flow extended into Kapapala Ranch and continued on toward Kilauea and the town of Volcano. The flow fronts of each of these fast flowing events deposited primarily a`a lava.

At this juncture, as is typical with eruptions on Mauna Loa, things suddenly changed. The fountains subsided and the flow switched direction. What was not easily visible from Hilo was that the vent had actually shifted and lava was now rising through an opening almost a mile away from the original source. It had shifted makai (down hill) along the Rift Zone and was now rising quietly through an obviously larger opening in the fault. There were no fountains associated with this flow and everything was now consolidated into a single stream.

The eruption site quickly shielded over and began sending lobes of pahoehoe down the mountain to the northeast. Slow moving frontal lobes of lava burned their way steadily thorough the Waiake Uku Forest for all of that winter and into the spring. The glow on the horizon above Hilo grew steadily stronger with each passing week. By early June it had passed through Kaumana town and was then only five miles away from the bay. Methane explosions in the forest could now be clearly heard by residents. A “day of prayer” was called by local Christian ministers. Most folks remained calm, but a few decided to pack up and move their belongings to Honolulu, even though they knew that the city was under a smallpox quarantine and they would not be able to leave.

On June 26th, the flow entered the stream course of Waipahoehoe on the upper city limits of town. Reverend Titus Coan described the event. “The lava came rushing down the rocky channel of a stream with terrific force and uproar, exploding rocks and driving off the waters. Hilo was now in trouble - we were now in immediate danger. Explosions and detonations were frequent. The glare of it by night was terrific. The progress of the flow was by now 100-500 feet per day."

The residents of Hilo had sent off several requests to Honolulu for what ever help the royal family could provide, but King Kalakaua was traveling in Europe at the time and the capitol was still under quarantine. Sometime in July, the ban of travel was finally lifted and Princess Ruth Ke`elikolani traveled to Hilo to lend her personal touch to the problem. She arrived late in that month, and was transported up to the flow front by horse and buggy just as it reached the area of the current day Mohouli Street. Here she offered traditional oli (chants) and paid ho`okupu (tribute) by throwing offerings into the active flow. King Kamehameha had done the same during the 1801 eruption on Hualalai. He is credited with stopping this earlier flow by throwing a large hank of his own hair into the flow. Princess Ruth was following in the footsteps of her ancestors. History does not record exactly what ho`okupu were offered that day, but we do know that the princess followed up the display by ordering that her encampment for the night be placed directly in line with the slowly advancing front.

Historians shall long debate the question of which of these atonements' to the gods was most effective. None will debate that it was Pele who finally acted to end the flow of lava on August 10, 1881. She left behind a continuous ribbon of pahoehoe that stretched for more than 25 miles. Skylights to the "pyroduct" systems within the flow would continue to glow with red eyes on the hillside above the city for weeks after the event finally stopped. The source at Pu`u Ulaula is at nearly 11,000 feet. The lowermost lobe lies on the grounds of current day University of Hawai`i, Hilo, just 1.5 miles above the Bay. Lava had flowed continuously for nine months and five days.

Members of the caving community could not ignore a feature as prominent as this. They knew with certainty that long runs of pahoehoe lava can only mean one thing, long lava tubes. An entrance into this underground system in Kaumana town was large enough that road crews decided to build the new Saddle Road around the feature and preserve it as a county park. The local Lions Club even produced a map featuring more than a mile of cave.

Even though the flow has long been known to contain extensive lava tubes, reaching them was still a challenging process. Kaumana Cave is the only easily reached access point. Red Hill cabin is a seven mile hike along the summit trail to Mauna Loa that is currently maintained by the NPS. There are only three other roads that cross the flow. All require several miles of 4-wheeling to negotiate.

Fred Stone was among the first of today's generation of cavers to reach the 1881 entrances and begin exploration. He had learned of an entrance along the Powerline 4-wheel access about midway along the flow. It was miles from the highway at Saddle Road, but he was willing and able to cover the distance and begin to explore the cave. Fred is a biologist, and one of the leading forces in the study of cave adapted invertebrates. His primary interest in the project was to try and determine just what sorts of arthropods would move into a relatively young volcanic cave system. And, oh yes, he also wanted to explore the cave. It didn't take long for him to realize that this was indeed a long, long cave, with many miles of passage to explore. Emesine is the name of one of the bugs that he collected while studying the cave and it quickly became the epicure for the lava tube, as well.

On January 8th, 1998 an effort to document the system with current day survey systems and cameras was begun. Kevin and Carlene Allred had been working to complete their amazing atlas of Kazumura Cave and were now looking for a new project. They lead a team into the mauka extension of the cave. The author and Pat Kambesis lead a team into the makai section of the cave. This spontaneous decision was to set the stage for most of the future exploration of the system. Kevin and Carlene ventured back to the mauka extension and completed a total of nine survey trips. They were supported by their sons, Flint and Sauron on many of these trips. Carlene produced excellent drafts of this end of the system. In his usual indomitable style, Kevin also produced survey work on at least three solo trips into the cave.

The makai regions of the cave became by default the major focus of work conducted by the author with cartographic support from Patty Kambesis. Over the course of the next four years, the author was to return to the cave on additional survey trips a total of twenty-two times. Ms. Kambesis returned for nine trips. Their permit to explore included an agreement to produce maps of the entire cave system. Pencil drafts on mylar were produced for their section of the cave. Work is ongoing to produce an atlas of the entire 13.7 miles of survey. Many other patient surveyors contributed to the effort with three to five trips into the cave. Andrew and Ali DuBois, Taco VanIeperen, Monique Castonquay, Peter and Ann Bosted, Ric Elhard, Steve Lewis, Bruce Dunlavy, Penelope Pooler, Mark Fritzke, and Doug Strait, along with many others complete the roster.

The cave is formed not unlike many others in the Aila`au Flow of Kilauea Volcano. Sinuous flow features are beautifully preserved in shades of color ranging from gun metal black through crimson red with accents of yellow and even green. The younger age of this Mauna Loa flow also preserve fantastic displays of late stage basalt formations including soda straws more than two meters in length, driblet spires and extrusion stalagmites up to .5 meters in height, and more than thirty well developed cockscomb formations. Fortunately most of these features are developed in sections of cave that are extremely remote and very difficult to access.

On average the passage dimensions within Emesine Cave are somewhat smaller than those in Kazumura. Nine months was apparently not a long enough period of time for the system to develop the extensive downcutting and tall canyons that are so prominent in the latter. The caldera flow that produced Kazumura may also have contributed a somewhat larger or more stable flow regime. Most of Emesine Cave is developed as quite comfortable walking passage with the ceiling usually just out of reach overhead. A noticeable increase in the average size of the main corridor is noticed roughly one mile below the primary entrance. At this point a large braid in the original flow rejoins the line of survey. The tributary added significant volume to the flow path. Long single passage sections are often complicated by areas of incredibly complicated maze. Crawlway braids are very common in these sections, but a primary route was always discovered to continue on down the mountain. Careful analysis of the survey data in these areas indicate that the maze sections tend to be developed in areas of slightly higher incline.

Work to reach additional areas of the 1880-81 flow has also discovered significant sections of cave passage. All were formed by the same flow event, but long gaps remain between the segments documented to date.

It’s a seven mile hike up the Mauna Loa summit trail to Pu`u Ulaula and the NPS cabin. The author has made the trek twice to date with assistance from Peter Bosted and Chrissy Frotten. Two caves have been documented here. One is located just below the later stage pahoehoe forming event that formed Emesine Cave. The other begins just beneath a large hornito at the highest point in the 1880 flow. This episode of the flow event deposited a`a at lower elevations, but did flow as pahoehoe near the source. This passage is unique in that the explorer can actually descend into the throat of the original vent for at least thirty vertical feet at the very apex of the tube. The high elevation and low rainfall combine to decorate both of these caves with unusual proliferations of frost like gypsum displays.

Stainback Road is a 4-wheel drive track off the Mauna Loa Observatory Road that crosses the flow at an elevation of just over 8,000 feet. Many short segments of cave have been surveyed here by the author and a current permit to Steve Smith has added additional cave sections at even higher elevations.

The Lion’s club survey of Kaumana Cave has now been reworked. It’s interesting to note that several hundred feet of cave have been cut off by a road construction project along Edita Street. The lowest point of the system is no longer accessible. Current survey efforts have accumulated more than two miles of survey extending mostly mauka from the entrance at the roadside park. Unfortunately the upper reaches of cave pass directly beneath modern day homes that have been built atop the lava flow. Many of these homes are currently using the cave for storm sewers, trash dumps and even septic disposal.

The 1880-81 Flow lasted for nine months and five days. Current day documentation of the cave systems formed by this event has been ongoing for nearly two decades. More than 19 miles of cave have been surveyed to date. Much remains to be done. The lower most areas of Emesine Cave have many unfinished leads. Access to this area require three miles of rugged 4-wheeling with an additional 2.5 miles of hiking through ever thicker Uluhe Fern. There should be more cave to discover along Tree Planting

Road. This is another 4-wheel drive track that accesses he flow roughly two miles below the Emesine surveys. Two short caves have been surveyed in this area to date with just .5 miles of survey combined. The main challenge with exploring this area is that it rains 300 inches a year on this flank of the mountain and the vegetation makes hiking roughly equivalent to trying to negotiate a tangled pile of bed springs. Upper Kaumana Cave continues. We believe that we are past the worst of the septic drains and will hopefully enter into a more hospitable environment. Steve Smith continues to accomplish long hikes at high elevations to access many new caves along the upper reaches flow. One of the most promising leads in the system is located at the lower end of the 1880 tube that originated at the apex of the flow. For reasons that have not been fully explained, the tube drops vertically into a pit located on the rift zone fault. It is more than 100 feet in depth and will require more rope than the explorers had on hand to reach the bottom.

The challenges to exploration are formidable, but the rewards should be, as well. I for one will be very intrigued to follow the exploits of cavers that choose to continue the documentation of the 1880-81 flow event on Mauna Loa Volcano, the Long Mountain with very deep caves.

LAVA CAVES IN SUBURBAN AUCKLAND NEW ZEALAND.

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Lava Caves in Suburban Auckland.

Abstract

Auckland, New Zealand is a city of 1.8 million people, built on 53 recent (250 ky to 500y BP) but hopefully extinct volcanoes.
These volcanoes have produced many small lava caves, but these are hidden under suburban houses and roads. The problems of finding more caves in this environment are explored, along with the associated problems of ownership, engineering, health and safety, and indigenous rights.

Introduction

Fig.1. Location map for Auckland.

Although New Zealand is a very techtonically mobile and volcanic set of islands, only the Auckland isthmus has the right type of basalt to form caves. The volcanoes are small, monogenetic and range in age from 250 ky to 500 y old. The base of the hills and craters vary from sea level to about 100 metres. The heights are up to 200metres. There are 53 volcanic centres, some are explosion craters, while others have extensive lava flows topped with a scoria cone. Most of the volcanoes with lava flows have produced normal lava tubes about one to two metres below the surface. 250 entrances have been located. The longest is 280metres in length.

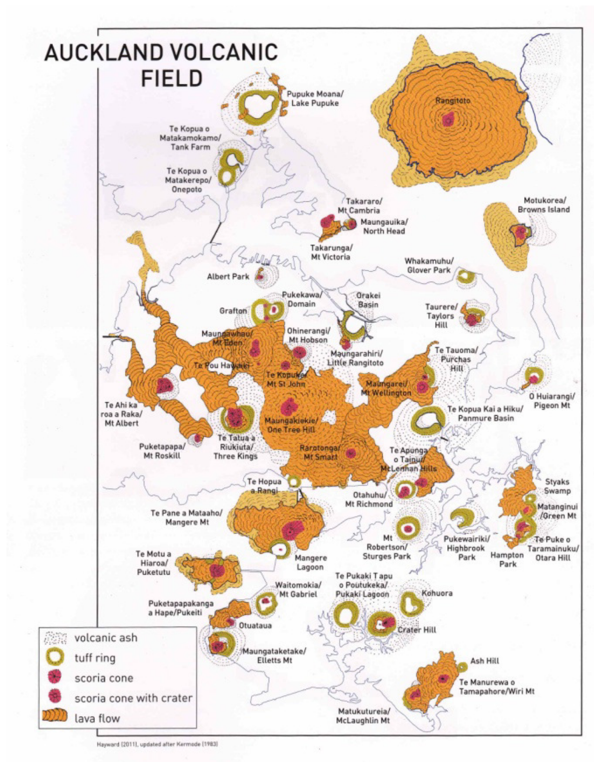

Fig. 2. Volcanic centres of Auckland.

Colonisation

There have been two major migration events, Maori about 800 years ago and Europeans about 200 years.

Maori came from Polynesia and were mainly a stone age culture and did not build permanent structures. Although they built extensive fortifications around the scoria cones; the lava fields were left relatively undisturbed apart from cultivation. They did however use the cave entrances as burial grounds or urupa. Some were very large but none remain open. Those that did

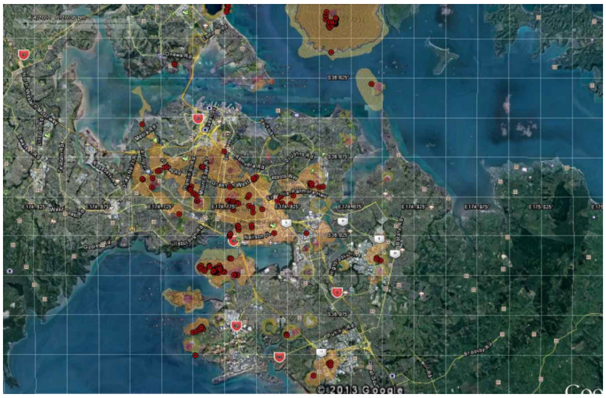

Fig. 3. Location of lava caves. (Red dots).

remain open have been pillaged for souvenirs or fertilizer. However, there is a resurgence of maori values and the heritage values are beginning to be recognized.

Fig. 4. Fortification and storage pits around one of the scoria cones.

The first European to visit New Zealand was Abel Tasman in 1642, but it was not until the late 19th century that Auckland became a European style colony. After 1900 roads became more than cart tracks and houses were built alongside them. Caves were used as tourist attractions or filled in if they got in the way.

Fig. 5. Several volcanic cones with lava fields between them covered with houses.

There are now 1.8 million people living in Auckland and there is little land now left uncovered by tar seal or housing lots. Almost all the caves are in private ownership. Some caves are part of the landscaping

Fig. 6. A delightfull entrance to an 80metre private cave.

But others have had manholes put in to protect them, either in the street or in school grounds.

Fig.7. A manhole entrance into a cave complex under the road.

The Wiri cave, which has been made into a scientific reserve, because of its value has a more substantial gate. This gets breached regularly as permission is rarely given.

Fig. 8. A vandalized entrance to a scientific cave reserve.

Because these caves can be quite extensive they can go under several properties. So far this has not been a problem as only the entrance owners usually know where the cave goes, but it can have serious consequences if there is a cave under a property if the owner wants to do some building work. As the caves are only 1 -2 metres below the surface then only light buildings can be erected, and no digging.

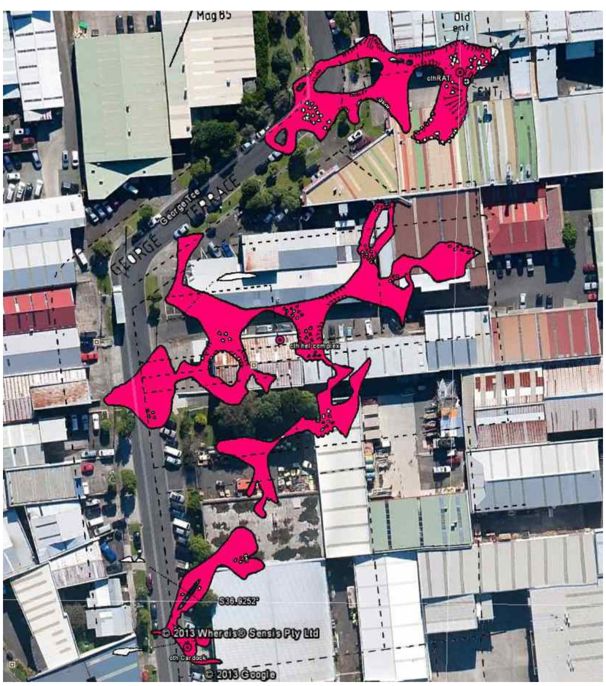

Fig.9 A complex cave in a light industrial area. The cave extends under several properties. The foundations are reinforced concrete slabs.

In the past , and in limestone areas, protection of the caves from vandals has been achieved by keeping entrances secret. In a city it is protection from developers and builders with bulldozers and diggers making foundations that is the worst problem. Thus we have to work with the council to publish the caves as scheduled and heritage sites on the property information maps.

Finding caves in the present day.

Incongruously it is the very agents of destruction, the bulldozers and diggers of construction sites that find the new caves now. Theoretically if a cave is found, then council should be informed so the inspectors, archeologists, Iwi and cavers can inspect the site to see if it needs to be preserved. This can be expensive if there are human remains as they have to be carefully removed and recorded and perhaps reburied. If the cave is large there may need to be extensive engineering modifications required.

Often, developers hide the caves as they know that it will increase their costs and of course decrease their profit. I often hear of caves that have been covered up.

One a private developer doing infill housing, found a cave in a trench and let the council know. I was rung up as no one was willing to enter and I am known for being able to explore and survey. So I did a survey both with tape, compass and camera.

Fig. 10. The cave is at the near end of the trench. The developer was stopped from filling in the trench which hampered deliveries to the building sites. The cave extends to left and right of the picture.

The cave in fact was quite extensive going under three properties and one of the proposed houses. The council was horrified at the thought of hoses collapsing and them being sued for wrong permits. So the owner was stung for getting all sort of engineers reports and designs and persuading them that the house next door would not fall down even if it had already been there a hundred years. The owner estimated it cost him 80k in delayed time and permits.

Fig. 11. The ceiling of this fine cave is only 80cm below ground causing concerns about the danger of collapse.

Fig. 12. The extent of the cave under the building site and surrounding houses.

The other , In December 2015 was part of a big 35km water pipe line extension construction, a multi million dollar project. It was known that it was likely to cut into caves and GPR, percussion and boreholes were done in advance and then an exploratory dig. A cave was found. The council was told. Iwi came and blessed it. The archaeologist walked by. Nobody could go in. It was a construction site. I was called in. I was allowed to go in briefly after inductions for the site with all PPEs (hard hat, boots, long trousers long sleeves, gas meter and signing off. A very quick survey on the back of a hand was enough to determine it was worth keeping. To do the proper survey, which also included a 3d laser survey, we had to spend a morning getting more inductions, drug tested, and two days to get a 'confined spaces certificate'. At the site we were signed in, the cave was gas tested , we also wore gas meters and we had observer safety officers inside and out of the cave. Whew! Seriously the risk of gas was important, as this was a suburban area with gas mains which can leak and two workers had been killed by an explosion in a pipe trench only recently, 1km away. It sharpens the thinking. The probable cost of the cave, tens of thousands plus the cost of a manhole to access the cave later.

Fig. 13. The large pipe trench traversing lava cave country.

Fig. 14. Machines to make a cave digger weep!

Fig. 15. Is it safe? The caver was lucky to get on site. He is wearing a helmet but no PPEs (personal protection equipment) ie fluoro vest, long trousers, long

sleeves, gloves, induction or confined space certificates. Next time he did have everything or else he would not have been let in.

Fig. 16. A worthwhile cave but needs a engineers design to span it with a water pipe.

Fig. 17. Caving is a spectator sport.

Fig. 18. The mapped extent of the cave. The water pipe will go up the right hand side of the road. There was a break in at the right hand lobe of the cave that had not been reported.

Fig. 19. The old and the new. On the left is the compass and tape survey. On the right is a $50,000 3D laser scanner. The white spheres are the control points.

Interestingly, at the end of the cave I found some recent fill that a just completed house builder had put into a hole he had created. No notification. No extra cost except a bit more concrete.

Conclusion

The result of these two recent cave discoveries is that the council has sharpened up its reponse to cave discoveries in construction sites so that the protocols are, or should be in place.

Council must be notified.

The Council will notify the archeologists, Iwi and cavers to access the cave.

Reports, and maps are supplied.

Hopefully a permanent entry is installed so that foundations can be checked or for scientific purposes.

We. As cavers now have the appropriate certification to go underground in an industrial site.

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KULA KAI, KANOHINA CAVES AND THE CCH

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History of Kanohina and CCH

It is impossible to know how and when the caves on the south west rift of Mauna Loa were discovered as it was certainly in pre written Hawaiian history by people long gone from life as we now know it. Evidence leads us to believe it may have been at least 200 to 300 years before present and probably longer ago. It was inevitable that contemporary men would find, explore and document the vast cave system in the Kula Makai area of the south flank of one of the world's greatest volcanoes.

The area known as Kula Kai is a section of land that was parceled off from a larger ranch holding known as Kahuku Ranch established 1866. In the late 1950's several sections were sold and parceled for subdivision in this district of Ka'u. The largest parcel is the Hawaiian Ocean View Estates. This 11,000 acre subdivision has significant cave trunks and passages associated with the Kanohina Cave system but it is in Kula Kai that the cave reveals itself as a world class geologic wonder of multilevel and braided lava ducts. Kula Kai is a subdivision of approximately 150 acres subdivided into 3 acre parcels. Kula Kai refers to a plain or open country facing towards the ocean. This aptly describes the area overlying the cave system we now refer to as Kanohina Caves.

Contemporary discovery of the caves in the kula area was certainly made by the bulldozer operators that pushed the roads for the subdivisions. A few stories remain regarding finding artifacts during this time but like the ancient history of these caves the stories are mostly lost and only discerned by exploring the caves and interpreting archeological remains. Little regard was made for the caves or archeology during the early days of land development. Roads were established according to planned grids and if the cave was in the way it was sacrificed by collapse or in fill. Artifacts were probably sold or added to private collections.

It was not by design only luck that persons interested in caves purchased land in the Kula Kai Estates. In 1990 there was only one developed lot in Kula Kai. Ric Elhard and Rose Herrera purchased a lot with one of the large entrances to the cave. The intention was to explore the possibility of establishing a commercial cave tour in Hawaii, something not done at the time. After a year of exploring the cave it was apparent that there were issues to be resolved before establishing any use of the cave. Initial exploration revealed that it was quite extensive and contained archeological areas. There was the concern of land use and the Hawaiian sensitivity to the heritage of the aina. Some of these concerns were addressed in the establishment of an Act for Cave Protection in 2002 which described owner ship of cave passages as well as artifacts found in caves. This sorted out a legal status regarding caves in Hawaii but the question of the geology and extent of the caves was not addressed until1998. It was in this year the official cartography effort was mounted in the Kula Kai caves. A map of the Kula Kai section existed but survey efforts revealed several miles of extensive cave was underlying this kula makai area of the volcano.

It became apparent that establishing a commercial offering had greater implications than hanging up a sign and open for business. The extent of the cave and its resources demanded a greater look towards managing any project associated with the cave. Ric and Rose projected a use that combined tourism, education and conservation utilizing the cave as the base for such a project. Little did they know that a dedicated group of cartographers, scientists, resource managers, as well as some of the Hawaiian community would become involved in discovering the lost history of the Kanohina Caves.

The greater cave was called Kanohina after the historic name of the lower area of the mountain called Kipuka Kanohina. Kanohina may be derived from Kano, a birding or broken stick and hina, a windy place.

This correctly defines the area as there is evidence of Hawaiians hunted birds on the surface areas and there is a perpetual wind blowing across the lava field. Other names associated with the cave are more contemporary. Initial survey efforts lent names like Kula Kai, Poha, Eli's and Maelstrom. Later additions to surveyed areas were dubbed Cordwinder, Xanadu, Ohana Kai Maze and other sections waiting exploration and naming. Survey efforts have connected many sections into 26 miles of passage, with a total accumulation of 40 miles of cave passage.

It became apparent in the early days of the survey that protection of this vast cave would be important for now and future generations. Some of the early proponents of establishing a cave conservancy in Hawaii were Bill Halliday and Fred Stone, both involved in cave science and geologic interpretation of cave resources in the early years of Hawaii cave science. Fortunately the exciting contemporary discovery and documentation of the Kanohina Cave started the serious discussion of conservancy for Hawaii. Discussion between Ric Elhard and Don Coons resulted in soliciting the IRS for a Non-profit status for the Cave Conservancy of Hawaii. A board of directors and officers receiving a 501C3 status in August of 2003 established a new dawn in the Hawaii caving community. Later work lead to CCH being recognized by the State of Hawaii as a not-for-profit corporation, with the additional benefit of making it a tax exempt corporation within Hawaii.

A nice ending to a story started in 1990 with an unclear story line has resulted in a tale of good news for Hawaii caving community. With the efforts of land owners, cavers, scientists, and the general public accomplishments include cave protection laws, successful business employing local residents, new and exciting science, education and conservation of resources we all explore and enjoy.... the caves of Hawaii.

Cave Conservancy of Hawaii Today

CCH today has evolved into a significant organization within the Hawaii community as well as the caving community. It has adhered to its primary mission to protect and preserve caves from negative impacts of development, primarily in the Kula Kai and Oceanview subdivisions. To follow this mission CCH has
1) Purchased land to preserve and protect portions of a major cave system;
2) Assessed cave resources in the region through surveys and photography;
3) Developed management plans for the caves it owns;
4) Engaged in education regarding the significance and importance of protecting cave resources;
5) Worked hard to develop good relations with landowner of caves and to educate them on best practices to protect cave resources;
6) Encouraged and supported cave related research projects in geology, archeology, biology and paleontology;
7) Done environmental clean-up of dumps related to caves; and
8) Become a focal point of cave related activity on Hawai'i.
9) A major present and future activity is fund raising. The funds are needed not only for new property acquisition, but also to caver the increasing amount of taxes on previously acquired property.
10) CCH is now embarking on a new mission with more responsibility that involves engaging with government organizations to do cave resource assessment on public lands.

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THE LONGEST LAVA TUBE IN THE LEVANT: THE 20.5 KM LONG SHIHAN-HARAN SYSTEM, SYRIA

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Abstract

Google Earth, topographic maps and verification from a small surveyed pyroduct segment (Ariqa Cave, Tawk et al. 2009) are used to infer the trace of the longest lava tube system in the Levant, without visiting the studied site. The studied system includes segments of intact pyroduct caves, collapsed segments and lava channels. The system is within the recent lava flows of Tell Shihan, Al-Lajāʾ, Harrat Ash-Shaam, southern Syria. The lava tube carried late Quaternary lava from the base of Tell Shihan volcano westward.

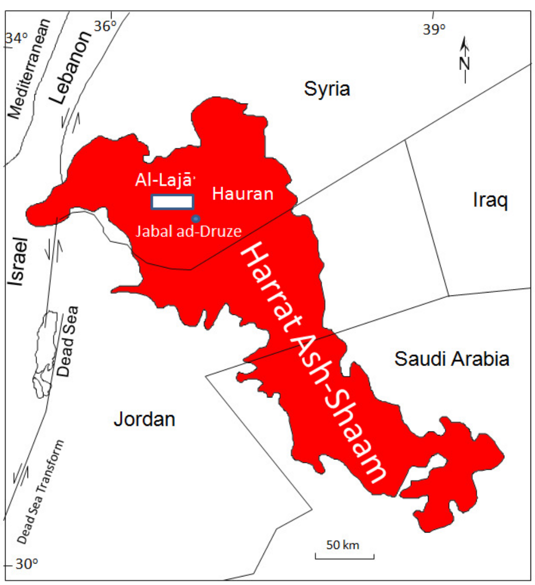

Figure 1. *The study area (rectangle) in Al-Lajāʾ, Haura n, SW Syria.*

Introduction

It is well known that where a lava tube (pyroduct) is close to the surface, sections of its roof may erode or collapse, creating a puka or skylight holes, as well as elongated unroofed caves. The continuous nature of such partially collapsed lava tubes and/or lava channels are often identified by remote sensing as 'dashed lines' of intact lava tube segments and channels, collectively referred to here as a 'lava tube system'. The ability of the human brain to detect patterns, such as alignments or continuous broken undulating lines, can be used for detecting traces of lava tube systems from above.
The intuitive and easy-to-use Google Earth has rapidly emerged as a global medium with increasing potential for lava tube prospection, outflanking other types of orbital imagery and remote-sensing sources. Google Earth imagery has improved dramatically, especially for the Middle East. Its high resolution SPOT Images are useful for detecting lava tubes in hardly-studied regions. The suggested reconstruction should be validated by future expeditions, as should be the case in planetary lava tubes.

Geographic setting

The largest volcanic region of the Levant is Harrat Ash-Shaam, covering some 40,000 km^2 (15,000 sq mi) in Syria, Jordan, Saudi Arabia, and Israel (Fig. 1). Several lava tubes are known in its northeastern area, the Hauran (e.g. Kempe et al., 2006; Frumkin et al., 2008). Tawk et al. (2009) reported a 562 m long lava tube, named Ariqa Cave (Fig. 2), in a Syrian village carrying the same name, NE of Jabal ad-Druze, the highest (summit elevation: 1785m) portion of the Hauran (Fig. 1). Using Google Earth, this cave is shown here to be a small segment of the longest lava tube system in the Middle East, >20 km long. This region of Harrat Ash-Shaam is called Al-Lajāʾ, (Arabic: “Refuge”), and is typically covered by rough Holocene basalt, with limited human access.

Figure 2. *Ariqa Cave (Tawk et al., 2009), central Shihan-Haran system. Photo courtesy Fadi Nader.*

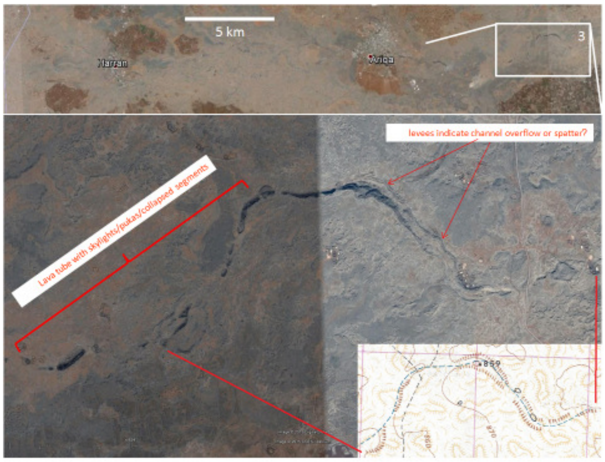

Figure 3. *Eastern portion of Shihan-Haran lava tube system, segmented lava tube trough is evident on Google Earth imagery and topographic map. Inferred levees indicate channel overflow or spatter (?).*

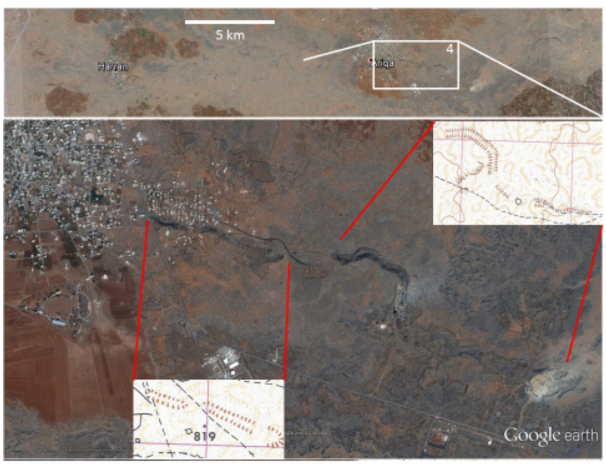

Figure 4. *East-central Shihan-Haran system, with Ariqa village (left).*

Results and discussion

The lava tube system is identified by its remotely sensed collapsed segments, forming an elongated line of troughs. These troughs are either unroofed lava tubes, or open lava channels, inferred by apparent lava levees (Fig. 3). The relief of the channels is emphasized by the typical shade of its southern wall (Figures 3-6). In addition, the channel/collapsed segments act as sediment traps, which become natural 'flowerpots' supporting denser vegetation, compared with the surrounding rocky lava. Some topographic troughs of the lava tube system are large enough to be indicated on 1:50,000 topographic maps. A corroboration for the existence of an uncollapsed lava tube segment is given by the 562 m surveyed cave (Tawk et al., 2009). Topographic maps, based on photogrammetry, show clear trenches, which are segments of collapsed lave tubes/channels. In addition to Ariqa Cave, two unexplored lava tube caves are indicated on topographic maps east of Ariqa village: Meg'arat Hamid and Meg'arat a-Shatab. Several segments of the lava tube system are observed on Google Earth imagery but not on topographic maps (Fig. 7). All these attributes are aligned along the inferred trace of the long lava tube system.

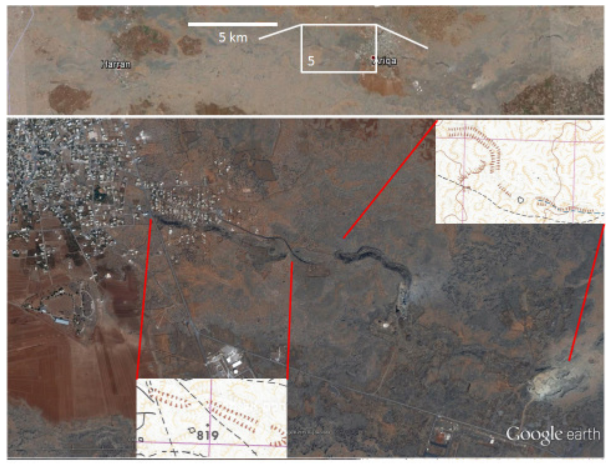

Figure 5. *Central Shihan-Haran system. Ariqa cave map is projected (after Tawk et al. 2009) in Ariqa village (right).*

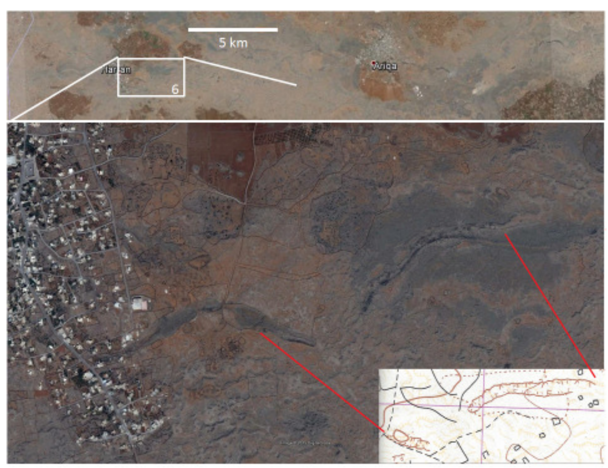

Figure 6. *West-central Shihan-Haran system, with Haran village (left).*

Conclusion

The lava tube segments are compiled and reconstructed from the remote sensing, topographic maps and cave survey data (Fig. 8). The inferred system is 20.5 km long, descending westward from 890 to 650 masl, with a mean gradient of 1.2% (Fig. 9). It spans most length of the β_5Q_4 pahoehoe lava field that flowed westward from Tel Shihan region (Ponikarov 1963, 1967; Razvalyaev, 1966), shedding light on the lava emplacement mechanism.

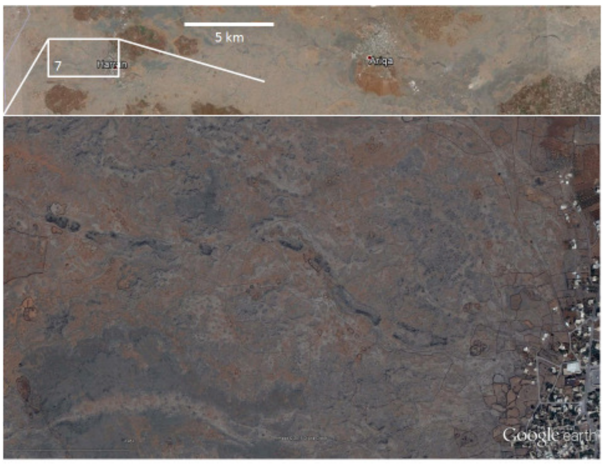

Figure 7. *Western part of Shihan-Haran system, with Haran village (right). The lava tube trough is observed on Google Earth imagery (from village center to NNW) but not on topographic maps, indicating shallow relief.*

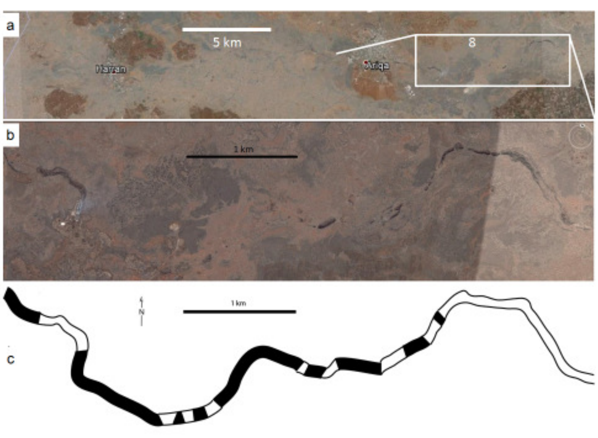

Figure 8. *Example of lava tube trace reconstruction. (a)Location on Google Earth imagery of the lava flow. (b) Enlarged Google Earth imagery of the segment of Shihan-Haran system. (c) Schematic map reconstruction. Inferred uncollapsed tubes in black, and channel/collapsed segments in white. Width is exaggerated.*

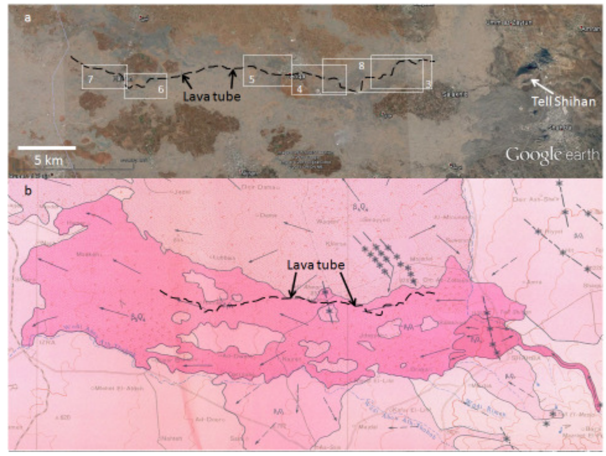

Figure 9. *The β_5Q_4 pahoehoe lava that flowed westward from Tel Shihan region (right) along the 20.5 km long Shihan-Haran system. Black dashed line indicates the reconstructed lava tube. (a) On Google Earth imagery. (b) On geological map (after* Ponikarov 1963, 1967; Razvalyaev 1966).

Acknowledgements

William Halliday invoked the idea to look for this lava tube. Fadi Nader has kindly allowed to use his photograph from inside Ariqa Cave.

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Estimation of lava tube cave heights of the Moon and the Mars from those of the Earth

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Abstract

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 compared with the lava tube caves of the Earth such as those of the Mount Fuji. This formulation was applied to estimate the height of the lava tube caves of the Moon and the Mars. Gravity, lava density, slope angle and Bingham yield strength are the decisive parameters that determine the cave height.

1. Introduction

When the lava spouted from a crater flows to a foot, the flow surface and the bottom part are cooled and become solid , then, a tube structure is formed. Only the interior part of the lava flow advances then drained out from the tube. It's thought that a lava tube cave is formed in this way[1)]. An example of a lava tube cave is shown in Fig.1.

Photo 1 Lava tube cave of Jinza-Fuketsu No1 in Mt.Fuji

By using the simplified model of the Bingham fluid flow in the inclined pipe, the forming conditions of the lava tube cave are obtained[2)]. The slope angle and the Bingham yield strength play the main role for the determination of the cave height[3)]. This model has been applied to the caves of Mt.Fuji[4,5)] , other Japanese lava caves[6,7,8,9)] and lava caves of foreign countries[2,10] on the Earth.

After introducing the study result of the lava tube cave of the Earth. this model was applied to the Moon and Mars to estimate possibility of the existence of the lava tube cave and their height. Because there is new discovery of Haruyama [12,13,14)] and later by Robinson[15)]on the Moon, the previously study[16)]was revised.

2. Lava tube cave formation conditions and previous studies on the Earth

Concept of Lava tube and cave formation is shown in Fig.1. (A)The lava supplied from the underground will get over the edge of the crater, and flow down though the slope to the foot. (B) The cooled surface of lava flow becomes solid and inner fluid lava will drain out when the supply of the lava from the crater is terminated. (C) Then, lava tube cave like a tunnel will be formed.

In modeling the discharge mechanism of this type of lava tube, we used an inclined circular tube model for the sloping section of the cave as shown in Fig.2. A simple model of steady state isothermal laminar flow in inclined circular pipes was used for analyses[2)].

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. Here, f_B is Bingham yield stress, η_B is Bingham viscosity, which takes specific value depending on the materials.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows[2,3)]

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

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

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

for $\tau_w = (\rho g \sin\alpha)R/2 < f_B$ では、

$u = 0$

Here, α is angle of slope or inclination of tube, ρ: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B: radius of the flowing position where Bingham yield stress takes f_B.

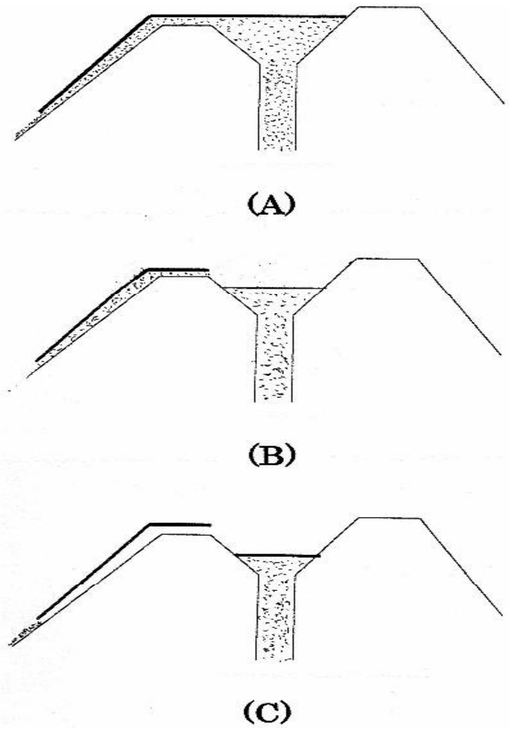

Fig.1 Concept of Lava tube and cave formation

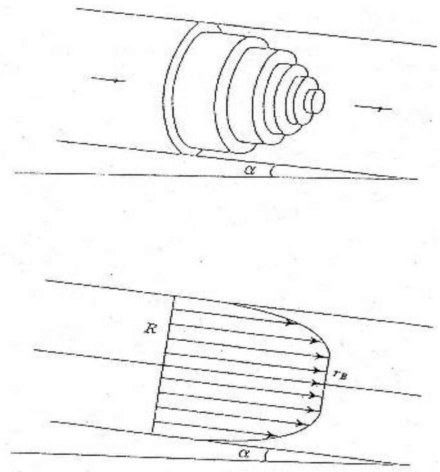

Fig.2 Flow speed distribution in the inclined pipe:Plug flow for Bingham fluid.

$(\rho g \sin\alpha)R/2=f_B$ is the limiting condition to see for the lava to be drained out or to be plugged in the tube.

For the given ρ,slope angle and f_B, the cave height $H=2R, H=2R=4f_B/(\rho g \sin\alpha)$ is given[3]. On the contrary, For the given, ρ,slope angle and the cave height H=2R, the yield strength f_B can be obtained[3].

As the typical examples for various lava cave topography [11] of the caves of Mt. Fuji 4,5), other japanese caves[6,7,8,9] and those of foreign countries[2,10], the plotted data for the slope angle and the cave height are indicated in Table1~6 and Fig 3~8. As seberal yield strengths of the lava are also indicated, the yield strength area of the lava of each cave can be seen. These obtained yield strengths are reasonable value in comparison with those of G.Hulme[17] as shown in Table 7.

Fig.9 shows a relation between obtained yield strength and SiO_2 wt% for the each lava. Summary of the results are shown in Table 9.

Table1 Slope angle and cave height of lava tube caves of Mt.Fuji
(*extracted from T.Honda(2001):Formation Mechanism of Lava Tube cave in Mt.Fuji,Fall meeting of Volocanological Society of Japan,p66)

Cave name	Slope angle	Inner height
Subashiri-tainai Upper part	20°	1m
Subashiri-tainai Lower part	15°	2m
Jinza-Fuketsu No1	13°	5-10m
Jinza-Fuketsu No3	11.5°	5m
Shoiko-Fuketsu No1A	10°	3.3m
Shoiko-Fuketsu No1B	7.6°	2m
Karumizu-Fuketsu	5.5°	4m
Fuji-Fuketsu No1	8.1°	10m
Motosu-Fuketsu No1	3.6°	10m
Inusuzumiyama-Fuketsu No1	12°	5m
Mujina -Ana	8.5°	5m
Inusuzumiyama-Fuketsu No2	13°	2m
Mitsuike-Ana	3.2°	10m
Atsuhara-Fuketsu	10°	2m
Banba-Ana	4.8°	5-10m

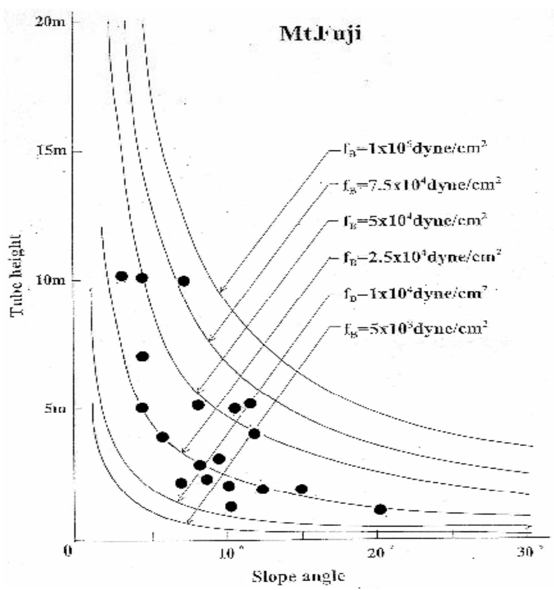

Fig.3 Slope angle and cave height for Mt.Fuji

Table2 Slope angle and lava tube cave height of Mt.Etna
(*extracted from Sonia Calvari,MarcoLiuzzo(1999): Excursion guide,Lava tubes and Lava cavern Etna volcano,9th Int.Symp.Vulcanospeloeology)

Cave name	Length	Denive lation	Slope angle	Inner height
Cutrona Cave	870m	97m	6.4°	6m
Immoacolatella I Cave	300m	20m	3.8°	10m
Serracozzo Cave	350m	60m	9.8°	2-3m
Tre Livelli Cave	1150m	304m	15.3°	3m
KTM Cave	643m	100m	8.9°	5m
Cassone Cave	246m	1m	0.23°	7m
Intraleo Cave	300m	16m	3.1°	9-3.8m
Abisso di Monte Nero Cave	756m	84m	6.4°	10m

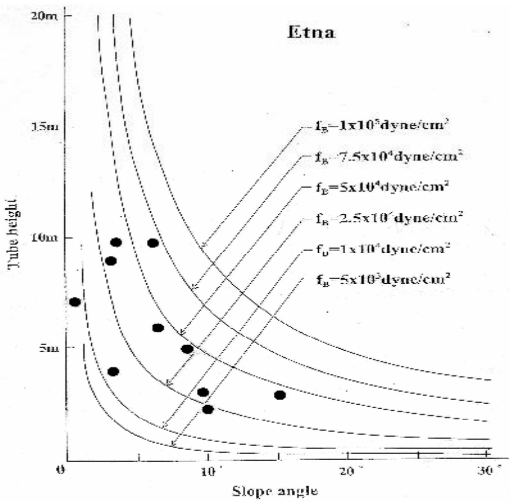

Fig.4 Slope angle and cave height for Mt.Etna

Table 3 Slope andgle and cave height for Kazumura cave of Kirauea(*extracted from K.Allred,C.Allred(1997): Development and Morphology of Kazumura Cave,J.Cave& Karst Studies,59(2),pp67-80)

Portion of cave	Average slope angle	Estimated erosion depths
Olaa	2.5°	5.6-19.9m
Sexton	2.0°	3.4-17.2m
Upper	1.7°	4.0-11.1m
Old	1.9°	3.4-10.1m
Lower	1.3°	3.4-10.1m

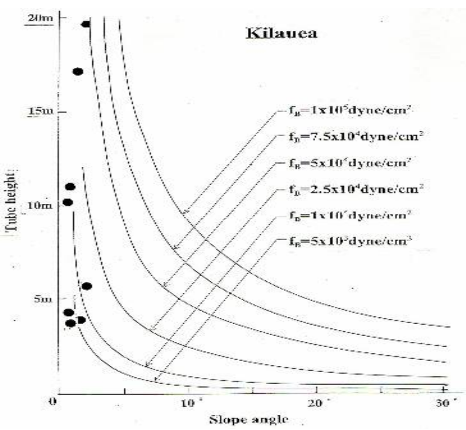

Fig.5 Slope angle and cave height for Kazumura cave of Kilauea

Table4 Slope angle and cave heigh of Mt.St.Helens (*extracted fromJ.H.Hyde &R.Greeley(1973):Geological Field Trip Guide,Mount St.Helens lava tubes,Washington)

Cave Name	Slope Angle	Maximum Height
Ape Cave	3.3°	11.6m
Barney's Cave	2.0°	2.7m
Bat Cave	16.2°	3.7m
Beaver cave	3.0°	9.1m
Flow Cave	3.2°	2.4m
Lake Cave	2.6°	15.5m
Little People Cave	4.5°	9.1m
Ole's Cave	2.1°	7.6m

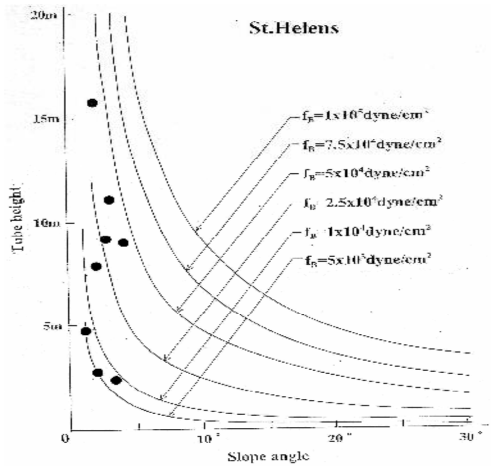

Fig.6 Slope angle and cave height for Mt.St.Helens

Table 5 Slope angle and cave height of Suchiooc,Mexico (*extracted from Ramon Espinasa Perena(1999), Thesis,Origen y evolucion de tubos de lava en la Sierra Chichinatzin:El caso del volcan Suchiooc,Univ.Nacional Autonoma de Mexico)

Cave name	Length	Denive lation	Slope Angle	Inner Height
Cueva de Aucomolijia	343m	44m	12.9°	4m
Cueva de Barreto	129m	24m	10.7°	6m
Cueva de Tepemecac	278m	38m	7.9°	9m
Cueva de la Tuberia	428m	116m	15.8°	5m
Cueva de Tiro Perdido	262m	22m	4.8°	15m
Cueva del Arbol	1480m	118m	4.6°	15m
Sistema Chimalacatepec	1388m	201m	8.3°	10-15m

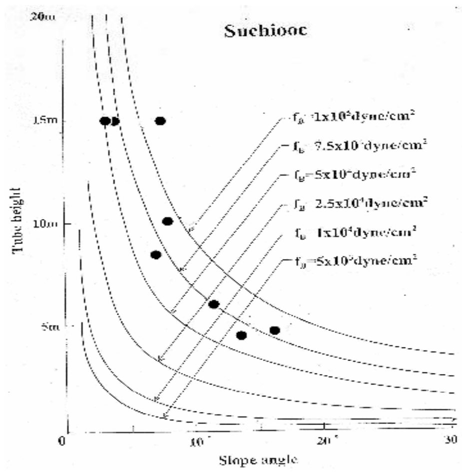

Fig.7 Slope angle and cave height for Schiooc in Mexico

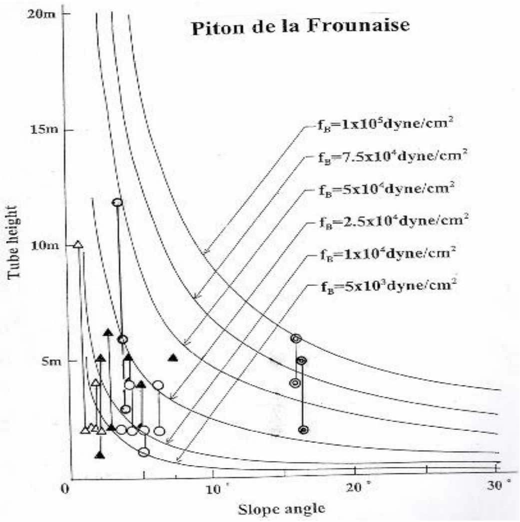

Fig.8 Slope angle and cave height for Reunion island including Piton de la Fournais(see Table6 in late page)

Table 7 Comparison between yield strength obtained by cave height and that obtained by other method

Volcano	SiO2 wt%	Yield strength obtained from cave height（Yield strength obtained from other method）
Mt.Fuji	49~51%	$1x10^4$~$7.5x10^4$dyne/cm^2
Mihara-yama, Izu-Oshima	52~53%	$5.0x10^4$dyne/cm^2 ($4.3x10^4$dyne/cm^2 by Hulme[17])
Mt.Etna	48%	$1x10^4$~$5x10^4$dyne/cm^2 ($7x10^4$dyne/cm^2 by Hulme[17])
Kilauea	47~50%	$2.5x10^3$~$2.5x10^4$dyne/cm^2 ($1x10^3$dyne/cm^2 by Hulme[17])
Piton de la Fournaise	48%	$5x10^3$~$7.5x10^4$dyne/cm^2
Mt.St.Helens	50%	$5x10^3$~$2.5x10^4$dyne/cm^2
Cameroon	43.5%	$7.5x10^4$~$1.0x10^5$dyne/cm^2 (~$1x10^5$dyne/cm^2 by Fitton[23])
Suchiooc	51%	$2.5x10^4$~$1.0x10^5$dyne/cm^2

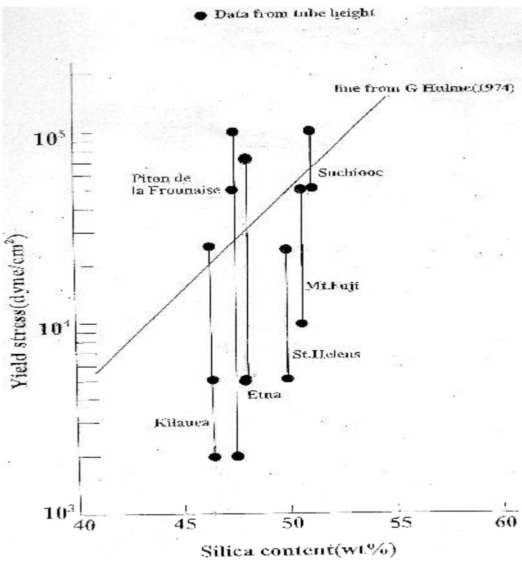

Fig.9 Relation between yield strenght and SiO_2wt%

3. Estimation of lava tube cave heights of the Moon and the Mars

If the yield strength and the angle of the slope are known, the height of the lava tube cave can be estimated by applying this model to the Moon and Mars. As shown in Table 8, The main difference with the Earth is only gravity. The lava density is same as 2.5 g/cm^3. The yield strength is indicated from the thickness of the lava and the surface levee estimated by the Hulme[17,18,19), Moore[20,21)] and Zimbelman[22)] . The details are shown in Table 10.

Table 8 Physical conditions

Planet	Gravity	Lava density	Yield strength
Earth	9.8 m/s^2	2.5 g/cm^3	$2x10^3$dyne/cm^2 ～$1x10^5$ dyne/cm^2
Moon	1.62 m/s^2	2.5 g/cm^3	$1x10^3$ dyne/cm^2 ～$2x10^5$ dyne/cm^2
Mars	3.71 m/s^2	2.5 g/cm^3	$3x10^3$ dyne/cm^2 ～$3x10^5$ dyne/cm^2

Fig.10 and Fig.11 show the relation of slope angle and cave height $H=2R=4f_B/(\rho g \sin\alpha)$ for different yield strength for the Moon and the Mars.

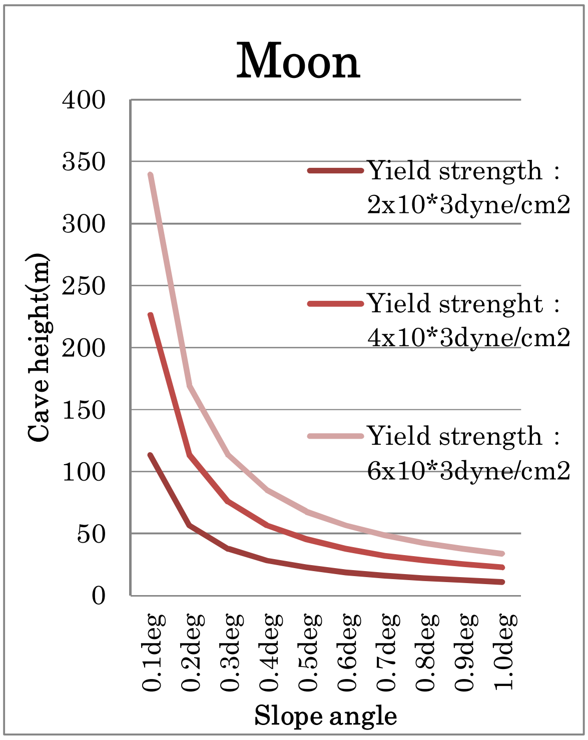

Fig.10 Lava tube cave height estimation for the Moon

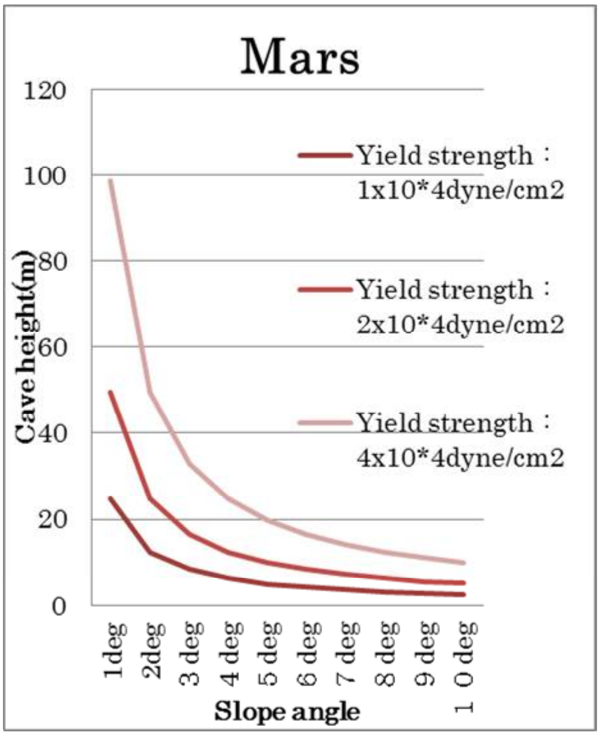

Fig.11 Lava tube cave height estimation for the Mars

Regarding the Moon, according to Hulme[17)], Mare Imbrium has 0.2 deg of slope angle and it's yield strength is $4x10^3$dyne/cm^2. The possible cave height can be estimated as 112m from Fig.10. As the lava thickness is about 30m for Mare Imbrium, the formation of lava tube cave would be difficult in this area. On the other hand, Marius Hills where an opening was found by Haruyama[12,13)], has an altitude of 1-2km and a diameter are 300km, so the degree of slope angle is approximately 0.38 deg~0.76 deg, so if the same yield strength of $4x10^3$dyne/cm^2 is used, the cave height will be 30~60m from Fig.10. So, if the thickness of the lava is more than 30~60m, there is a possibility that a lava tube cave is formed in this area.

Regarding the Mars, according to Zimbelman [22)], Acraeus Mons has 5 deg of average slope angle and yield strength of $2.1x10^4$dyne/cm^2. The lava tube cave height can be estimated as about 10m from Fig.11. As the lava thickness is said to be 15-45m, so there is a possibility that a lava tube cave is formed. Pavonis Mons has an altitude of 8.7km and the diameter is 375km, so the degree of slope angle is 2.66 deg. If the same value of yield strength of $2.1x10^4$dyne/cm^2 is used, the lava tube cave height can be estimated as 19m from Fig.11. The formation lava tube cave would be possible if the lava thickness is higher than 19m at Pavonis Mons.

If the more precise degree of slope angle,lava thickness and yield strength of the lava flow are known, it is possible to predict more precisely the cave height..

4. Conclusions

If the lava tube caves of the earth and of other planet such as the Moon and the Mars are formed from the same mechanism, the lava tube cave height of the Moon and the Mars can be predicted by the same model. The main difference remains in the gravity. The lava density and the lava yield strength seem not be so different. Other elements are slope angle and lava thickness. In Table 9 and 10, Summarized values are shown for the Earth, the Moon and the Mars.

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Table 6 Lava tube caves in the Reunion Island

(*from ref.1 and ref.2 for length and denivelation)

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Ref-2: D.Cailhol,S.Fulcrand(2011) :Mission d'Expertise: Tunnel de laves de l'ile de la Reunion

Cave name	Length	Denivelation	Location/area	Slope angle	Inner height
○Tunnel de 2004:Branche nord	741m	44m	East,Piton de la Fournaise	3.4°	2m
○Tunnel de Dimanche	275m	24m	East,Piton de la Fournaise	5.0°	1-2m
○Tunnel de Gendarmes	340m	25m	East,Piton de la Fournaise	4.2°	2-4m
○Tunnel de Brule de Citron-galets	680m	94m	East.Piton de la Fournaise,Saint-Philippe	6.1°	2-4m
△Caverne Bateau	1910m	34m	Central,Le Tampon	1.0°	2-10m
△Caverne de Butor	100m	4m	Central,Saint-Joseph	2.3°	2m
△Caverne des Fees	820m	26m	Central,(Piton des Fees),La Plaine des Palmistes	1.8°	2-4m
△Trou no2 de la Plaine-des-Palmistes	947m	30m	Central,La Plaine des Palmistes	1.8°	2-4m
△Caverne de Pylone,Amont	80m	2m	Central, La Tampon	1.4°	2m
△Caverne de Pylone,Aval	160m	6m	Central, Le Tampon	2.2°	2m
◎Caverne de la Ravine Saint-Francois	165m	47m	Central plateau, (Piton des Cabris),La Plaine des Palmistes	14.7°	2-5m
◎Trou du Sentier de Piton Textor	175m	48m	Central Plateau,(Piton Textor) Le Tampon	15.9°	4-6m
▲Le Trou d'eau	350m	45m	West,Piton des Neiges Saint-Paul	7.4°	5m
▲Caverne de Bernica	369m	31m	West,Piton des Neiges,Saint-Paul	4.8°	2-4m
▲Caverne de la Ravine Fleurimont	200m	9m	West,Piton des Neiges Saint-Paul	2.6°	2-6m
▲Caverne de Quatre Voies	136m	11m	West,Piton des Neiges, Saint Paul	4.6°	4-5m
▲Grotte des Salanganes	550m	21m	West,Piton des Neiges Saint-Paul	2.1°	0.5-5m

Table 9 : Lava tube caves of the Earth

Planet	Location of lava flow/lava tube cave(Reference)	Slope angle of lava tube cave	Yield strength obtained from lava tube cave height	Height of lava tube
Earth	Mt.Fuji(T.Honda[4])	3.2 °~20.0 °	1x10^4~7.5x10^4dyne/cm^2	1~10m
	Mihara-yam.Izu-Oshima(T.Honda[8,9])	~30 °	5.0x10^4dyne/cm^2	~1.5m
	Hachijou-jima,Nishi-yama(T.Honda[6,7])	4.0 °~14.0 °	2.5x10^4dyne/cm^2	2~5m
	Kilauea(T.Honda[3])	1.0 °~4.0 °	2.5x10^3~2.5x10^4dyne/cm^2	3~17m
	Mt.Etna(T.Honda[3])	0.2 °~15.3 °	1x10^4~5x10^4dyne/cm^2	2~10m
	Mt.St.Helens(T.Honda[3])	2.1 °~4.5 °	5x10^3~2.5x10^4dyne/cm^2	3~16m
	Piton de la Fournaise(T.Honda etal[10])	1.0 °~16.0 °	5x10^3~7.5x10^4dyne/cm^2	1~12m
	Suchiooc(T.Honda[3])	4.6 °~15.8 °	2.5x10^4~1.0x10^5dyne/cm^2	4~15m
	Cameroon(T.Honda[3])	~14.0 °	7.5x10^4~1.0x10^5dyne/cm^2	6~8m

Table 10 : Lava tube caves of the Moon and the Mars

Planet	Location of lava flow(Reference)	Slope angle of lava flow	Yield strength obtained by lava flow configuration	Estimated cave height
Moon	Mare Imbrium(Hulme[17])	0.2 °	4x10^3 dyne/cm^2	(112m)
	Imbrium flow(Moore/Schaber[20])	0.13°,sinα=0.0023	1~2x10^3 dyne/cm^2	
	Marius Hills(elevation /diameter:1-2km/300km)	0.38°~0.76 °	(4x10^3 dyne/cm^2)	(30~60m)
	King Crater(Moore[21])	sinα=0.08~0.22	(2.41±1.71)x10^5 dyne/cm^2	
	Aristarchus Crater(Moore[21])	sinα=0.12~0.36	(1.94±1.13)x10^5 dyne/cm^2	
	Aristarchus Crater(Hulme[19])	sinα=0.15~0.66	1.0x10^4~1.3x10^5dyne/cm^2	
	Copernicus(Hulme[19])	sinα=0.09	1.8x10^5dyne/cm^2	
	Tycho(Hulme[19])	sinα=0.04~0.10	4.0x10^3~1.0x10^5dyne/cm^2	
Mars	Ascraeus Mons(Zimbelman[22])	3.5 °~6 ° Average:5 °	3.3x10^3~8.3x10^4dyne/cm^2 Av:2.1x10^4dyne/cm^2	(10m)
	Olympus Mons(Hulme[18])	sinα=0.04 sinα=0.06 sinα=0.09	(8.8±1.3)x10^3 dyne/cm^2 (2.0±0.3)x10^4 dyne/cm^2 (4.5±0.6)x10^3 dyne/cm^2	
	Olympus Mons(Moore[21])	sinα=0.082,0.089	Av:(3.06±1.24) x10^5dyne/cm^2	
	Arsia Mons(Moore[21])	sinα=0.021~0.070	Av:(1.00±0.82) x10^4dyne/cm^2	
	Pavonis Mons(elevation /diameter:8.7km/375km)	2.66 °	(2.1x10^4dyne/cm^2)	(19m)

The role of surface tension on the formation of lava stalactite and lava stalagmite

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Abstract

The role of surface tension of lava on the formation of lava stalactite and lava stalagmite is analysed by two different physical models. A hydrodynamic instability model is used for a lava stalactite formation and a fallen droplet model is used for a lava stalagmite formation. The surface tensions estimated from two different models show a good coincidence and reasonable value as surface tension of lava.

1.Introduction

Inside the lava caves and lava tree mold voids formed by the basalt lava flow, lava stalactites and lava stalagmites are often observed. It is a phenomenon in which the droplet of lava falls from a ceiling and deposits on the floor. By using two simple models where the balance between gravity and surface tension acting on lava surface are taken into consideration, the estimation of surface tension of lava from the pitch of lava stalactite and size of lava stalagmite appeared in lava tube cave and tree mold void are performed and compared with various lavas.

2.Estimate of surface tension from lava stalactite

Fig.1 shows a genral feature of the inside of lava tree mold. 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[1~3]. 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 or lava tree mold void as shown in Fig.2. The pitch P is shown as $\mathbf{P=2\pi(\gamma/g\rho_L)^{1/2}}$, where γ is surface tension of liquid ρ_L is density of liquid, g is gravity acceleration. From the pitch of lava stalactites on the roof surface, the surface tension of lava $\boldsymbol{\gamma = P^2 g\rho_L / 4\pi^2}$ 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 or ribbed wall (**P**=3 to 4cm) (see Fig.3 to Fig.19), the surface tension of lava was determined as 560～990 dyne/cm. The estimated surface tension matches with the experimental results by melting the lava in the Laboratory[4].

Fig.1 Void in Funatsu Tainai Lava Tree Mold

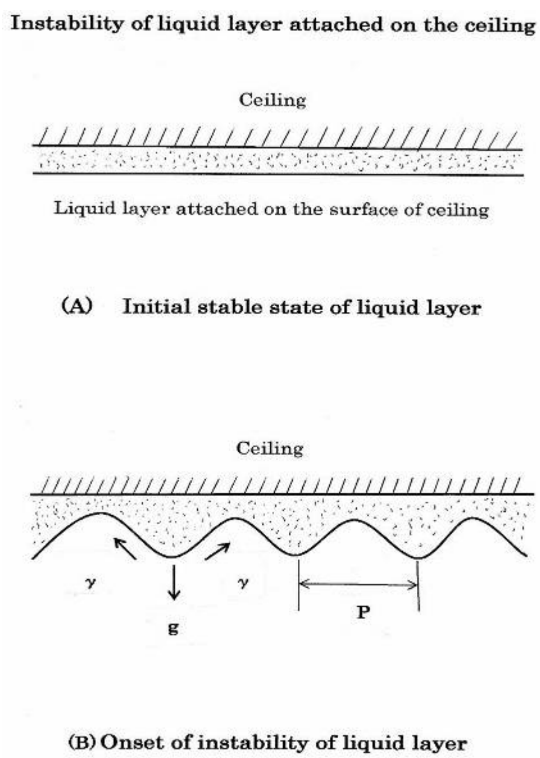

Fig.2 Instability model of liquid layer on the roof

Fig.3 Lava stalactite in Yoshida Tainai Lava Tree: P=3～4cm,γ=560～990 dyne/cm

Fig.4 Ribbed wall in Yoshida Tainai Lava Tree: P=3～4cm,γ=560～990 dyne/cm

Fig.5 Ribbed wall in Funatsu Tainai Lava Tree: P=3～4cm,γ=560～990 dyne/cm

Fig.6 Lava stalactite in Hachijojima Lava Tree: P=3～4cm,γ=560～990 dyne/cm

Fig.7 Lava stalactite in HornitoCave of Mihara-yama in Izuoshima : P=～3cm,γ=～560 dyne/cm

Fig.8 Lava stalactite in Daikon-jima,Shimane : P=～3cm,γ=～560 dyne/cm

Fig.9 Ribbed wall in Mitsuike-ana lava tube cave: P=3～4cm,γ=560～990 dyne/cm

Fig.10 Lava Stalactite on the roof in the tunnel of 2004 lava flow of Piton de la Fournaise: P=3～4cm,γ=560～990 dyne/cm

Fig.11 Ribbed wall in the tunnel of 2004 lava flow of Piton de la Fournaise: P=3～4cm,γ=560～990 dyne/cm

Fig.12 Fig.11 Ribbed wall in the tunnel of 2004 lava flow of Piton de la Fournaise: P=3～4cm,γ=560～990 dyne/cm

Fig.13 Lava stalactite on the ceiling of Mushpot Cave in Lava Bed National Monument: P=3～4cm,γ=560～990 dyne/cm

Fig.14 Ribbed wall of Catacombs Cave in Lava Bed National Monument: P=3～4cm,γ=560～990 dyne/cm

Fig.15 Lava stalactite in the lava tree mold of Newberry Volcano,Lava Cast Forest

Fig.16 Ribbed wall in the lava tree mold of Newberry Volcano,Lava Cast Forest: P=3～5cm, γ=560～1740 dyne/cm

Fig.17 Lava stalactite of ChuBluck Volcano of Vietnam,C0Cave:P=3~4cm, γ=560～990 dyne/cm

Fig.18 Ribbed wall of ChuBluck Volcano of Vietnam,B14Cave:
P=3~4cm, γ=560～990 dyne/cm

Fig.19 Ribbed wall of ChuBluck Volcano of Vietnam,C3Cave:P=3~4cm, γ=560～990 dyne/cm

3.Estimate of surface tension from lava stalagmite

After the droplet's falling either from the liquid layer of a ceiling or from a straw formed from a ceiling, the droplets of lava may be acumulated one after another on the floor. The cylindrical configuration of the lava droplet has a certain radius and length in such a way that the configuration of the droplets has almost the same size. It is thought that the surface tension of the droplet is playing an important role in this phenomenon. When it becomes impossible for surface tension to bear the weight of the droplet, the droplet will fall down. After that, again the liquid lava will be supplied, then, the droplet will repeat to fall down. Consequently many lava droplets will be deposited on a floor area. This phenomenon is very similar to the "weight of falling drops technique" which is the general method of measuring the surface tension of a liquid. Based on this idea, the study model for determining the surface tension γ of lava is made[3]. When mass of the droplet is set to m, the force which pulls the droplet downward is $f_1 = mg$ (g is acceleration due to gravity), and the force of pulling up this upwards is $f_2 = 2\pi r\gamma$, where r is the radius of the lava droplet. The surface tension γ is calculable for $f_1 = f_2$ if the weight of the lava droplet is known. As $f_1 = mg = \pi r^2 \ell \rho_L g$, where ℓ is length of the lava droplet, ρ is the density of the lava, the surface tension $\boldsymbol{\gamma = r\ell\rho_L g/2}$ can be obtained from r and ℓ of the lava droplets accumulated on the floor as shown in Fig.20. If we introduce $\rho_L = 2.5 g/cm^3$ and $g = 980\ cm/s^2$, and by the fields observation of r and ℓ, for example, the surface tension $\gamma = 490$ dyne/cm can be obtained for r=0.2 cm, and ℓ=2cm, and $\gamma = 980$ dyne/cm can be obtained for r= 0.25 cm, and ℓ=4cm. From the measurement of r and ℓ of the various stalagmites, the serface tension γ is estimated as shown in Fig.21 to Fig.26. The surface tension of lava was in the range of 600 to 1000 dyne/cm in general.. The estimated surface tension matches with the experimental results by melting the lava in the Laboratory[4].

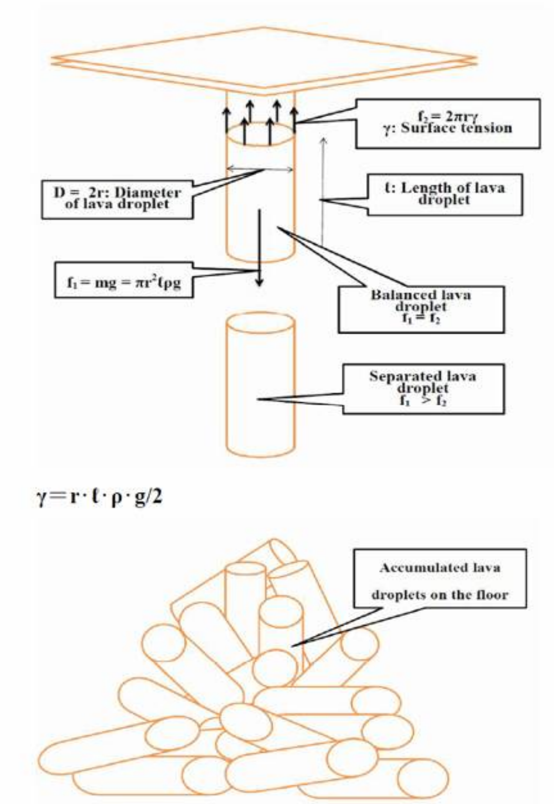

Fig.20 Fallen droplet model

Fig.21 Lava stalagmite on the floor of Mitsuike-ana lava tube cave: r=0.2~0.25cm, ℓ=2~4cm, γ=490～980 dyne/cm

Fig.22 Lava stalagmite on the floor of Funatsu Tainai Lava Tree: r=0.25cm, ℓ=3cm, γ=920 dyne/cm

Fig.23 Lava stalagmite on the floor of Miyakejima Lava Tree: r=0.25cm, ℓ=5cm, γ=1530 dyne/cm

Fig.24 Lava stalagmite on the floor of Miyakejima Lava Tree:r=0.1cm, ℓ=5cm, γ=610dyne/cm

Fig.25 Stalagmite of Hachijoujima lava tree: r=0.2~0.25cm, ℓ=2~4cm, γ=490~980dyne/cm

Fig.26 Stalagmite in the tunnel of 2004 lava flow of Piton de la Fournaise: r=0.2~0.25cm, ℓ=2~4cm, γ=490~980dyne/cm

4.Conclusions

The value of such surface tension obtained from the lava stalagmite is in good agreement with the surface tension acquired from the pitch of the waving of the liquid layer by the simple hydrodynamic instability model of gravity/surface tension acting on the melting liquid layer attached on the inner surface of the lava cave. This value also agrees well with the extrapolated value at the temperature arround 1100 degrees Celsius obtained by I. Yokoyama and S.Iizuka[4)] in the melting lava surface tension measurement experiments in Laboratory. As a conclusion, we could say that the surface tension plays a preponderant role for the lava stalactite and stalagmite formation in the lava cave and lava tree void. It seems that there is no significant difference between surface tensions of different basaltic lavas though further study for various lavas will be continued . The estimated surface tensions are summarized in the Table1 in Appendix.

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Appendix

Table 1 Summary of the estimated surface tensions for various area

Name of Volcano, Area	SiO_2 weight%(Reference), Eruption year	*Cave or T-Mold	**Measured P , r and ℓ	Estimated surface tension
Mt Fuji, Inusuzumi-yama, Mitsuike-ana	49.09%(H.Tsuya) , before 7000	Cave	P=3～4cm r=0.2~0.25cm,ℓ=2~4cm	560～990dyne/cm 490～980 dyne/cm
Izu-Osima, Mihara-yama	52~53%(T.Minakami), 1951	Cave	P= ～3cm	～560 dyne/cm
Shimane,Daikon-zima	47%(I.Sawa), before 190000	Cave	P= ～3cm	～560 dyne/cm
France, Reunion, Le Piton de la Fournaise	48.8~49.8% (N.Villeneuve),1998 48~50% (A.Peltier),2004	Cave	P=3～4cm r=0.2~0.25cm,ℓ=2~4cm	560～990 dyne/cm 490～980 dyne/cm
Vietnam, Central Plateau, Chupluk Volcano	48~52% (N.Hoang)	Cave	P=3～4cm	560～990 dyne/cm
US,California, Medecine Lake Volcano,Lava Beds National Monument	52.3 Average%(J.Donnelly) 36±16ka	Cave	P=3～4cm	560～990 dyne/cm
Mt Fuji,Ken-marubi, Funatsu-tainai	50.88%(H.Tsuya), 937	T-Mold	P=3～4cm	560～990 dyne/cm
Mt Fuji,Ken-marubi, Yoshida-tainai	50.88%(H.Tsuya), 937	T-Mold	P=3～4cm	560～990 dyne/cm
Izu-Osima, Mihara-yama	52%(S.Nakano, T.Yamamoto), 1986	T-Mold	P=～4cm	～990 dyne/cm
Miyake-zima, O-yama	53~54%(T.Fujii et al),1983	T-Mold	r=0.1~0.25cm, ℓ=5cm	610～1530 dyne/cm
Hachijo-zima,Nishi-yama,	50.4~50.5%(M.Tsukui), Before 1100	T-Mold	P=3～4cm, r=0.2~0.25cm,ℓ=2~4cm	560～990 dyne/cm 490～980 dyne/cm
US,Oregon,Newberry Volcano, Lava cast forest	49～50%(J.Donnelly), Before 7000	T-Mold	P=3～5cm	560～1740 dyne/cm

*T-Mold=Lava Tree Mold

**P=Pitch between lava stalactites or Pitch of ribbed wall, r=Radius of lava stalagmite, ℓ=Length of lava stalagmite

Vietnam Volcanic Cave Survey Project Report

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Abstract:
From December 2013 to January 2015, the joint team of the Geological Museum of Vietnam belonging to the General Department of Geology and Minerals and NPO Vulcano-Speleological Society of Japan carried out a survey for volcanic caves in the lava flowed from the Chu'B'luk Volcano located in the central Vietnam plateau in Dak Nong Province,Krongno District[1,2] (Photo1-Photo7).

As a result of the survey, the joint team explored 18 lava tube caves, among which the measured total length of the caves C2,C3,C4,C6, C61,C7,C8,C9 and A1 is 4832.5 m(Fig1-Fig9). The longest lava tube cave found is C7 which has a total length of 1066.5 m. The second longest cave is 967.8m of C3+C4 lava tube cave. The third longest cave is 791.0m of C8 lava tube cave. The sixth longest cave is 475.5ｍ of C0 lava tube cave. The seventh longest cave of A1 lava tube cave has a length of 438m. The eighth longest cave of C2 lava tube cave has a length of 402.2m.

So far the longest lava tube caves known from South East Asia since then was Hang Doi 1+2 Km 122 cave (549m) and Hang Doi 1+2 Km 12 3cave(495m) discovered by a team of speleologists from the German Speleoclub Berlin and members of the Vietnam Academy of Sciences (Institute for Tropical Biology) in the Tan Phu area of Dong Nai Province[3,4].

Consequently, Hang Doi 1+2 Km 122 and Hang Doi 1+2 Km 123 cave is fourth and fifth longest lava tube cave in South East Asia. Then, after C0, A1 and C2, Gua Lawa II cave in Indonesia[5] will be ninth longest in South East Asia. Vietnam hosts now eight longest lava tube caves in South East Asia. Total integrated length measured as a tube system of lava caves C2~C9 is 4393.8ｍ.

Also, it is worth to mention that the large lava tree mold(Photo8,9) is found on the surface of the inner side wall of C2 and C3 lava tube cave[1,6].

Joint team member: Kazutoshi Suzuki,Katsuji Yoshida, Hirofumi Miyashita,Akira Miyazaki, Yumi Kuroishikawa,Hirohisa Kizaki, Yuriko Chikano,Yukari Yamaguchi, Futa Hirayama, Hoang Thi Bien, Katsuaki Nishikawa,Minoru Shiokawa,

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Photo1 Chu'B'luk Volcano (Photo by Tsutomu Honda)

Photo2 C7 Lava tube cave(Photo by Katsuji Yoshida)

Photo3 C3+C4 Lava tube cave(Photo by Katsuji Yoshida)

Photo4 C8 Lava tube cave(Photo by Katsuji Yoshida)

Photo5 Lava stalactite of ChuBluck Volcano of Vietnam,C0 Lava tube cave (Photo by Tsutomu Honda)

Photo6 Ribbed wall of ChuBluck Volcano of Vietnam,C3 Lava tube cave (Photo by Tsutomu Honda)

Photo7 Ribbed wall of ChuBluck Volcano of Vietnam,B14 Lava tube cave (Photo by Akira Miyazaki)

Photo8 Lava tree mold in C3 Lava cave(Photo by Tsutomu Honda)

Photo9 Lava tree mold in C2 Lava cave(Photo by Hiroshi Tachihara)

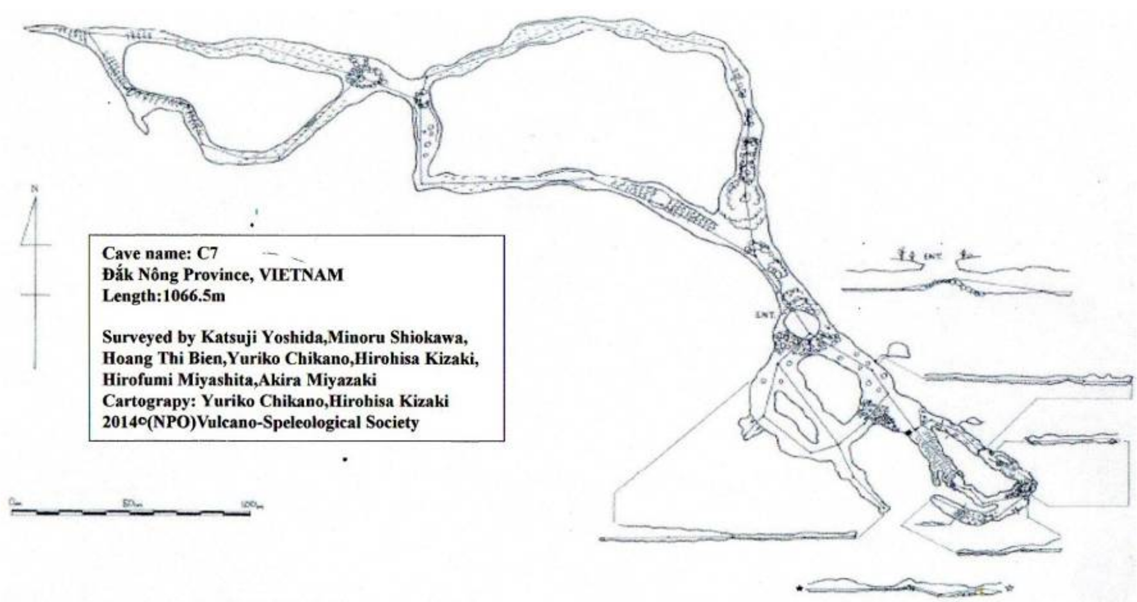

Fig1 Topography of C7 Lava Tube Cave

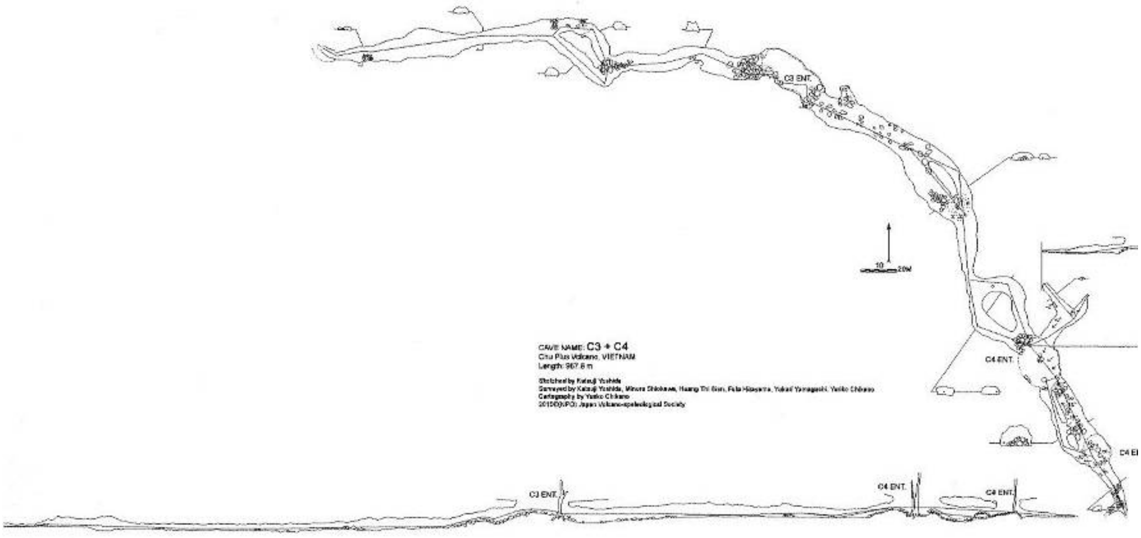

Fig2 Topography of C3+C4 Lava Tube Cave

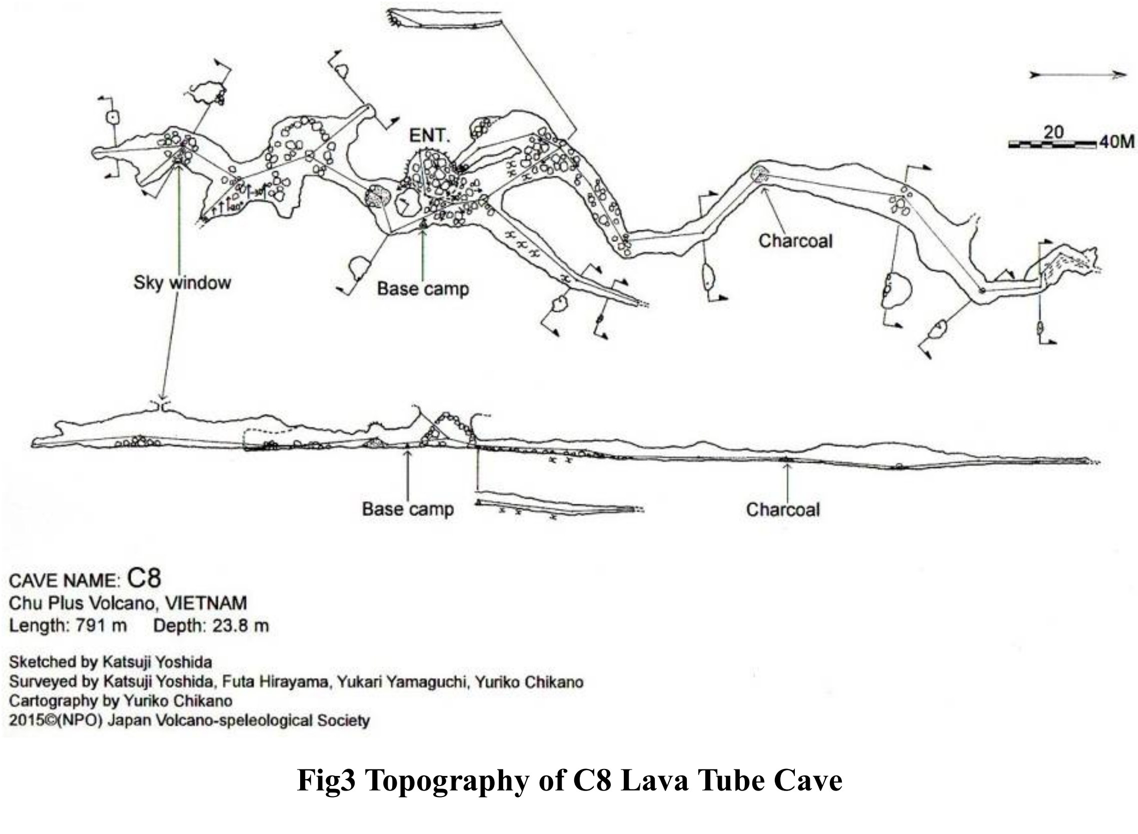

Fig3 Topography of C8 Lava Tube Cave

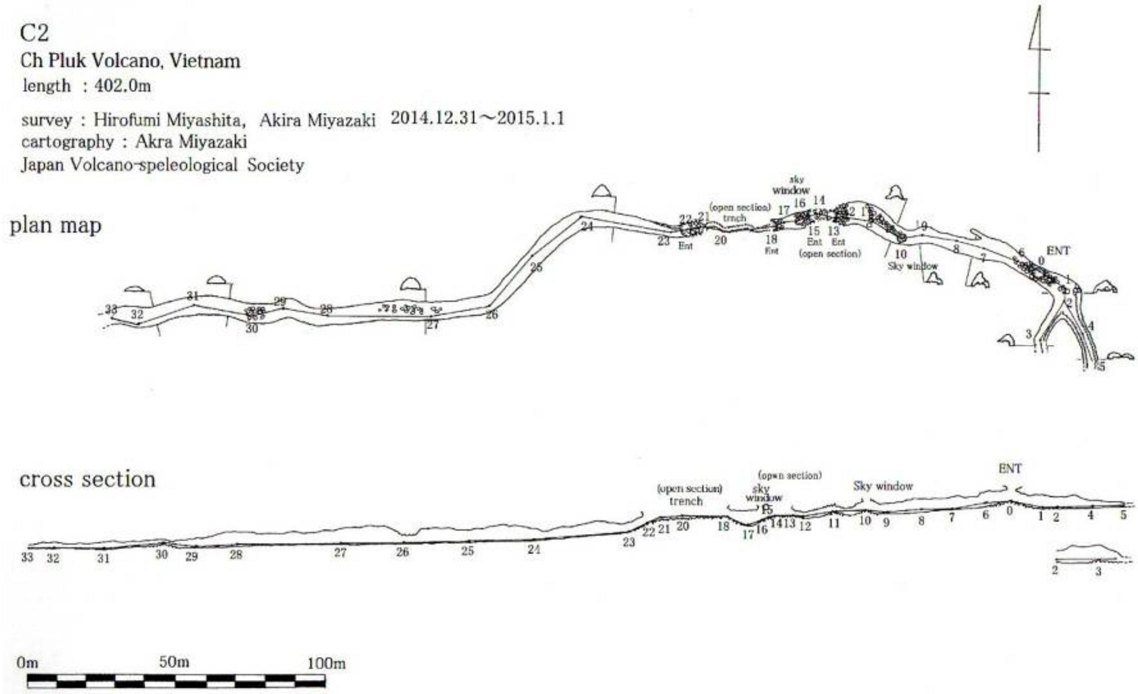

Fig4 Topography of C2 Lava Tube Cave

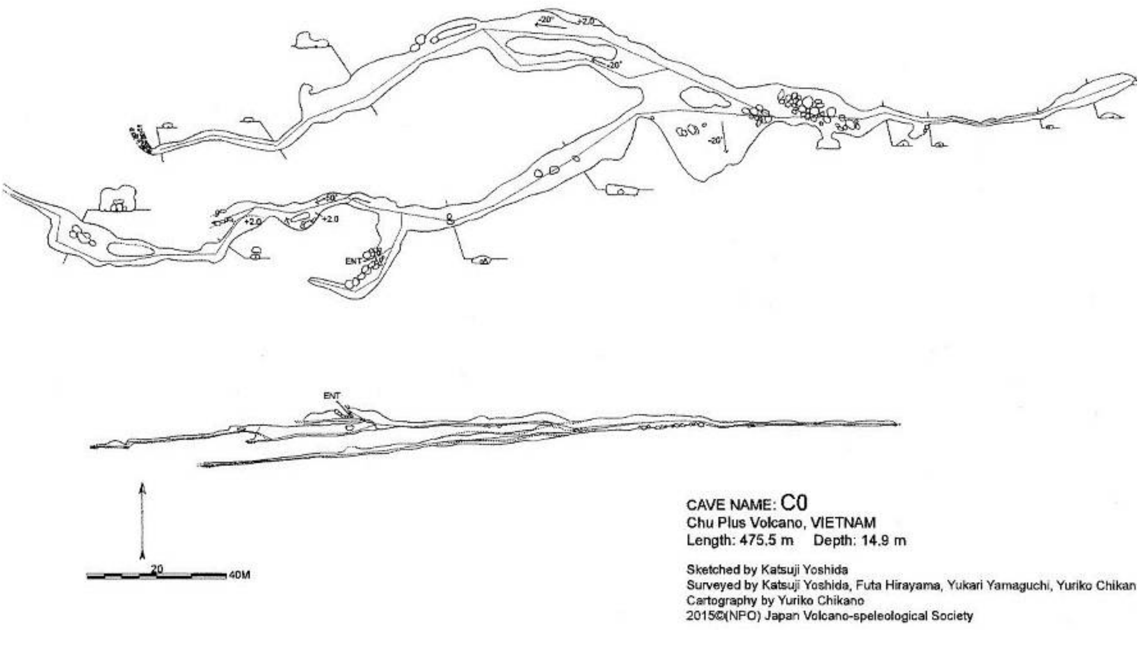

Fig5 Topography of C0 Lava Tube Cave

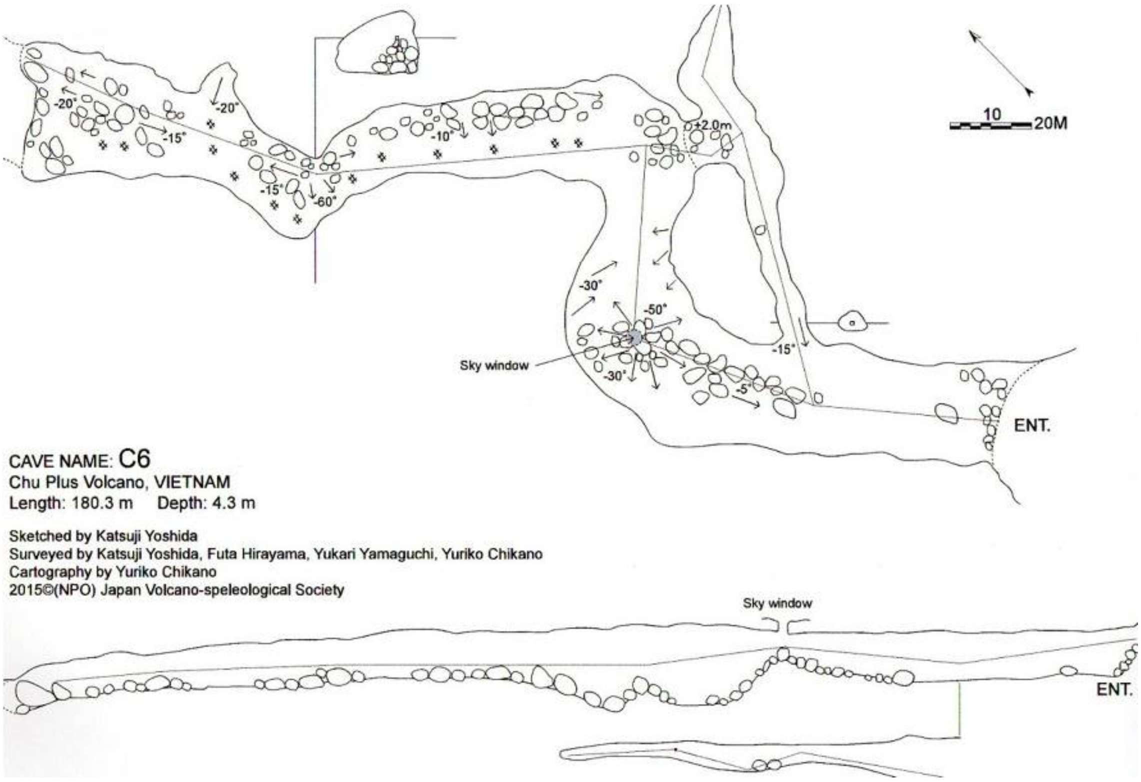

Fig6 Topography of C6 Lava Tube Cave

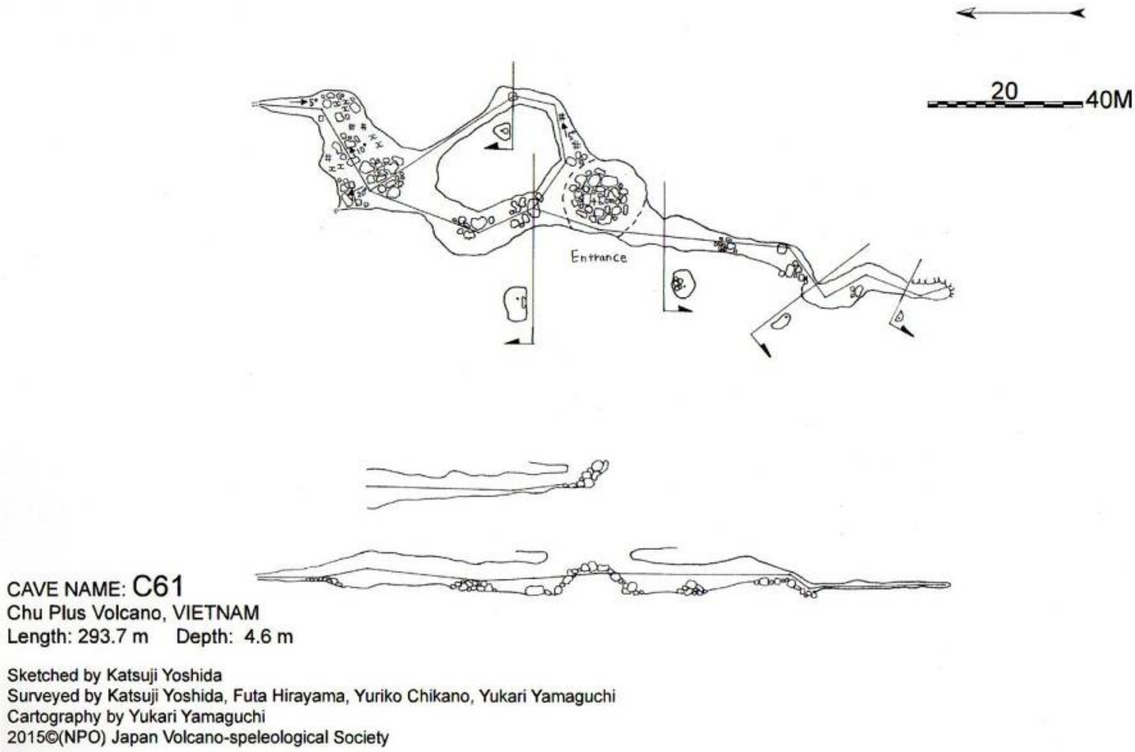

Fig7 Topography of C61 Lava Tube Cave

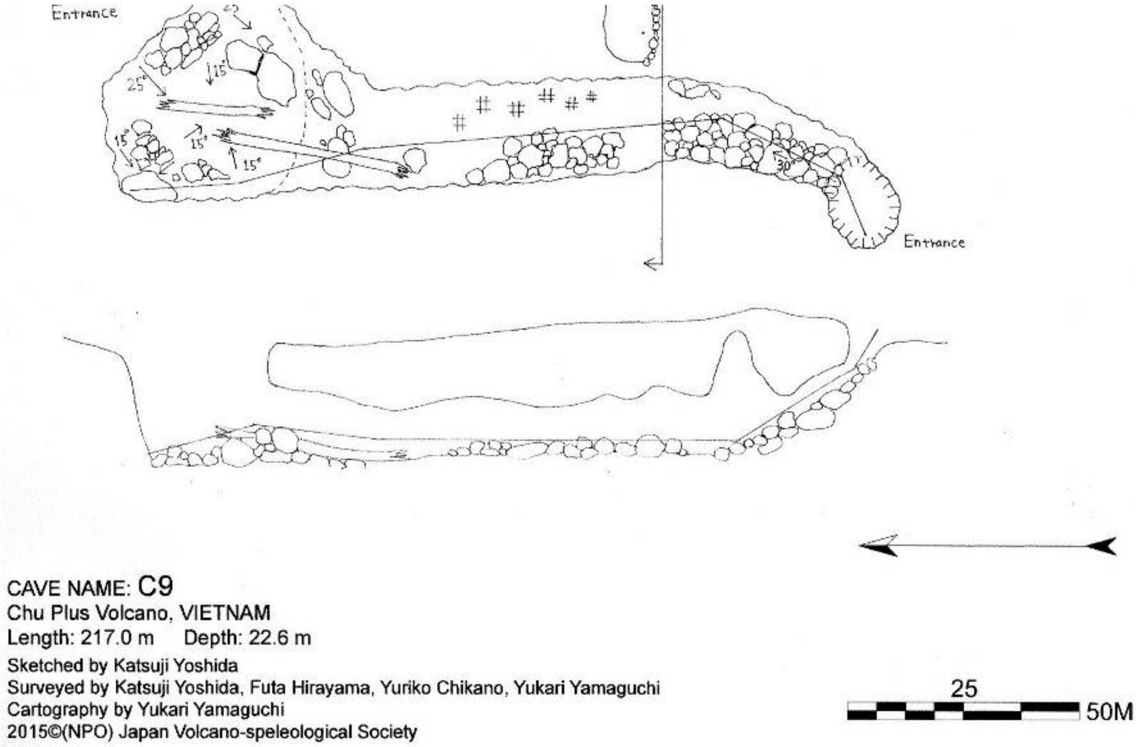

Fig8 Topography of C9 Lava Tube Cave

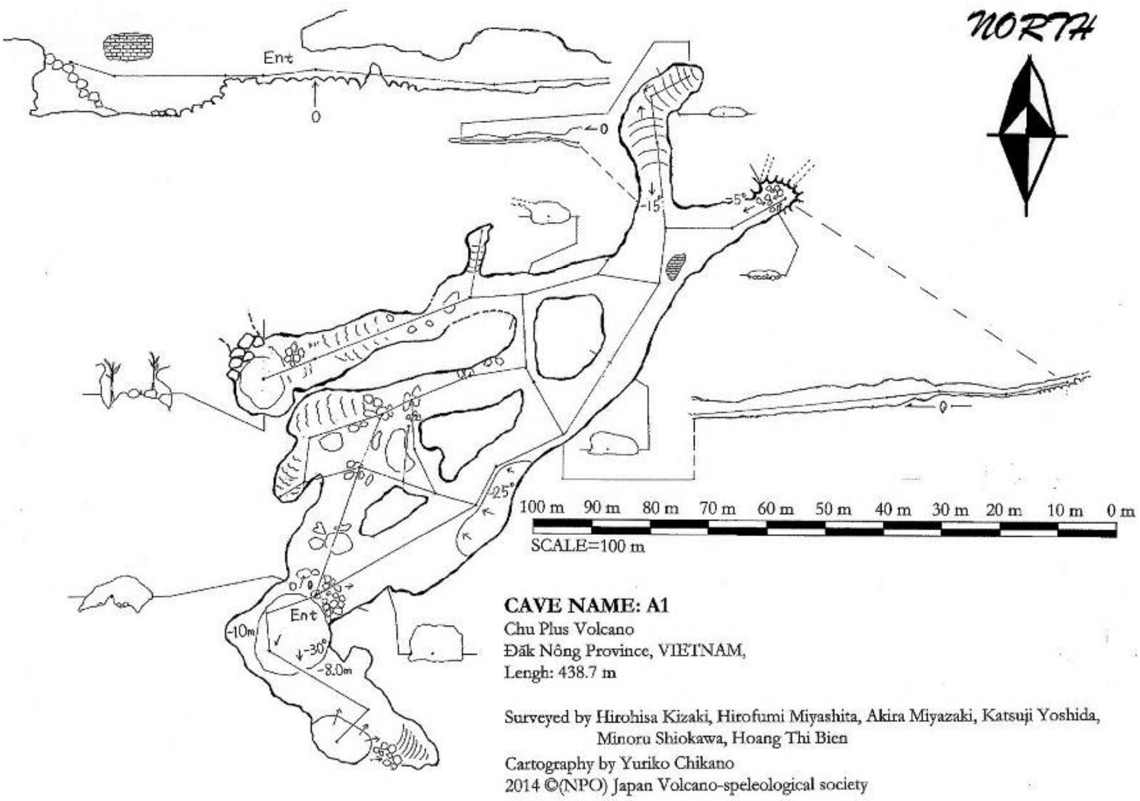

Fig9 Topography of A1 Lava Tube Cave

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

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Abstract

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

1.Introduction

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

2.Hydrodynamic Models and classification for Lava Tubes

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

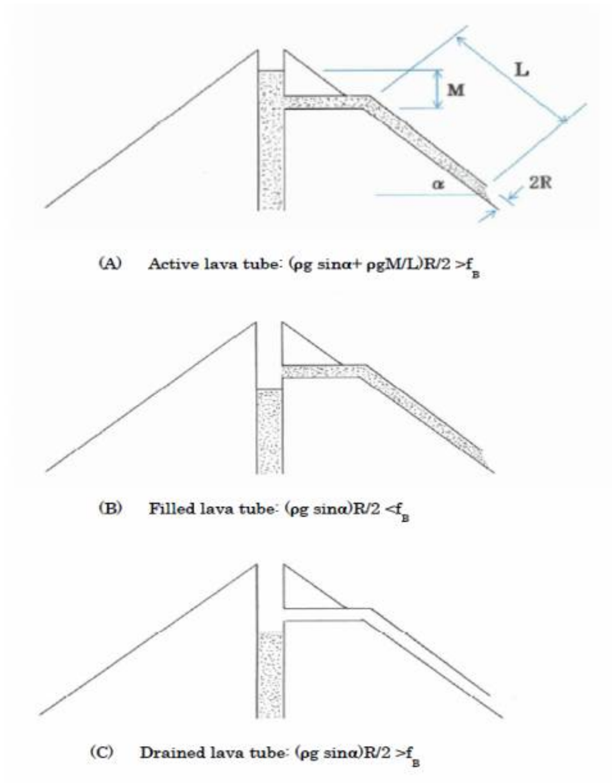

Fig.1 Hydrodynamic Model for Lava Tubes

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

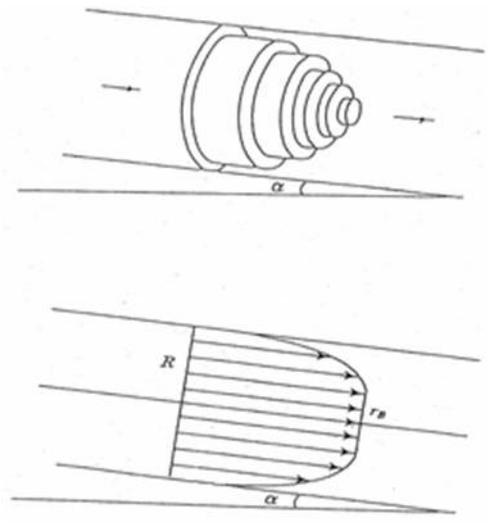

Fig.2 The flow speed distribution in the tube

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

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

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

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

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

$u = 0$

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

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

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

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

3.1 Lava tube cave and SiO_2 weight content

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

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

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

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

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

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

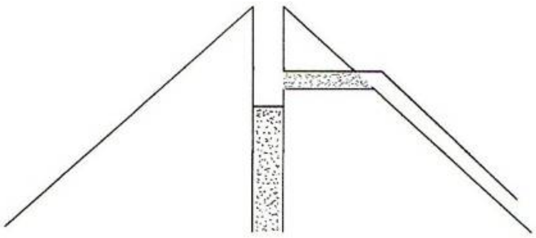

Fig.3 Schematic of Filled lava tube at the edge of the vent

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

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

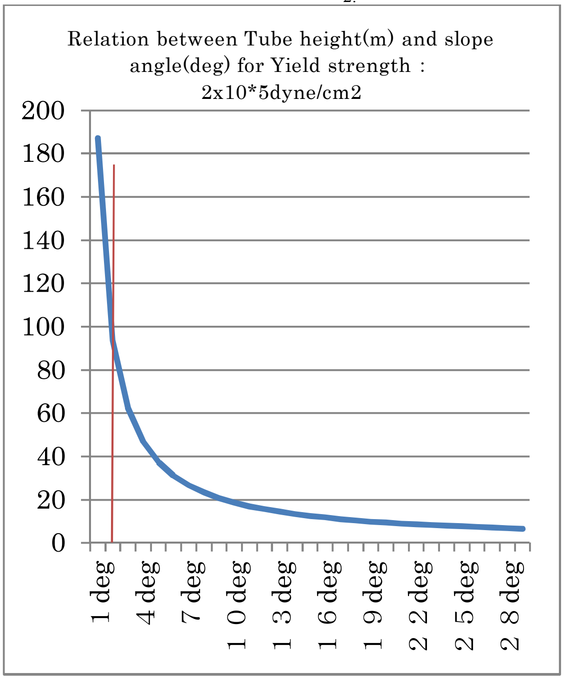

Fig.4 Tube height and slope angle for yield strength for $2.0x10^5$dyne/cm^2

4.Conclusions

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

[Acknowledgement]

We are grateful to Dr. Julie M.Donnelly-Nolan of U.S.G.S. for providing the detailed information and precious comments/discussion on the lava characteristics of Medicine Lake Volcano(MLV).

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Table 1 Classification and formation conditions of Lava Tubes

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

Table 2 North Area of Medicine Lake Volcano*

Map unit	Name of lava flow	SiO_2 weight %	Age of eruption	Lava tube caves?
bt	Basalt of Tionesta	48.3%	late Pleistocene	Existing
bc	Basalt of The Castles	48.6%	late Pleistocene	Existing
bdh	Basalt of Devils Homestead	51.3~51.4%	12320yrBP	Existing
bec	Basalt east of Cinder Butte	51.6%	late Pleistocene	Existing
bmc	Basalt of Mammoth Crater	52.3% Avg	36±16ka	Existing**
bci	Basalt of Caldwell Ice Caves	52.8%	late Pleistocene	Existing
bvc	Basalt of Valentine Cave	53.0% Avg	12,260yrB.P.	Existing
mna	Basaltic andesite northeast of Aspen Crater	53.7% Avg	late Pleistocene	Existing
mts	Basaltic andesite of Three Sisters	54.4%	late Pleistocene	None
mcf	Basaltic andesite of Callahan Flow	55.1% Avg	1,120yrB.P.	None**
asb	Andesite of Schonchin Butte	57.2% Avg	65±23ka	None
anr	Andesite of north rim	60.7% Avg	100±3 ka	None
rgm	Rhyolite of Glass Mountain	61.3~74.6%	890 yr B.P.	None

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

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

Table 3 South Area of Medicine Lake Volcano*

Map unit	Name of lava flow	SiO_2 weight %	Age of eruption	Lava tube caves?
bug	Basalt under Giant Crater lava field	49.3, 50.8%	445±27 ka	Existing
bgc	Basalt of Giant Crater	49.5%Avg	12,430yrB.P.	Existing
byb	Basalt of Yellow jacket Butte	49.5–53.1%	86±14 ka	Existing
bdc	Basalt of Deep Crater	50.3%	middle Pleistocene	Existing
bwc	Basalt of Water Caves	52.4%Avg	late Pleistocene	Existing
mdp	Basaltic andesite of Doe Peak	55.2%	middle Pleistocene	None
abl	Andesite of Burnt Lava Flow	57.3%Avg	2,950 yr B.P.	None
asr	Andesite of south rim	61.4%Avg	124±3 ka	None
rlg	Rhyolite of Little Glass Mountain	72.6–74.2%	940 yr B.P.	None

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

TOWARDS UNDERSTANDING THE STRUCTURE OF KAUMANA CAVE, HAWAII

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Abstract

Kaumana Cave is one of the youngest lava caves on Hawaii, formed during a few weeks at the end of the 1880/81 Mauna Loa eruption that stopped short of downtown Hilo. We surveyed a small section of the cave above and below the Kaumana County Park entrance in order to document the stratigraphy and development stages of the cave. Results show that the roof is composed of a >10 m thick sequence of lavas layers, with a >3 m thick primary roof formed by five to six inflationary lava sheets. The initial pyroduct had a cross-section of about 3 m^2. After the placement of the roof a cave developed upward by collapse of wall and roof sections. With the opening of a surface hole, air entered freezing a secondary ceiling above the flowing lava river. A spill of lava, oxidized red by inflowing air, across the secondary ceiling was the last event during activity. The estimated lava volume that was issued through the cave amounts to about $9*10^6$ m^3 of lava, yielding a flow rate of 2.3 m^3/sec.

Introduction

Kaumana Cave is – after Thurston Lava Tube (Kempe et al., 2008) – the second-most visited lava cave on the Island of Hawaii. Its main entrance is the dominant feature in the small County Park "Kaumana Cave", uphill from downtown Hilo. The entrance (19° 41.21'N/155° 7.84'W), a roof collapse, is equipped with a staircase. On the surface a roofed-over picnic table, restrooms and a parking lot complete the County Park's conveniences. After Thurston Lava Tube (Powers, 1920), Kaumana was the second Hawaiian lava cave, for which a rough map was published (Greeley, 1974). In 1987 (pers. com. F. Stone) it was even surveyed professionally between the County Park Entrance and its lower entrance at Edita Street, with bolt-marks documenting the stations. W.R. Halliday published 2003 another map, showing some of the salient cave features. The cave is listed with a length of 2197 m according to W.R. Halliday with no vertical data given (Gulden, 2015). This figure represents, however, not the entire length of the cave. A further survey conducted by D. Coons and P. Kambysis, has not yet been published. So far, no longitudinal profile, nor cross-sections nor any detailed geological information were published.

Kaumana Cave is part of the pyroduct that was responsible for the advance of the 1880/1881 Mauna Loa pāhoehoe[1] lava flow towards Hilo (USGS, 1995). Thus, it is one of the latest caves formed in Hawaii available for study. The 1880/81 eruption began with fountaining on November 5th, 1880 at an elevation of 3350 m on the Mauna Loa north-east rift zone. At first two extensive ‘a‘ā flows going both north towards the saddle and south towards Kilauea were produced. After two weeks a new crack opened makai of the original eruption site and large volumes of pāhoehoe began to pour towards the northeast. By March 1881 the flow had advanced to within seven miles and by June 1881 the flow front was less than five miles from Hilo downtown. Concern spread and some people evacuated from Hilo. On June 26th, lava reached the stream channels above Hilo that funneled the flow downhill. After entering Waipāhoehoe stream (near today's Chong Street Bridge) the evaporating water caused alarming roaring. Reverend Titus Coan (the coiner of the term "pyroduct", Coan 1844), reported that the lava "*came rushing down the rocky channel of a stream with terrific force and uproar, exploding rocks and driving off the waters. Hilo was now in trouble - [everyone knew] we were now in immediate danger. Its roar, on*

[1] The following Hawaiian words are used here: (i) pāhoehoe = ropy lava, (ii) ‘ā‘a = blocky lava, (iii) puka = collapse hole, (iv) mauka = uphill, (v) makai = downhill

coming down the rough and rocky bed of the ravine, was like that of our Wailuku River during a freshlet, but a deeper and grander sound. Explosions and detonations were frequent; I counted ten in a minute. The glare of it by night was terrific. The progress of the flow was by now 100-500 feet per day" (cited after USGS 1995). On August 10th, a narrow lobe had crossed what today is Mohouli street and stopped 300 m above Kapiolani street, covering the distance of ca. 4 km within 46 days. The pyroduct of Kaumana has delivered the respective amount of lava. Thus we have the singular situation that we not only know the date, when the cave formed, but we can also estimate roughly how much lava the conduit delivered within a known time frame, thus estimating flow rates.

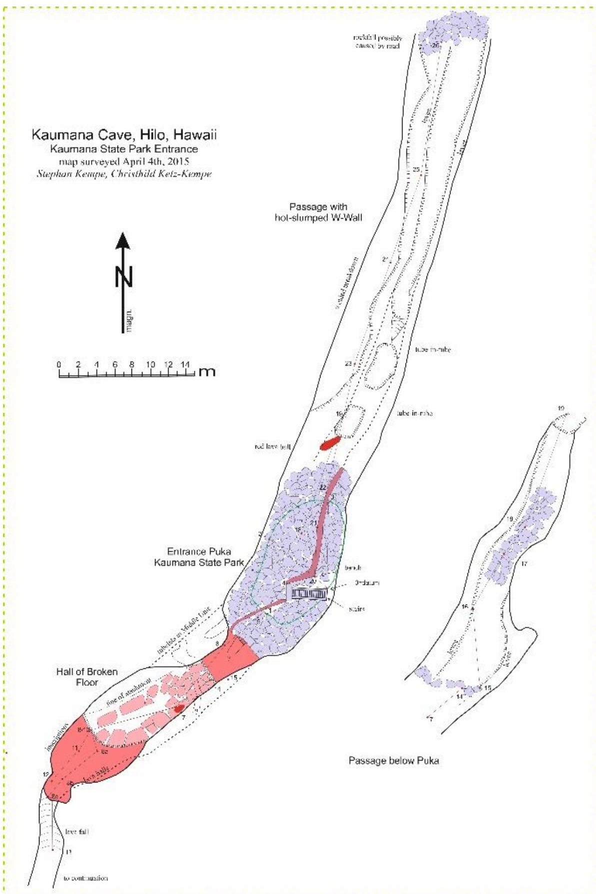

Figure 1.
Map of Kaumana Cave in the vicinity of the County Park Entrance. Dark red designates the secondary ceiling in the Hall of the Broken Hall, light red are the collapsed slaps of the ceiling. Light blue are cold breakdown blocks. The green line shows the perimeter of the puka.

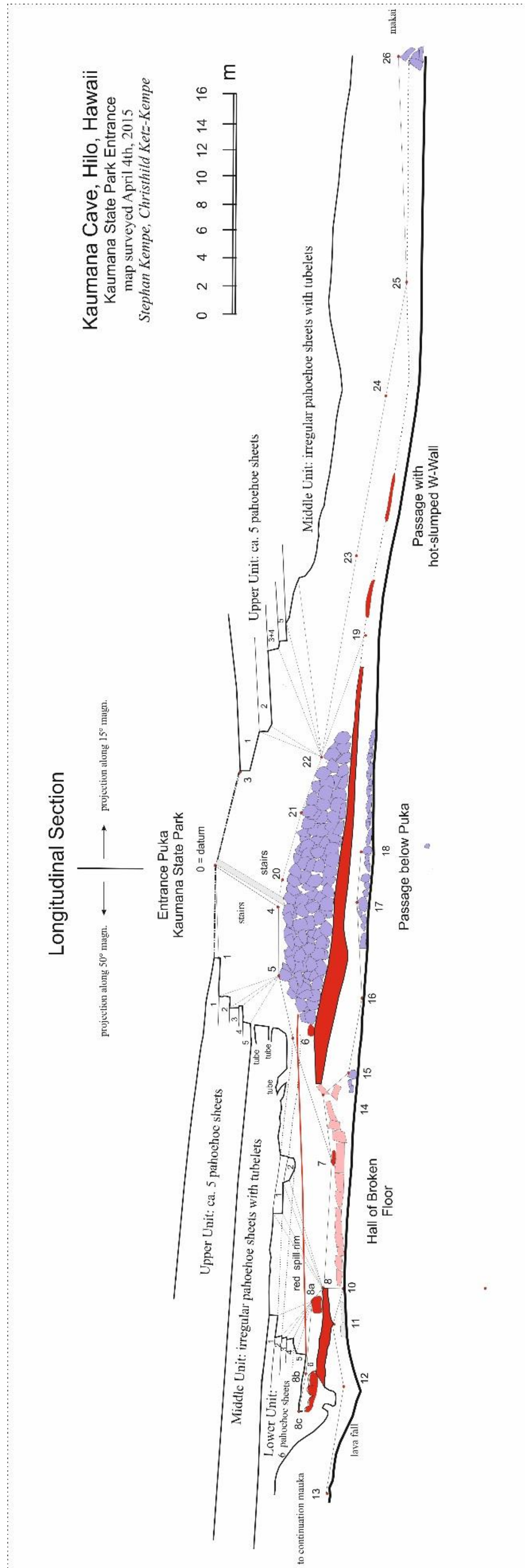

Figure 2.
Longitudinal section of of Kaumana Cave in the vicinity of the County Park Entrance. Colors as in Fig. 1.

Stratigraphic analysis of the Kaumana Entrance profile

In April 2015 we resurveyed a short section of Kaumana Cave (Fig. 1), both makai (downhill) (67 m) and mauka (uphill) (47 m) of the present day County Park Puka (collapse entrance). Between Stations 13 (most mauka) and 26 (most makai) the added main-passage length is 114.5 m (111.45 m horizontal). St. 13 is on the floor and at St. 26 the floor is 2 m below the station, resulting in a total vertical floor drop of 7.42 m. The floor thus has an overall slope of 3.8°.

This survey served to understand the stratigraphy of the lava exposed and to unravel the order of events that led to the formation of the pyroduct, its consequential enlargement and the collapse of the entrance puka.

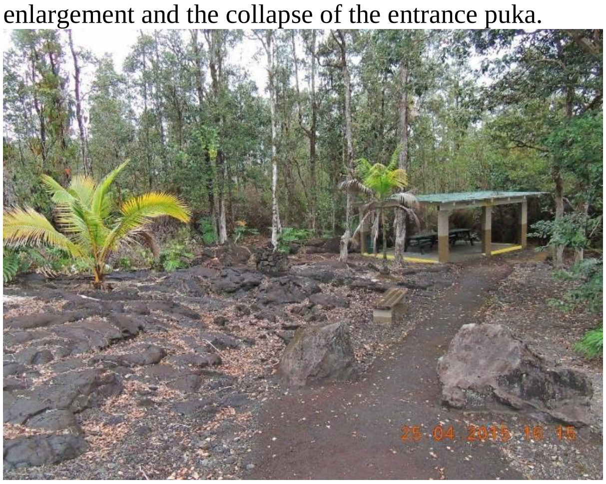

Figure 3.
Surface pāhoehoe sheets of the Upper Unit around the entrance of Kaumana Cave.

It turns out that the best information about the roof-structure is obtained in the mauka section of the survey, involving the W-wall of the puka and the adjacent “Hall of the Broken Floor” (HBF). Three units can be discerned (Fig. 2): The Upper Unit consists of the black, bulbous pāhoehoe sheets that form the present-day surface (Fig. 3). These layers, four to five depending on where one counts, and ca. 3.4 m thick, cause also the overhanging of the puka along its perimeter (Fig. 4). The Middle Unit is composed of irregular, well-welded surface lavas with short tubelets and cavities, about 3 m thick (Fig. 5). These are seen to the right of the mauka entrance in the wall of the puka and within the ceiling of the short passage leading to the HBF. The Lower Unit is composed of five to six lava sheets forming the HBF’s walls (Fig. 6), ca. 4 m thick. In the investigated mauka section of the cave only the two upper units are apparently well exposed.

Figure 4.
View of the Kaumana County Park puka looking mauka. Note the overhanging Upper Unit around the perimeter of the puka

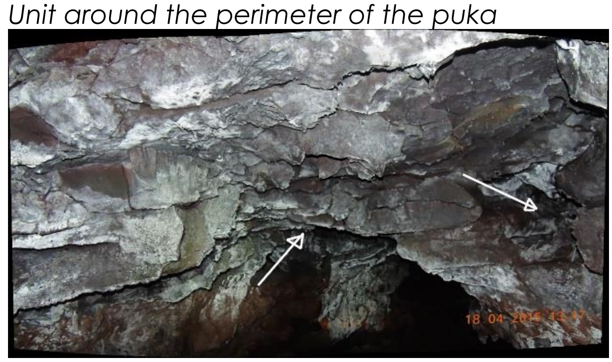

Figure 5.
Panorama view of the irregularly structures Middle Unit mauka at St. 6. Tubelets marked by arrows.

Because the sheets of the Lower Unit extend uninterrupted across the passage, they must be part of the original roof. The conduit must have originated below them. Thus the Lower Unit represents the primary roof. In the HBF the layers dip with about 3° makai. Since the layers appear to be mostly welded together and because they are rather regular in thickness, they can be interpreted as having been formed by inflation, i.e. the oldest sheet is the one on top, while the lower ones were emplaced by lifting the older layers up (Hon et al., 1994; Kempe, 2002). Thus, here the cave can be classified as an inflationary pyroduct.

The Middle Unit is more difficult to interpret. Most probably, it formed on the surface by overshooting, convoluted lava tongues. This could have happened after the primary roof formed (as a flow originating

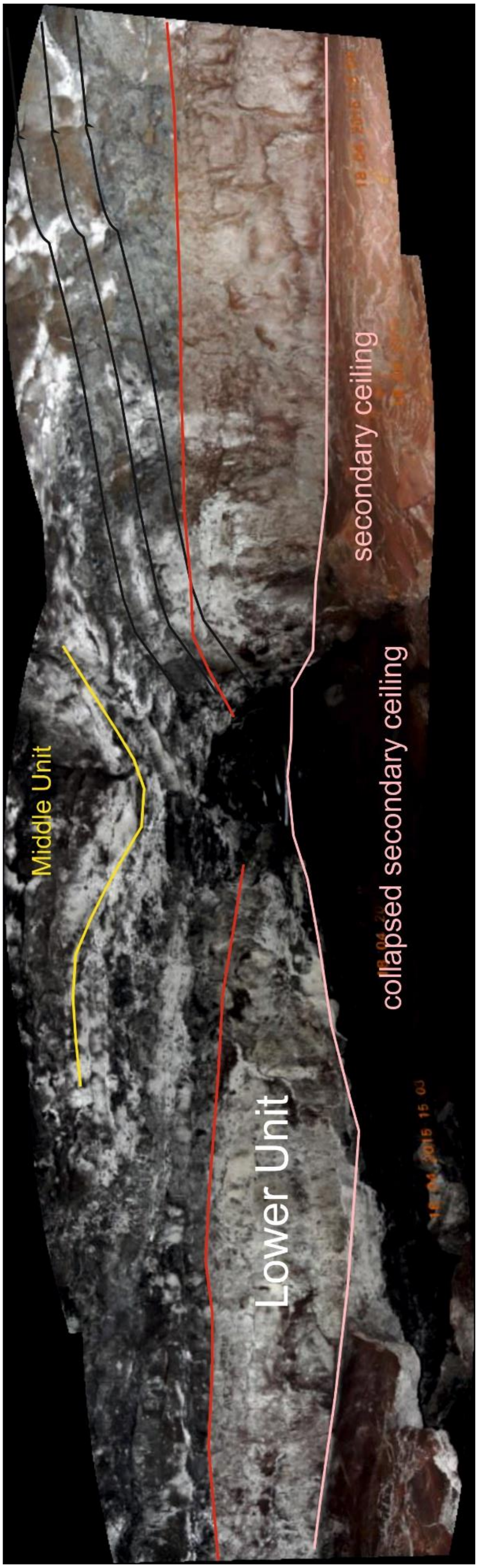

Figure 6.
Makai view of the "Hall of the Broken Floor" (HBR). Note the steeply inclining sheets of the primary roof (Lower Unit; black lines), underlying the Middle Unit (yellow line). Note also the horizontal spill rim of oxidizes red lava above the secondary ceiling that is collapsed in the center of the hall.

from an opening of the pyroduct above) or it could represent the actual flow front that was later uplifted by the inflationary sheets. If this is the case, then the Middle Layer should be the oldest of the series.

The Upper Unit finally seems to have been deposited onto of the lower two units in normal stratigraphic order, i.e. by consecutive, relatively cool and thick surface flows, originating from some source (an overflowing hot puka for example) further mauka.

Reconstructing the events forming the present cave

The entrance series offers many clues as to the order of events that took place to form the cave as it exists today. The first observation is that the cross-section of the cave varies substantially. Together with the fact that the primary roof is preserved only above St. 12 in full, one must conclude that the cave was enlarged mostly upward. In the HBF almost all of the primary roof sheets up to the Middle Unit (its underside forming much of the central roof) collapsed and were carried out. Remains of the uppermost layer still adhere at the ceiling above St. 7 (see longitudinal section). In the passage makai of the puka, roof and wall collapse occurred along the N-wall, involving mostly the Middle Unit and some sheets of the Upper Unit. The ongoing collapse is still clearly visible because the northern wall is characterized by a bench composed of welded breakdown material (Fig. 7). The ongoing collapse forced the lava river to flow along the S-side of the passage. This prevalence of upward enlargement, in contrast to downward erosion, was already documented in case of Whitney's Cave (Kempe et al., 2010).

The next most important feature in the cave is the existence of a secondary ceiling, dividing the cave into two levels. It begins mauka at St. 12 and extends to 2.1 m mauka of St. 19, passing underneath the puka. The ceiling (or, if standing on it, the false floor) is 59 m long. In the Hall of the Broken Floor, the ceiling collapsed for 14 m. Thus about 45 m remain to be added to the length of the surveyed cave.

The existence of this ceiling hints towards a source of cool air, which was most likely provided by the initial opening of the puka. The hot air convecting out of it was replaced by cold surface air, cooling the surface of the lava river. Prior to the opening of the puka much of the primary ceiling must have already collapsed and the material carried away. Along the puka's south wall, the collapse, however, was partially left in place, forcing the lava to flow along the N-side of the puka (see map).

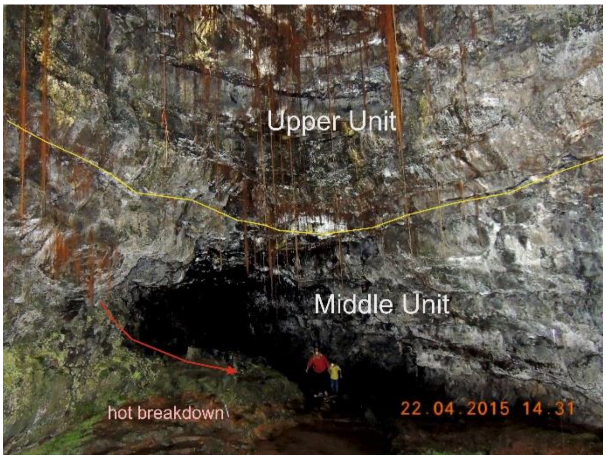

Figure 7.
View makai of the Entrance Puka into the main passage of Kaumana. The cave has been enlarged upward by collapses of the Upper Unit and the Middle Unit. Breakdown blocks from the left wall forced the flow in the cave to the right side, some of them were not only welded but also covered by the red spill (foreground left).

Figure 8.
Makai view from the "Hall of the Broken Floor" towards St. 6 and the Entrance Puka. Note the increase of the thickness of the secondary ceiling towards the puka. To the right is the entrance to the lower passage crossing underneath the puka. Note also the red spill rim on the walls. This event and the formation of the secondary ceiling and its red surface proves that the puka is a "hot puka", i.e., it opened during the final phase of activity.

The puka opening also caused a ponding of the lava within the HBF. Here the secondary ceiling does not show any inclination. In fact, the mauka rim appears to be 1.3° lower than the makai rim. This, however, is probably caused by the sagging of the secondary ceiling after the pool evacuated. Within the HBF, the secondary ceiling collapsed for 14 m, leaving a jigsaw of big plates on the floor. This collapse occurred after the activity terminated because plates do not appear to be encased by the lava flowing underneath. The collapse most likely occurred because the ceiling was not very thick in the center of the hall, in fact at least one degassing hole was noticed in the collapsed plates. At its mauka rim the ceiling is 10 to 20 cm thick and 50 cm thick at its makai rim (Fig. 8). Towards the puka the ceiling increases in thickness, a fact explaining that it is able to carry the load of the collapse blocks that accumulated on it after the secondary ceiling formed.

When crawling underneath the secondary ceiling below the puka makai of St. 16, one can find places where the lining of the secondary ceiling detached, depositing platy breakdown on the floor. At about St. 17 the inner structure of the ceiling is visible: it is composed of stone-sized, angular lithoclasts, held together by bulbous injections of lava ("squeeze balls") (Fig. 9). Therefore, this part of the secondary ceiling may have been caused by floating rock fragments welded by lava flowing over it, injecting the squeeze balls. These stabilized the ceiling in addition to the lining accreted from below. Roofs consisting of welded lithoclasts are seen in parts of Kula Kai and seem to be associated with the process of crusting-over of lava channels. Where these clasts came from is open to discussion. They could have been floating on the flowing lava, but then they should have been covered with a thin layer of lava (i.e., forming "lava balls") or they could represent fragmented puka collapse material.

Some of this intermediate puka collapse material is preserved also at the foot of the present- day puka collapse cone (Fig. 10). It is coated with a black lava veneer, indicative of a quick spill, possibly caused by ceiling or wall blocks splashing into the flowing lava before the secondary roof closed.

Figure 9.
Lithoclasts in secondary ceiling seen from below. Note "squeeze balls" solidifying the lithoclasts from above.

Figure 10.
Lithoclast from the makai foot of the puka collapse cone covered first with a black and then with a red lava coating.

Figure 11.
Mauka end of "Hall of Broken Floor" and origin of final lava spill. Note the hole above the secondary ceiling beneath the sheets of the Lower Unit, the primary, inflationary roof. From here a spill issued flooding the hall and leaving a thin, red glazing and a horizontal spill level. Note also the blocks that fell on the secondary roof and were covered by the spill.

The next event that is documented in this section of Kaumana, was a rapid inundation of the HBF with hot, fluid lava, followed by its quick draining. This event left a thin layer of red lava above the secondary ceiling with a horizontal rim along the walls of the HBF standing 106 cm high above the secondary ceiling at St. 6 (see Figs. 6, 8). It can be followed downward along the puka walls and further down the makai passage. It stood 30 cm above the level of the secondary ceiling at St. 22 in the makai passage, covering also the breakdown blocks previously covered with the black lava spill (Figs. 7, 10). The origin of this spill is the little passage above the secondary ceiling at the mauka end of HBF (Fig. 11). Here lava issued from the underlying lava fall passage (St. 13 to 12). In its ceiling, a hole temporarily opened, allowing the HBF to be filled with lava above the secondary ceiling. This opening closed quickly by being blocked with floated lava balls, seen both mauka (Fig. 12) and makai of the opening. It appears that the spilled lava was ponded behind the breakdown of the puka breaking finally through and emptying the pond quickly downhill.

Figure 12.
Spillhole seen from the inner side below St. 13 with lava ball stuck in the spillhole, closing it.

The spill covered several breakdown blocks that had dropped onto the secondary ceiling. Some sit on the mauka end of the HBF (Fig. 11), one on a collapsed floor slab and one on the makai end of the ceiling (Fig. 8). Another large one sits on the end of the secondary ceiling at St. 19 (Fig. 13). The lava of this spill is hematized (oxidized) at the surface, showing that the puka must have been wide open at this point in the cave development, allowing ample supply of oxygen.

Below the makai end of the secondary ceiling at St. 19, the open lava channel roofed-over along two short sections, forming a “tube-in-tube” structure. Further down, levees developed along the openly flowing lava river, marking the final structural alterations during the activity of the pyroduct.

Figure 13.
View of the end of the secondary ceiling at St. 19. Below, the passage issuing from underneath the secondary ceiling grades into a floor channel. Above it sits a collapse block coated by the hematized spill.

After the lava ceased to flow, more breakdown occurred in the puka and at St. 26. Here loose blocks spilled all the way into the leveed lava river bed. It can be suspected that this breakdown is caused by vibrations on Kaumana Road crossing the cave close by.

Observations beyond the surveyed section

Mauka of St. 13 the passage opens up considerably. The ceiling rises up to 7.7 m above the floor. Even though this passage looks like a canyon, it is genetically not. Rather it must have been enlarged by breakdown of ceiling and walls, i.e. by upward enlargement above the flowing lava river at its bottom. At the end of this passage the ceiling comes down abruptly (Fig. 14). Again, clearly discernable sheets form the ceiling across the now only 2 m high passage. These must be the inflationary sheets of the primary roof.

Makai of the Entrance Puka, a little beyond St. 26, the passage narrows again. The lava river undercut the N-wall exposing ‘a‘ā rubble. In way of a preliminary explanation the lava river may have cut laterally into the shoulder of an older ‘a‘ā flow. Continued collapse of the lateral wall may have caused the constriction, preventing that the upward enlargement of the cave formed a stable roof (Fig. 15). Small outcrops of ‘a‘ā rubble are already seen behind the lining at around St. 19.

Figure 14.
Sheets of the primary roof (Lower, sheeted Unit) visible at the end of the high passage, view mauka. The passage below is at the level of the original conduit. Makai of this the cave opens upward, looks like an erosive canyon, but is created by upward collapse.

Further makai the passage is divided once more into two levels by a secondary ceiling formed by the lateral growth of shelves (Fig. 16).

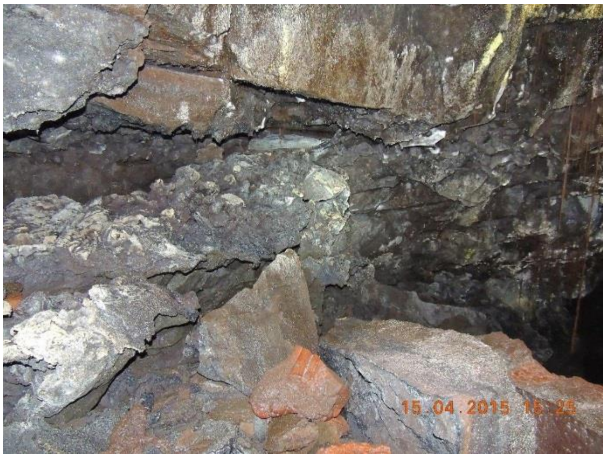

Figure 15.
Outcrop of ʻaʻā rubble behind the collapsed lining near St. 26.

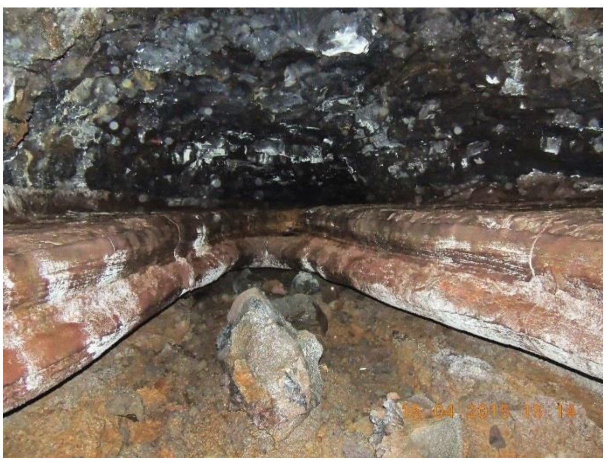

Figure 16.
Closure of secondary ceiling makai of surveyed section.

Reconstructing flow rates

Kaumana Cave is characterized by drastic changes in its cross-section. The surveyed part begins (St. 13) where both floor and ceiling slump down with >10°, narrowing the cross-section to less than 2 * 2 m. Thus, this constriction functioned as a kind of valve for flow in the passages makai. The lava passing through this valve excavated a shallow depression below the mauka end of the secondary ceiling as seen on the longitudinal profile (below St. 12, Fig. 1). Even though this "valve" has a larger slope than the rest of the duct, it nevertheless determined the discharge rate available for the advance of the flow at the tip.

The length of the 1881 flow below the section of the surveyed cave is about 5.2 km. Its width varies between 100 and 600 m. Since the initial flow line followed the morphological valleys (validated by the historic observations cited above) the thickness of the flow should be largest along the line of the evolving pyroduct. Since the roof of Kaumana Cave is about 10 m thick, the average thickness of the flow should be less. Assuming 5 m as an average thickness of the flow we obtain an estimated volume of 5,200 m * 5 m (600+100)m/2 = 9.1 10^6 m^3. For the time of activity, i.e. 46 days, the discharge rate must have been about 2.3 m^3/sec. With a cross-section of 3 m^2 at St. 12 a velocity of 0.8 m/sec is obtained. In larger cross-sections, like in the center of the HBF, the flow rate would be the same, only the flow velocity was less.

This calculation has one caveat, however, and that is connected with the observations presented for the stratigraphy of the Entrance Puka above. As described, much of the stratigraphic thickness is provided by surface flows that transgressed the primary, sheeted inflationary roof. Thus the transport rate calculated may present an upper value only. To resolve these questions we need much more information of the stratigraphy of the flow below the Kaumana County Park Entrance.

Conclusions

Kaumana Cave is a pyroduct that operated for a relatively short time (less than 50 days), nevertheless, it does not have the appearance of a "tube", simply "piping" lava downhill. Rather it displays rich morphological diversification. Within the short surveyed section mauka and makai of the County Park Puka, it is possible to construct the following order of events that shaped the present appearance of the cave:

(i) Deposition of a primary roof consisting of at least five lava sheets with a thickness of over 3 m by inflation (Lower Unit) and development of a proto-conduit below it;
(ii) deposition of a tube-bearing layer of small-scaled surface flows, 3 m thick (Middle Unit) on top of the primary roof;
(iii) deposition of another stack of 3.4 m thickness composed of about five pāhoehoe surface flows;
(iv) the effective cross-section of the conduit is probably in the order of 3 m^2 and the flowrate may have amounted to between 4 and 5 m^3/sec;
(v) the roof develops contraction cracks due to cooling, causing the collapse of sections of the primary sheets, blocks are carried out with the flow and the upward and lateral growth of the cave is initiated;
(vi) the lava begins to flow with a free surface throughout an open cave in most sections;
(vii) further breakdown at the site of the puka leads to spills of black lava across breakdown blocks, flow is forced to the N-wall below the developing puka;

(viii) collapse breaches even the thick pāhoehoe sheets of the Upper Unit forming a "hot puka" and a secondary ceiling begins to solidify below the puka; mauka the flow is ponded behind the puka collapse causing a rather flat surface of the secondary ceiling;
(ix) few additional collapse blocks fall onto the secondary ceiling; the puka enlarges;
(x) lava seeps through the ceiling of the conduit above the secondary, ponding in the HBF about a meter above the secondary ceiling temporarily because of puka collapse blocks,
(xi) the ponded lava breaches the collapse blockage and the lava spills out makai, leaving a thin layer of lava along the walls and breakdown blocks that is oxidized red by ample supply of air through the puka;
(xii) the lava river forms levees and a tube-in-tube structure makai of the puka;
(xiii) the eruption ceases emptying the HBF below the secondary ceiling that collapses in turn due to contraction cracks formed during cooling;
(xiv) further puka collapse deposits loose blocks on the secondary ceiling without breaching it, forming the present day 18*9 m large puka;
(xv) most recently, ceiling and wall collapse produce breakdown in the vicinity where Kaumana Drive crosses the cave makai.

With 4° the slope is higher than some of the Kilauea caves, but well within the range of published slopes for pyroducts (e.g., Kempe, 2012).

The example of this short survey once more shows that pyroducts do not follow the simple model implied by the term "lava tube". Rather, any initially lava-filled conduit is quickly, apparently within days, developed into an underground, gas-filled cave with a lava river flowing at its bottom. In case of Kaumana no time was available for substantive downward erosion but the analysis shows that upward enlargement can just as well cause the speedy evolution of a substantial cave volume. One of the next steps would be to estimate the volume of the cave and its evacuation caused by hot breakdown. One could than calculate ratios of lava flow versus lithoclast removal. One more unresolved question is, if these lithoclasts are just carried out, or if they are resorbed.

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COMPARISON OF MAIN ION COMPOSITION OF WATER SAMPLES FROM LAVA CAVES ON HAWAII, USA, AND JEJU ISLAND, SOUTH KOREA

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Abstract

In spring 2015 we collected twelve water samples from various caves and three from the hydrothermal seawater pool of Ahalanui Park in Hawaii. An additional nine samples, including one from the island's tap water, were collected from caves on Jeju Island, South Korea, in August 2015 (see Kempe and Woo, 2016, this volume). Temperature, pH and conductivity were measured in the field on most of the samples and major cation and anion concentrations were determined by ion-chromatography at the University of Hamburg. Results were given in mg/L (ppm) and then recalculated for their equivalent concentrations (meq/L) by division of the individual equivalent weights. Total Alkalinity (TA = bicarbonate) was calculated by the equivalent charge balance between cations and anions:

TA= sum of cations – sum of anions.

Only one sample (No.4, Pool Pa'auhau) showed a negative balance, suggesting a very low alkalinity. TA was therefore set to zero.

Results show a remarkable spread in the concentrations of Total Dissolved Solids (TDS in mg/L) (Fig. 1) as well as in relative composition (Figs. 2, 3). This came as a surprise since all samples (apart those from the thermal pool and the Jeju tap water) represent waters that

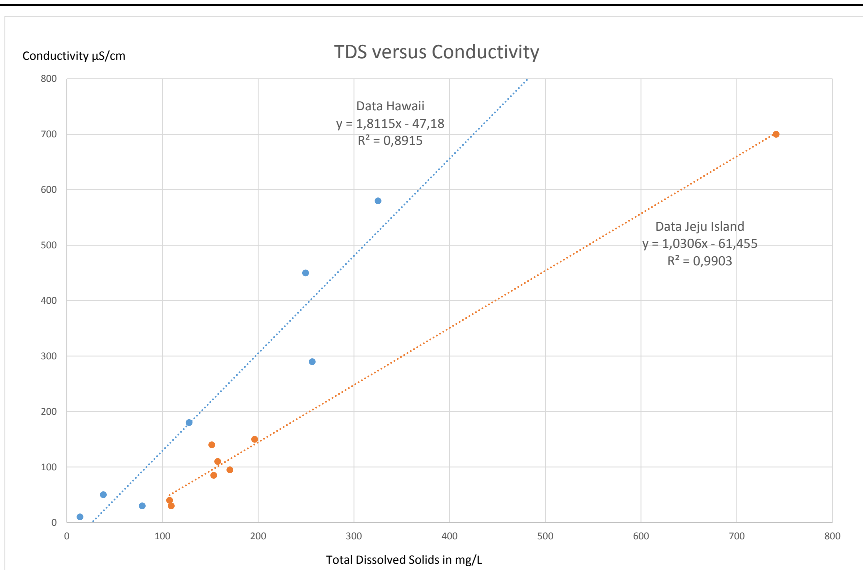

Figure 1. *Relation between TDS and conductivity for the two sample sets. Note the pronounced difference in the slope of the linear regressions possible due the higher relative divalent ion concentration) (Ca plus Mg).*

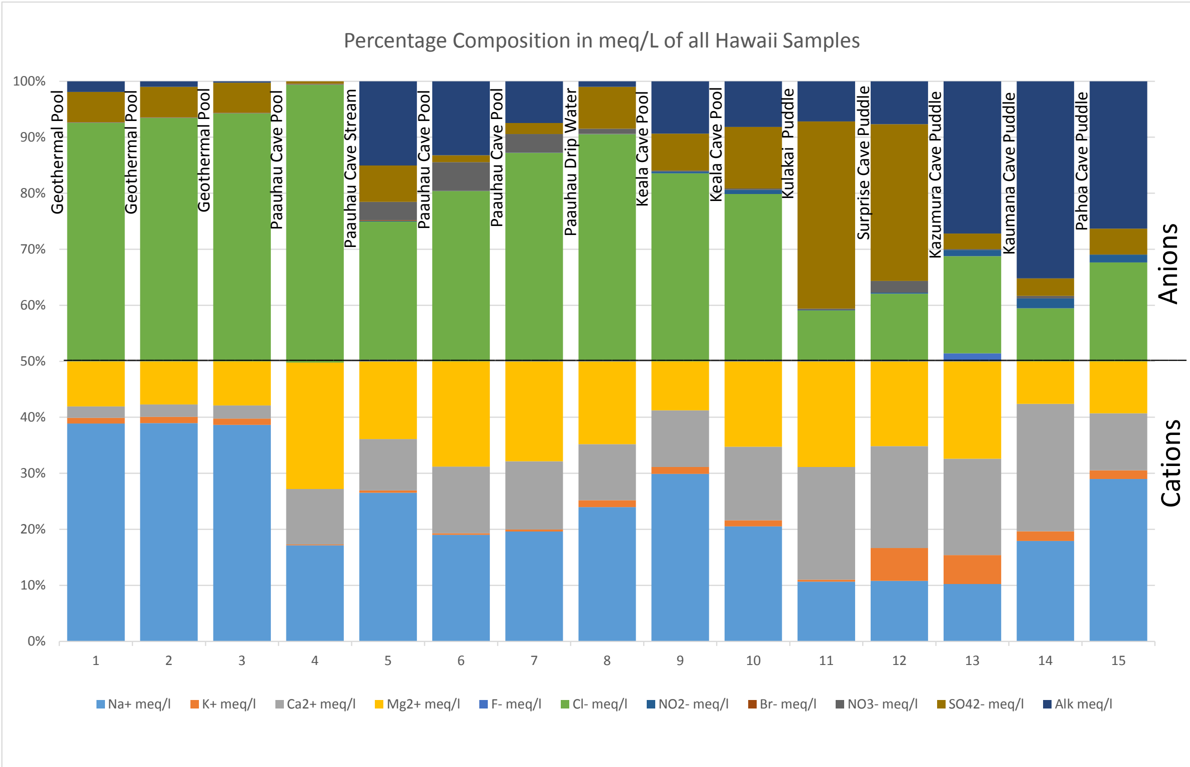

Figure 2.
Relative composition of water samples from Hawaii.

filtered through relatively thin cave roofs composed of basaltic lava. It was expected that they show a relatively similar composition and that only the total concentration (TDS) would vary due to different rates of evaporation. Figure 1 shows the correlation of TDS versus conductivity of the cave samples (where data are available).

The sample with the highest mineral load (2350 mg/L; No. 4 in Figure 2; not on Figure 1) from Hawaii is from a pool near the entrance in Pa'auhau Cave (Kempe et al., 2003). Its main anion is chloride. Its main cation is Mg followed by Na and Ca. From all cave waters these are also the absolutely highest Mg, Ca and Na concentrations (261, 375, 189 mg/L, respectively). This suggests that the pool (relatively near to the entrance of the cave) has been concentrated by evaporation and any alkalinity has been forced out of solution by precipitation of $CaCO_3$. The high TDS suggest that possibly also gypsum saturation had been reached.

The second highest concentrated sample (740 mg/l and 700 µS/cm) is not from an stagnant cave puddle but from a ceiling seep in Bilemot Cave (Jeju) that is not concentrated by evaporation but is characterized by a very high nitrate concentration (390 mg/L) (Sample point upper right on Fig. 1; No 4 on Fig. 3). Thus its mineral load must derive from agricultural drainage, not from the weathering of basalt.
The three hydrothermal pool samples show stable relative compositions similar to seawater. Their relative composition is clearly different for all other samples, showing that the cave waters are not derived from seaspray.

Overall the Hawaii samples seem to have higher relative sodium and chloride concentrations but lower total alkalinities than the Jeju samples. Tentatively this may suggest a quicker seepage because of younger ages of the lavas involved. Also Hawaii has higher sulfate relative concentrations suggesting that the younger lavas still leach more sulfate than the older lavas on Jeju.

The five samples from Pa'auhau Cave (samples 4 to 8) are all very different in terms of alkalinity content. From all caves sampled on Hawaii this is the geologically oldest (Kempe et al., 2003) but also the one with the thickest roof (about 10 m). Its magnesium concentration varies the most and sulfate is relatively low, again suggesting longer weathering history that gave time to remove most of the sulfur contained in the lava. Remarkable is also the high nitrate concentration, suggesting contamination by sewage. Sample 8, Pa'auhau

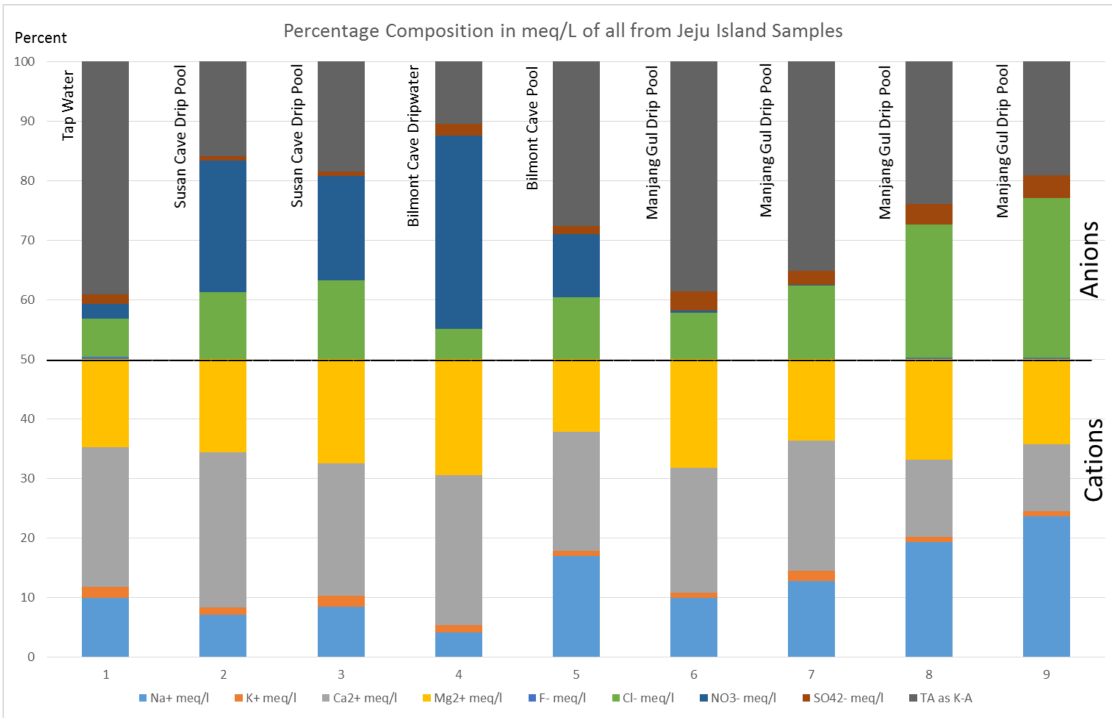

Figure 3.
Relative composition of water samples from Jeju Island, South Korea.

Dripwater, has also a measurable ammonia concentration (ca. 4 mg/L), suggesting input of raw sewage from the village above. Thus some of the variance in the Pa‘auhau samples may be anthropogenic in origin.

It was difficult to find puddles in Kulakai and Surprise caves large enough to take samples. These two caves are situated in the dry area of the Ocean View Area and therefore show high sulfate and calcium values in accordance with the wide-spread occurrence of gypsum in the area.

The samples from Kaumana (see Kempe and Ketz-Kempe, 2016, this volume), Kazumura and Pahoa Caves seem to form one group of high similarity, all with high alkalinities, collected in the windward, moist area of Big Island. Keala Cave is in the same area and should therefore be similar, but it is not. Specifically it has very low alkalinities. The reason for these differences remains unclear.

The samples from Jeju seem to fall into two groups, one with significant and even very large nitrate concentrations (Bilemot and Susan Caves) and one that has only very small nitrate concentrations. The latter samples derive from Manjang Gul, a World Natural Heritage Site that has no agriculture above ground.

Overall there seem to be three significant sources for cave waters: Precipitation (sodium and chloride), agriculture and sewage (nitrate, ammonia), and the products of rock weathering by carbonic acid (the bulk of the remaining ions). Both total concentrations and relative concentrations vary significantly. A dependence on the climatic situation and on the age of the rock and duration of weathering can be hypothesized.

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GEOLOGICAL OBSERVATIONS IN PYRODUCTS OF JEJU ISLAND (SOUTH KOREA)

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Abstract

Jeju Island, south of Korea, rest on continental rock but is covered by volcanics. About 130 lava caves are known. Several – among them famous Manjang Gul – are protected as World Natural Heritage sites. In August 2015 we investigated Bilemot, Susan and Socheon Caves to be possibly protected in that program as well. Bilemot is not only important because of its length of 11.7 km but also of its unusual braided structure. Susan Cave is special because it derived from a very low shield vent, hitherto not recognized as such, and because its lava contains enormous amounts of continental crust xenoliths, mostly white quartzite, unlike any other cave. Socheon Cave is special because of its pronounced downward erosion and its lower section containing secondary calcite speleothems.

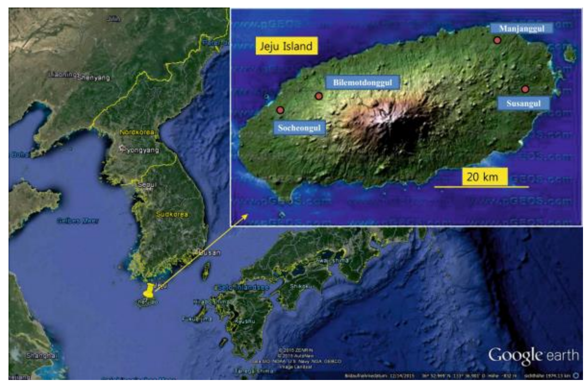

Figure 1: Google Earth view of the situation of Jeju Island at the southern tip of the Korean Peninsula and location of caves discussed.

Introduction

Jeju Island (Fig. 1) is entirely composed of volcanic rocks. It is classified as a composite volcano in spite of its shield volcano-like appearance (Yoon et al., 2014) with the Hallasan Volcano at the center. Furthermore, it rests on continental crust. If Jeju volcanism is driven by a hot-spot source or generated by magma, rising from the upper mantel along a tectonic fissure, is still in debate. So far, about 130 lava caves are known on the island. In so far Jeju and the importance of its caves has to be compared not so much with the marine hot spot- or fracture-generated islands like Hawai‘i, Iceland, Galapagos, Azores, Tenerife, Reunion, Easter Island and others, but with the intra-continental basalt fields such as those stretching from Jemen, through Saudi Arabia (about 10 caves), Jordan (20 caves) and Syria (2 caves) and the basaltic fields in the western and Northwestern continental US, in the Trans-Mexican Lava fields, along the shoulders of the East-African rift, the Aetna on Sicily, the basaltic lava fields of Eastern Australia (among them the Undara volcanic province) and a few other basaltic fields in Vietnam, China and Argentina. If compared with these areas then Jeju Island may have the highest lava cave density (possibly with the exception of Mount Aetna) of all of those. This underscores the overall importance of these caves for our understanding of continental basaltic volcanism and their importance for long-range lava transport.

Basics

Lava caves belong to the class of primary caves that form at the same time as the rock containing them. They are much less common than caves that form secondarily in soluble rocks such as limestone, dolomite, gypsum, anhydrite or salt. The first to bring lava caves to the attention of an educated readership was Olafsen (1774-75) who visited Iceland between 1752 and 1757. In the original description of Surtshellir (§ 358, p.130) he stated: „*Der fließende Hraun ist wie ein Strom durch diesen Canal geflossen;…*“ (i.e. “the running lava flowed through this channel like a river…”) (see Kempe, 2008). But even today lava caves are still under-researched and are treated as a mere curiosity in most volcanological textbooks. Exploration and survey of lava caves is mostly carried out by private caving organizations and not by the professional volcanological community.

While the lava flow advances with the help of the pyroduct, many processes can occur that shape the growing cave, so that very unique situations can arrive.

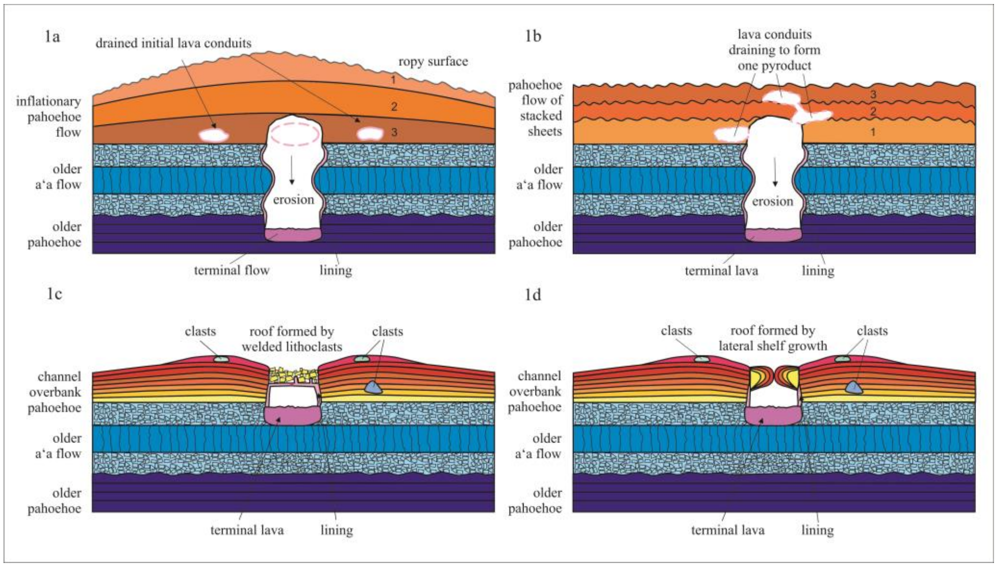

Figure 2: *Within the pyroduct type at least four different formation modes exist: Caves formed by inflation of the lava flow front and later downward erosion (1a), caves formed by coalescence of small ducts and consecutive downward erosion (1b), caves formed by the crusting-over of channels by floating lithoclasts, welded together (1c), and by channels crusted-over by lateral shelf accretion and consecutive closure (1d)*

Apart from a variety of short lava caves, some of them even forming secondarily such as sea caves, fissure caves, talus caves etc. the most important ones are “pyroducts” (for terminology and general volcanology see Lockwood and Hazlet, 2010) commonly also known as “lava tubes” (for review see Kempe, 2002 and 2012a). This cave type is intimately connected to the functioning of shield volcanoes. Pyroducts form during lava-producing volcanic eruptions, petrographically concentrated within the “basalt window”, including picrites, tholeiitic basalts and alkali basalts. They are built forward and downslope and serve to conduct lava gravitationally over long distances. As pāhoehoe (ropy lavas) lava flows advance, they internally form conduits that insulate the lava to such a degree, that it maintains its fluidity for many dozen kilometers. A lava flow with an internal pyroduct displays positively self-enforcing properties and lava is conducted within a flow not visible to the outside observer. Shield volcanoes would not come about without pyroducts, they serve to give this type of volcanoes their very gentle slope that may range from a few tenth to several degrees in inclination.

Thus, lava caves are a quite diverse natural phenomenon, not adequately described by the term “tube”. So far, we can differentiate between four different “modes” of generation (compare Kempe, 2012b), two involving the crusting over of lava channels and the others by strictly subcrustal processes (Fig. 2). The most widely spread mode in forming long primary lava caves seem to be the “inflationary” mode.

Bilemot Gul

With 11.7 km surveyed length, Bilemot Gul is currently the seventh longest lava cave known. It surpasses Manjang Gul, already part of the UNESCO World Heritage, by several kilometer (Ahn, 2010, quotes a length of 7.9 km, while Loyd, 1999, reports a total length of 8.9 km placing Manjang Gul at either eleventh or tenth on the list of the world’s longest lava caves; Golden, 08/2015 http://www.caverbob.com/lava.htm).

Inspection of the cave on August, 27th, 2015:
The available map of Bilemot Cave based on 3D scanning shows a bundle of passages that split and rejoin, forming a braided pattern. In the upper section (about 600 m) that we inspected all passages followed this basic scheme. Thus, they all belong to one flow event and can be, in spite of its braided property, be

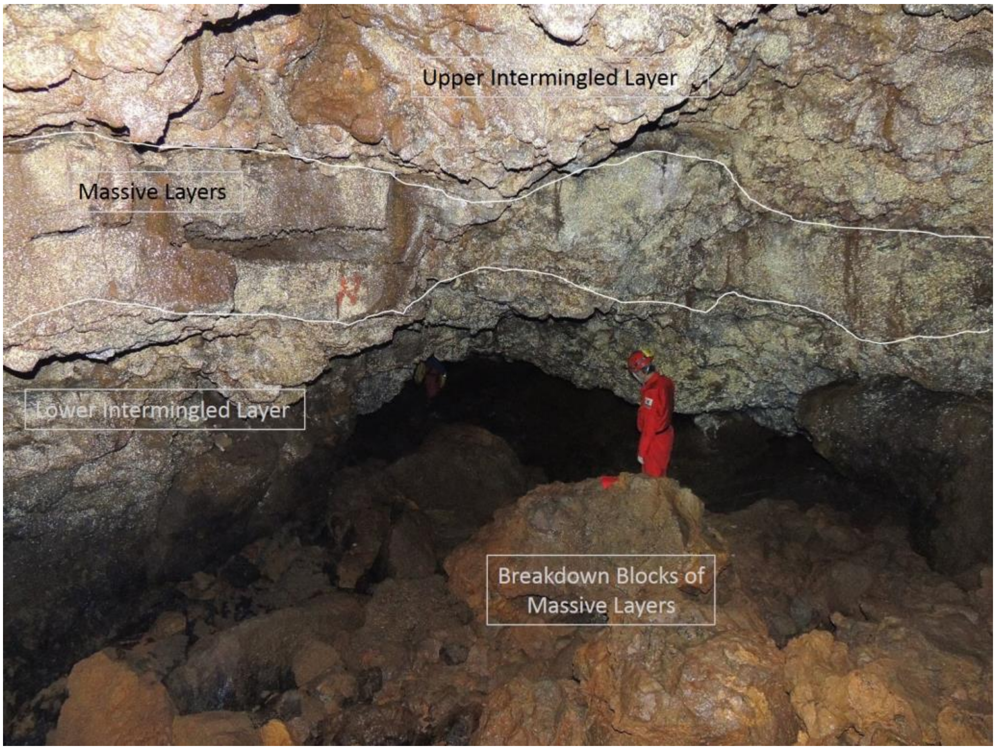

Figure 3: *View downhill in a typical breakdown-dominated passage of Bilemot with stratigraphy indicated.*

classified as a "mono-trunked" system (Kempe 2012a). In such lava conduits, many parallel passages develop initially, and, if activity is longer-lived, one of them will evolve to become the "master" or "trunk" conduit, draining the others one after the other as its collected flow power cuts down into the underlying strata. In Bilemot this downcutting is not very pronounced, it is a meter in places or less. This trunk passage is also followed by the recent water flow that caused noticeable water erosion on the bottom sheet of the cave, partly obliterating its pāhoehoe ropy surface pattern.

In order to understand in what "mode" a lava conduit has formed, it is important to study its roof structure. In case of Bilemot Cave this can be easily done as breakdown has occurred almost everywhere in the cave, opening the view into the internal composition of the roof. One can differentiate four units from bottom to top (Fig. 3):

1) The glazing of the lava conduit, consisting of an up to 30 cm thick dense, sometimes sheeted layer of black and shining lava, displaying "shark" tooth stalactites.
2) An "intermingled" unit, consisting of irregularly oriented fragments of pāhoehoe plates, and large "Pele's toes" mostly welded together by lava injected from above in the form of "squeeze balls". This unit is prone to breakdown due to its high degree of macro porosity and sometimes can be disintegrated by hand. Its thickness is variable and may be a meter or more. The general yellow color of this unit is in striking contrast to the black glazing. This color suggests that the unit was exposed to rainwater during its cooling, transforming some of the iron in the basaltic glass to the mineral goethite.
3) A massive unit consisting of a 1 to possibly 3 m thick, solid, dark-colored lava with large vesicles. It is structured by widely-spaced contraction cracks along which large blocks separated forming strikingly different breakdown blocks as compared to the intermingled unit. The massive layer seems to have pāhoehoe ropy texture. This unit is the source of the "squeeze balls" stabilizing the intermingled unit. It also seems to be responsible for the stability of the cave roof.
4) Above the massive unit there seems to be another intermingled unit, exposed only at places where the massive unit has collapsed and thus it is difficult to assess in its structure.

The three last units are best interpreted as representing two thick pāhoehoe flow consisting of fragments of the advancing flow-front buried below the advancing core of the flow.

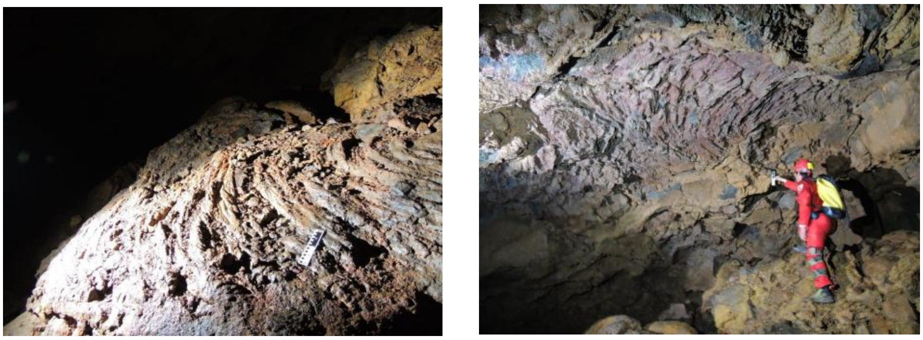

Figure 4: *Bilemot Cave: Pahoehoe ropy texture on top of the Massive Layers and the corresponding imprint of the breakdown block in the Upper Intermingled Unit. Scale-bar: 20 cm.*

This seems possible because the massive layer carries ropy signature on top, and the upper intermingled unit carries the negative imprint of this pattern (Fig. 3). The question remains, how then the conduits were able to develop below such a unit. The suggestion is, that the entire unit was inflated by another solid layer of pāhoehoe. This was easily done due to the high porosity and therefore overall low density of the units above. Within this sheet, the conduits developed initially and then quickly eroded part of the intermingled unit so that the cave developed more upward than downward. Thus, the down-cutting into preexisting subsurface seems to be minimal. For the time being, one has to assume that Bilemot Cave is an inflationary cave, albeit with a rather strange primary roof.

Two further observations are interesting; one is the development of "honey-comb like cupolas" and the other the discovery of an internal ʻaʻā flow:
Where the roof was formed by the massive unit during activity (i.e. in places were the lower intermingled unit had been removed by the flowing lava in the conduit) the blocks, defined by the contraction cracks, have been subject to intense heat, hollowing them out by partial remelting. The contraction cracks, being cooler and permitting gas exchange, remain as ridges, thus giving the ceiling the appearance of - albeit irregular – honey combs: The center of the blocks displaying cupolas (the chambers of the honey comb) and the contraction cracks protruding as ridges (the chamber walls of the honey comb). The resulting melt often is seen running down in thick, bulbous stalactites, another rare form not described yet from other places in detail (Fig. 4). All in all these forms of remelting must result within an environment of convecting very hot gasses. All this is not physically well understood, nor modelled.

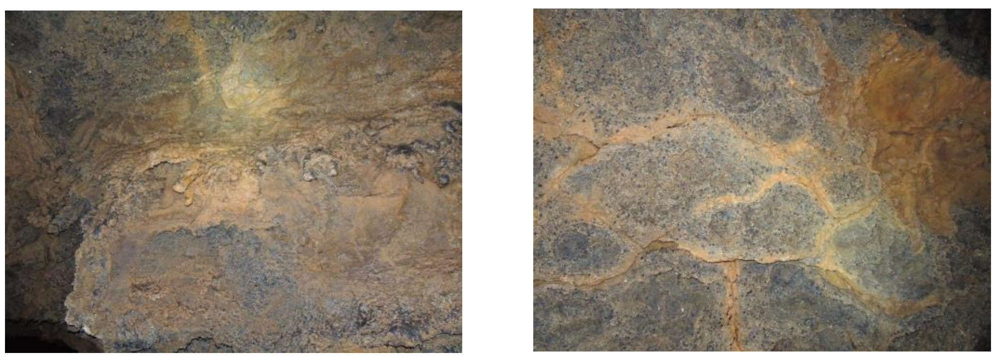

Figure 5: *"Honey-Combing", i.e. remelting of the interior of blocks defined by contraction cracks within the Massive Layers. Note (left) thick cylindrical stalactites caused by the running and dripping down of the created melt.*

According to the published geological map and the personal communication of Dr. Youngwoo Kil, the petrography of the flows in which Bilemot Cave occurs is of basaltic-trachy-andesite composition, i.e. the lava's composition is of higher alkali concentration than normal basalts. If this proves to be true (work is in progress by Dr. Kil), then Bilemot Cave would be the first described having this petrography world-wide.

The other interesting discovery was a 50 cm thick flow of welded ‘a‘ā rubble above the otherwise very smooth pāhoehoe floor of the cave (Fig. 6). Closer inspection showed that this flow originated nearby through a passage within the massive unit and represents a later intrusion from above, suggesting that the Bilemot flow was not the final lava covering this area. The intrusive flow at first has a platy appearance before is cascaded down into the main passage forming a large pyramidal column the foot of which turned into the observed ‘a‘ā flow unit, that flowed for less than 20 m along the floor of the cave.

Figure 6: *Front of later surface intrusion that turned to a 50 cm high front of welded ‘a‘ā at the tip of the flow. The floor below (foreground) is the flat pāhoe-hoe floor of the conduit.*

One more observation should be recorded: Just below the entrance on a shelf (formed by the cave-initiating pāhoehoe ?) there are many potshards with a few metal artifacts, obviously from the 20th century. How much potential for earlier archeological material the cave offers is hard to assess. Due to the water running in the cave, anything originally deposited near the entrance may have been eroded and washed further into the cave; but nowhere lithics (artefacts made of stone) or shards of older age have been noticed during our visit.

In summary, Bilemot cave is of global interest mainly due to three facts:

1) Its sheer length (7th world-wide) of 11.7 km;
2) its unusual braided structure unlike any of the other long lava caves;
3) and its development in a petrographically unusual rock type (basaltic-trachy-andesite) currently not documented for any other lava cave (pyroduct).

Overall, the cave is of world-wide scientific interest geologically and speleologically. Its biological and archeological potential should be evaluated separately. There is no potential to develop the cave for the public due to the overall small sizes of its passages.

Susan Gul

We visited Susan Cave (33°N25´26.1´´/ 126°E50´36.7´´) on August 28th.
Susan Cave is listed with 4.67 km length by Loyd (1999) and appears as the 24th longest lava caves in the world in Bob Gulden’s list. The Guidebook (2008) as 4.52 km long and states that it is not entirely explored and surveyed. The map shows a major branch north of the entrance and a long meandering passage with a few oxbows and short blind side passages.

Figure 7: *Showing the entrance to Susan Cave on an inconspicuous topographic rise, possible a shield (left Aug.20015, right Sept. 2008). Pāhoehoe lava in foreground left appear tilted by inflation and could be direct outflows from hidden vent.*

The small entrance is situated on a local high point and surrounded by a fence (Fig. 6). As such, this is not uncommon for lava cave entrances since the pyroducts very often are below the center of a flow ridge. Nevertheless, this observation will play a role in the conclusions to be drawn below.

The 3 m deep entrance drop leads unto a pile of breakdown blocks rocks (Fig. 8). First, we proceeded south along a meandering main passage that appears to become smaller in cross-section downhill. Since there is hardly any breakdown, there is no way to look for stratigraphic information. The floor is rather smooth and shows deep contraction cracks in places, indicative of a relatively thick bottom layer, such as arises from local ponding of final lava. A few small lava falls and lava cascades occur along the first kilometer, indicative of possible downcutting.

Figure 8: *Views of the southern main passage towards the entrance (left). It appears as if there is much more breakdown than actually is missing rock mass on the ceiling. View uphill of the main passage below the entrance (pictures 2008).*

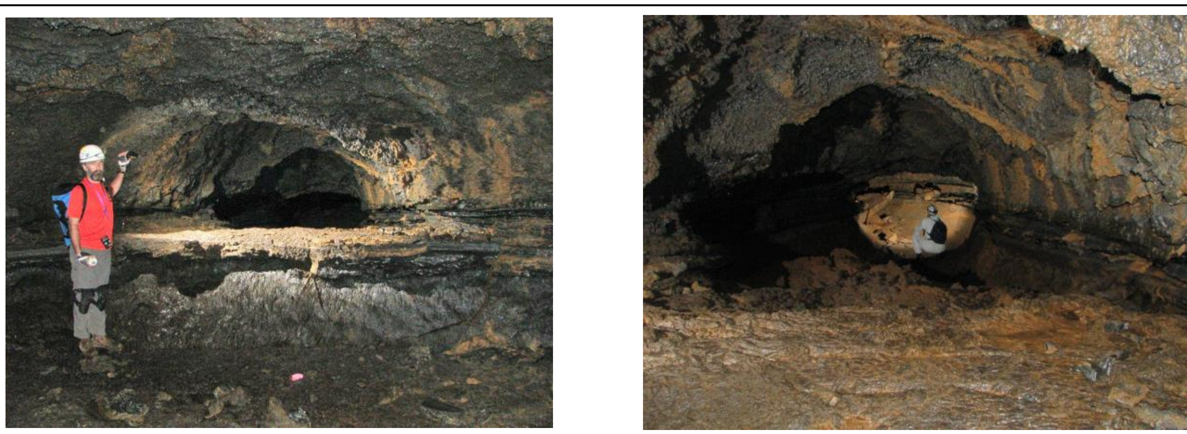

Figure 9: *Entrance to oxbow, that is dammed off by a levee (left) and view across the levee into the oxbow that is today 35 cm deeper than the main passage where caver (to left) stands (pictures 2008).*

At the point where the cave begins to trend toward the SE a side passage enters, that ends blindly because it was backfilled by lava from the main passage. It starts behind a levee, indicative of a later rise in the lava level in the conduit. Where the passage originally branched from the main passage is not seen and may be hidden by this diagnosed later rise in lava level behind the intact glazing. A little further, there is an oxbow, but again, entrance and exit of it are blocked by 1 m high levees build by flows from the main passage into this cut-around (Fig. 8). It is interesting to note, that the floor of the side passage/oxbow is 35 cm lower than that of the main passage. This can only happen if after the initial downcutting of the main passage below the level of the side passage and its consecutive draining, the level in the main passage rose again, building a levee towards the side passage, incompletely filling it and then failing to drain the main passage completely. That there is a thick level of lava on the floor of the main passage is also indicated by deep contraction cracks in the floor.

At this site a lava fall is found as well (Fig. 9). On its one side (Fig. 9) and uphill of it the lining came off (Fig. 10) revealing an at least 1 m thick loose reddish rubble and coarse sand. This layer, without closer analysis, seems to be tephra; ‘a‘ā rubble would not have a sand-sized component. Thus, the conduit has encountered here tephra from a nearby cinder cone. Its erosion was easy and an undermined notch in the lower wall is well visible. Above the tephra a solid, 1 to 1.2 m thick layer of pāhoehoe lava (probably consisting of two sheets) is protruding from the wall. Its lower face shows tephra that was welded onto it as the hot lava crept over the tephra deposit. These pāhoehoe sheets must have contained the primary conduit that later was enlarged to become the present cave. Above this solid pāhoehoe layer, we encounter a reddish intermingled layer, about 1 m thick. Like the intermingled unit in Bilemot, is consists of lithoclasts welded together by “squeeze balls” injected from above. Further down-passage this intermingled unit collapsed as well, exposing an at least 2.2 m thick massive layer, that guarantees the stability of the cave’s roof. Similar to Bilemot, this sequence probably belongs to a first massive pāhoehoe layer, that was later uplifted by the lower two sheets. Thus, here we have evidence also of an inflationary origin of the cave.

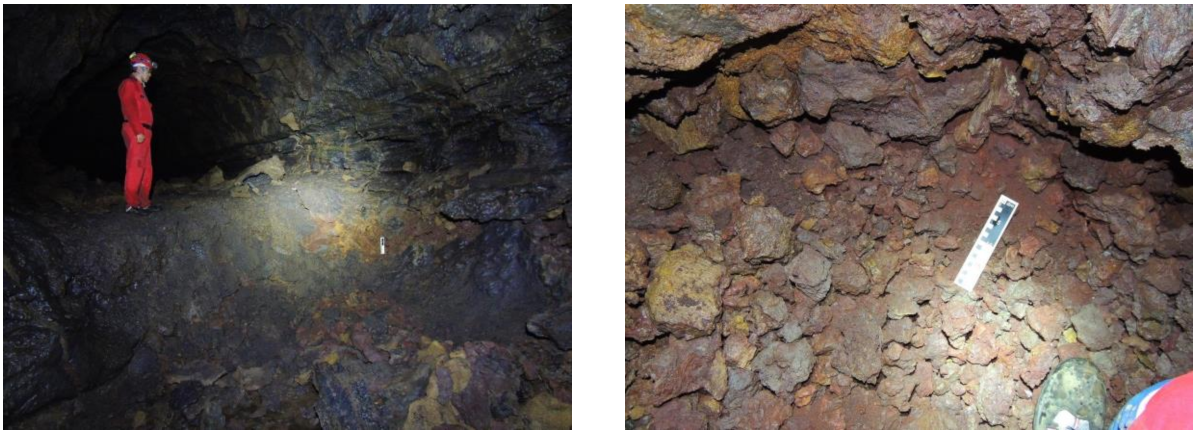

Figure 10: *Lavafall near the entrance to the oxbow (left) that excavated tephra as visible below the lining (right). The tephra is composed of lapilli and coarse ash (right) (scale bar 20 cm).*

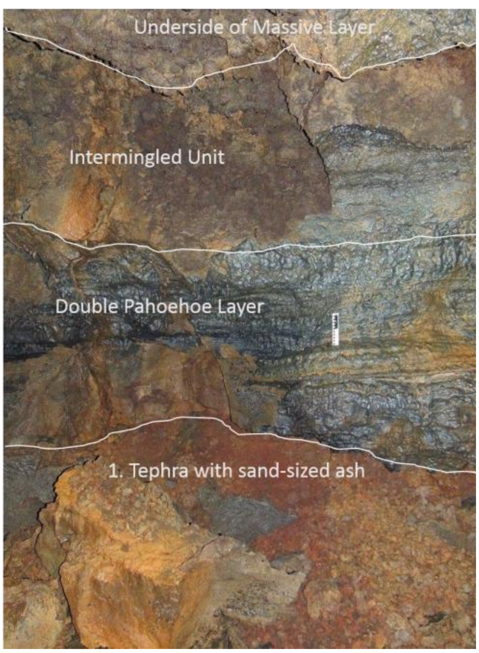

Figure 11: *Stratigraphy of Susan Cave near the first oxbow above the lava fall in Fig. 9, right wall looking uphill (scale bar 20 cm).*

Near the lava fall, the ceiling shows pronounced “honey-combing” (Fig. 12), just as in Bilemot. It developed in the uppermost massive layer. The interior of the blocks are deeply hollowed-out by melting, while the colder contraction cracks form ridges. Some of the blocks have concave cavities, up to 30 cm deep. Remains of the melt cling to the lower lips of the cavities, but different to Bilemot, no thick cylindrical stalactites formed. Honey-combing is also often seen in the ceiling of the passage uphill.

After clarifying the stratigraphy, we turned around and went back to the entrance to look at the “upstream” section. However, after a few meters we found a small lava fall going down and about 50 m in we encountered a large lava fall, also going down five meters (Fig. 13). We were extremely puzzled, how could the passage go down into both directions? Why did nobody wonder about this during the excursion in 2008 (including the author?). But, there is no doubt, the entrance marks the

Figure 12: *Showing the deep „honey-combing" in Susan Cave in the ceiling, signs of remelting the interior of the still hot blocks of the upper massive layer while the colder contraction cracks form ridges.*

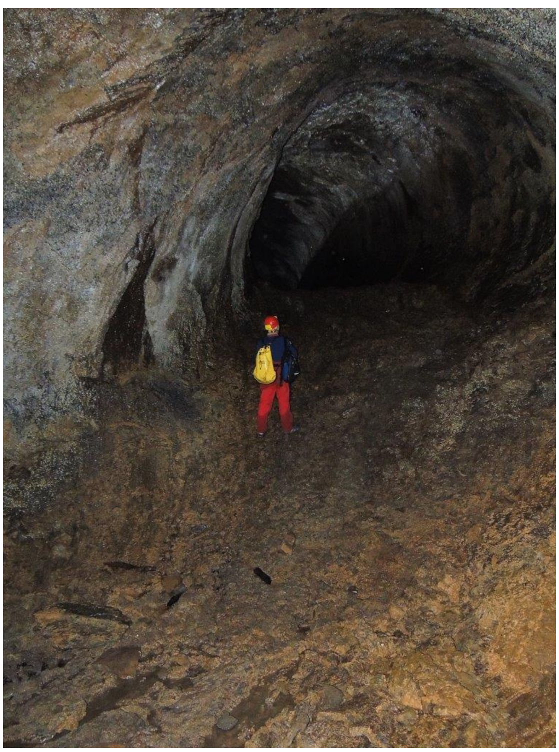

Figure 13: *Ca. 5 m high lava fall below the entrance towards the NE looking uphill.*

highest point in Susan Cave. Therefore, there must have been a vent below the entrance, from which lava was erupting and going downhill into two directions. No other likely explanation can be offered. This is in accordance with the observation that the entrance is on a high point (compare Fig. 7), now to be interpreted as a low shield volcano issuing basaltic lava. So far I know of only one example were the vent of a shield volcano is directly below a cave and that is in a small, unnamed shield on the SW rift of Kilauea, Hawai'i (Kempe, 1999).

Just beyond the lava fall is a large hall (Fig. 13), stretching at right angles right and left. It is filled with huge breakdown blocks from a single massive pāhoehoe layer. The ceiling does not offer any stratigraphic information. At this point we only can speculate what that means. One possibility is that we are below the filling of a lava pond, filling a former depression. This was not the only surprise, even more surprising was the petrography of the lava: it is packed full of xenoliths. Most of them are milky metamorphic quartzite (Fig. 14), just as seen in Manjang Gul, but other components occur as well: gneiss, metamorphic schists and metamorphic sediments and possibly granites, just to name a few that we saw (Fig. 15). To the right, the passage goes on for some time, it becomes very low, and the slightly convex floor suggest a ponding of the terminal lava. Similarly the passage ponds to the left in two short annexes.
One more geological interesting observation was made: along the far wall piles of welded plates are found (Fig. 16). These must have shed off the wall while cooling, suggesting that this part of the cave has been very hot for a long time, even after the flow had subsided. This would be in accordance with the suggestion that the hall is below a very thick unstructured filling of a lava pond.

Last but not least, we found reed torches and remains of reeds (Fig. 17). This could be an interesting archeological finding, worthwhile to try dating by C^{14}. It looks as if someone had explored this part of the cave with very primitive lighting.

Figure 14: *Panorama view into the large hall filled with large breakdown blocks which feature a large number of xenoliths, largely of quartzite.*

Figure 15: *Breakdown blocks with large quartzite xenoliths.*

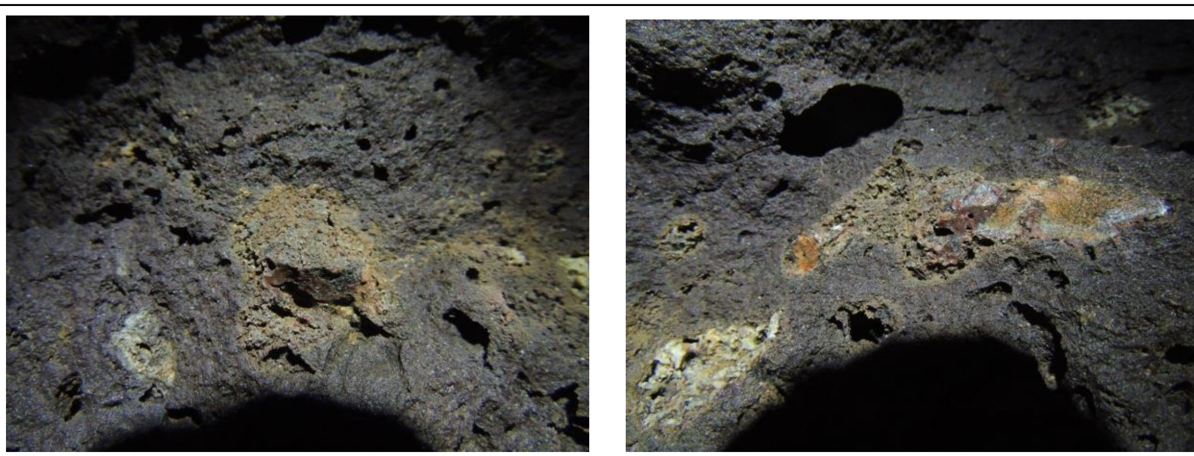

Figure 16: *Various kinds of continental crust xenoliths.*

In summary Susan Cave is of world-wide interest because of two facts:

1.) It is the only cave yet described as deriving from a hidden shield vent.
2.) It displays the richest, yet described in a basaltic lava occurrence of continental crust-derived xenoliths.

Figure 17: *Welded plates that fell off the wall while the cave was still very hot. Note drip stalagmite left of scale bar (20 cm).*

Figure 18: *Remain of a reed torch of unknown antiquity. Scale bar 20 cm.*

Susan Cave is furthermore in an amazingly pristine state of preservation, featuring no garbage nor any other alteration by man (save the survey bolts).

Socheon Gul

The visit to Socheon Cave (33°N21´53´´/126°15´37´´) on August 29th was relatively short. Socheon is listed as 3,074 m (Loyd, 1999) or 3,100 m (Guidebook, 2008), but these numbers are referring to its state before the newly opened section. We therefore first visited the

Figure 19: *Newly dug and secured Opening 3 of Socheon Cave. Note fence and retaining wall around perimeter. At the bottom cave opening leading into newly opened section.*

newly dug entrance (Opening 3) and then went into Opening 1 (the main entrance to the cave) and proceeded underground to shortly beyond Opening 2.Opening 3 is about 10 m deep and was recently dug out and consolidated by civil engineering measures (Fig. 19). It features a metal fence around its perimeter, topped by barbed wire coils. Inside this about 25 m wide enclosure and leaving an about 2 m wide terrace a retaining wall build of large lava blocks rests on the bed rock of the cave's roof. It forms another about 1.5m wide irregular terrace, not actually wide enough for safe navigation. No specific anchor points for cable ladders or rope descent were constructed. Therefore, the fence posts serve as anchors if needed. The cave's roof itself was punctured by an about 7 m wide collapse hole. The walls of it are overhanging on all sides for about 5 m. Cave passages lead off to both downhill and uphill. Both seem to be wide open.

This amazingly affluent construction, however, does alter the entire cave climate fundamentally, possibly with highly unwanted consequences (see below).

We then proceeded to Opening 1, next to the street. It is also gated. The entrance is a typical "cold collapse", i.e. a collapse the happened after the cooling of the conduit.

It occurred because at this site the roof was relatively thin. Figure 19 shows its structure: The roof consists of a series of pāhoehoe sheets, with the top sheet being the thickest. This is typical for "inflation"-type roofs (see Fig. 1), whereby the top layer was emplaced first and the consecutively thinning (and hotter) layers were injected below, thus "inflating" (or lifting) the first sheet. Within the last injected sheet, which is the hottest, the proto-cave was initiated, providing for rapid transport of the hot lava to the tip of the flow. This is seen at the lower entrance opening where the lining of the pyroduct is still intact just below the primary roof. After having climbed down the entrance breakdown pile, one stand in an irregularly shaped canyon (Fig. 21), suggesting that the cave has cut down into older layers. The slope is relatively high, certainly higher than in Manjang Gul. Other than in Manjang Gul and Susan Cave, there are several, short side passages branching off at a high level about 3 m above the floor. Below two of them are artificial rock piles, as if made to support short ladder to reach theses passage. These short passages, ending blindly according to the cave map, are typical for the level of the primary conduit, when several ducts developed in the beginning of activity (such as also seen in Bilemot) in parallel. As the main conduit started to cut down, they drained and were often filled at their upper ends.

Figure 20: *Panorama view of Socheon's cave roof, view downhill at Opening 1. Note the continuous thick primary sheet and the much thinner layers injected below, constituting the inflation of the lava flow.*

Figure 21: *View into the canyon of Socheon Cave below Opening 1. Note prominent ledges, most probably remains of the core of an 'a'ā layer eroded through, note also deeply undercut walls where 'a'ā rubble was removed.*

Figure 22: *View uphill into the Opening 2 of Socheon Cave, created by a "cold breakdown". Note Prof. Woo for scale.*

The canyon-shaped passage continues downward including a few not-too-steep lava falls or lava cascades, again suggesting active downcutting. After passing the big rock-fall that created the second opening (Fig. 22), the right wall is well accessible to stratigraphic studies because of substantial rock-fall off ceiling and walls.

At the ceiling, a layer with an imprint of pāhoehoe ropes is seen. Since (compare Fig. 2) in an inflation roof, only the top layer has ropy surfaces, this means that the primary ceiling at this site was superseded by another (or several) further pāhoehoe sheets by later flows. These flows could be generated by a breakout of the pyroduct uphill, by neighboring flows of the same eruption or even by much later, independent eruptions. It all depends if the breakdown occurred during activity ("hot breakdown"), then the superseding flow was of the same eruption or after the conduit cooled ("cold breakdown"), then the superseding flow could be of the same or a later eruption. Due to the presence of a large amount of breakdown, it must be assumed that this is a cold breakdown (otherwise it would have been removed by the active flow) and that it cannot be decided if the superseding was of the same or a later eruption.

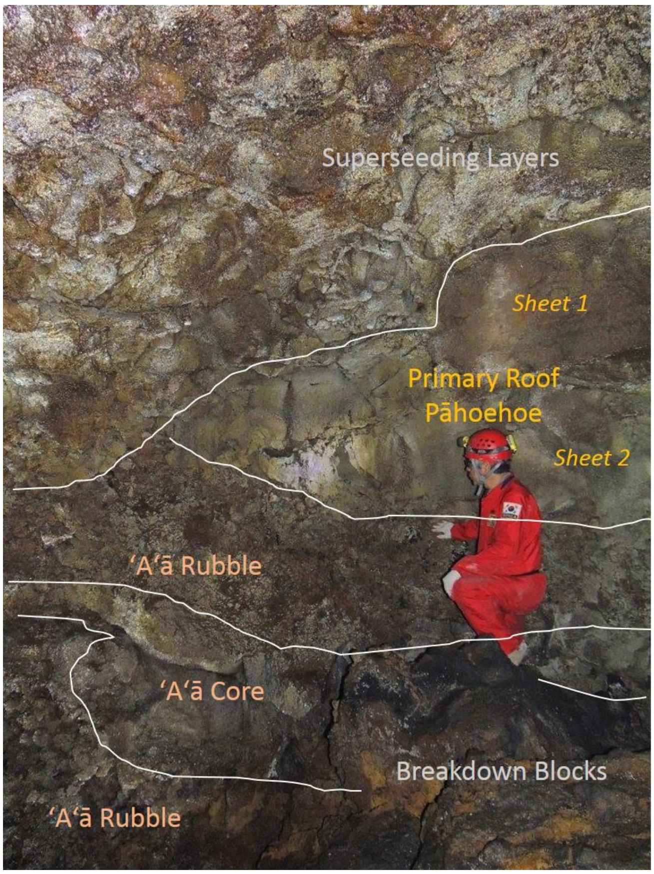

Figure 23: *View of right wall below Opening 2. Due to pronounced breakdown of the walls, the layers composing the side of the cave are exposed. It appears as if the primary pāhoehoe sheets superseded an 'a'ā flow and pinched out laterally. Later a pāhoehoe surface flow superseded the primary roof replacing it as roof material due to cold breakdown.*

Along the walls another interesting observations can be made: Here layers of 'a'ā are seen, consisting of typical, fist-size rough clasts, mostly not fused (Fig. 23). Between these rubble layers the about 1 m thick core of the 'a'ā flow is noticed. Since pyroducts do not develop in 'a'ā flows at low slope (at least none are known), the discovery of these layers in the wall of the cave suggest substantial downcutting, substantiating the observations stated above about the canyon-type passage. It is logical that the erosion of 'a'ā rubble is easier than the erosion of massive 'a'ā-cores or pāhoehoe sheets. Thus, the passage shape depends very much on what substrate the pyroduct encounters: Where 'a'ā rubble is encountered the passage can become wider and deeper, where other layers are encountered, the passage shows protruding ledges and may be less wide and deep. These observations show, that Socheon Cave was substantially enlarged by downward erosion, much more than in the case of Bilemot and Susan caves.

The map of Socheon cave shows a mono-trunked patter with a few oxbows and early, high level, partly filled side passages and one larger side passage. Such pattern arise if the lava flow splits and progresses into two adjacent depressions. Normally one of them will stop to be delivered with hot lava as the other one erodes down more quickly.

Socheon, of the three caves visited, has the largest bat colony. We noticed possibly several hundred bats, hanging and flying, while only one flying bat was seen each in Bilemot and Susan Caves. In Socheon, the bats have colored ceiling cupolas, used as roosts, pitch black and bat guano covers the floor with black smear. One bat skeleton was found on the floor (Fig. 24). Flies were abundant in the section between the entrances. The cave also offers archeological potential. The two cairns were mentioned already. Near the first entrance several stone rings are present, used for fires.

Figure 24: *Bat skeleton found near the entrance in Socheon Cave.*

When judging the importance of Socheon (for example as an eminent example of lava erosion) one must critically evaluate the new, third opening. Cave air flow in general is governed by the temperature difference between the cave (hoovering at around average annual temperatures of the respective latitude and altitude) and the size and altitude differences of the entrances. In case of Socheon, the third entrance altered the existing pattern of air flow fundamentally. Before its opening the section below Opening 2 was, meteorological speaking, a cold air trap. Because the altitude difference between the upper two entrances is small, the air flow there must have been minimal also. With the opening of the lower entrance, cold air rapidly flows out of the system, being replaced by warm air in summer. In winter, the opposite occurs with warm air rising from the upper two entrances and colder air being drawn in at the bottom. Thus, the area where the bats roost experiences much a higher annul temperature variation than before. Furthermore, the fast air exchange will cause a quicker drying out of the cave. Bats that are relying on constantly deep temperatures and a high humidity for their hibernation, may either be in danger of dying or they may decide to look for more constant conditions. These constant conditions they may now find in the section below the third entrance, Opening 3 that is now playing the role of cold air trap. Thus, it is possible that the bats move there. With their urine and guano, they will destroy the very features to be protected: the beginning of a brightly white calcitic secondary speleothem growth.

What this climatic change means to the other cave fauna will need to be explored as well. One more change is provoked by the third entrance: as the air in this section will be exchanged during cold nights in winter, the CO_2- pressure of the air will be lowered on average; compared to the conditions when this cave section was without a rapid air-exchange. This should enhance degassing and speed flowstone growth; but is that what is wanted? These are not the natural conditions that should be protected.

Note added in proof: It was recently decided to reinstall the original meteorological conditions at the new opening.

Acknowledgements

This study was made possible by travel support from UNESCO, World Heritage Program. In the field we were competently supported by Dr. Ryeon Kim, Cave Research Institute of Korea, Dr. Ung-San Ahn, World Heritage and Mt. Hallasan Research Institute, and the indefatigable Mr. Jae-Hoon Choi, Cave Research Institute of Korea and Christhild Ketz-Kempe, Germany.

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PYRODUCTS, THE THIRD MOST COMMON CAVE TYPE ON EARTH

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Abstract

After limestone and gypsum, lava is the third most important cave-bearing rock on Earth. In contrast to the standard notion that lava caves are simple, uninteresting and featureless circular or semicircular "tubes", many different processes serve to create a score of various lava cave classes, with more being discovered (Kempe, 2002, 2012b). The most important type is longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas. They act to build low-slope (often < 2°) shield volcanoes. Initially reported from Iceland, they were first observed actively forming in Hawaiʻi and in 1844 named "pyroducts" (Coan, 1844; Lockwood and Hazlet, 2010). Within the pyroduct type at least four different formation modes exist (Figure 1; Kempe, 2012a)): Caves formed by inflation of the lava flow front and later downward erosion (1a), caves formed by coalescence of small ducts and consecutive downward erosion (1b), caves formed by the crusting-over of channels by floating lithoclasts, welded together (1c), and by channels crusted-over by lateral shelf accretion and consecutive closure (1d). Thermal erosion, probably both by re-melting and mechanical processes, ensures that a gas-filled cave is already created during the

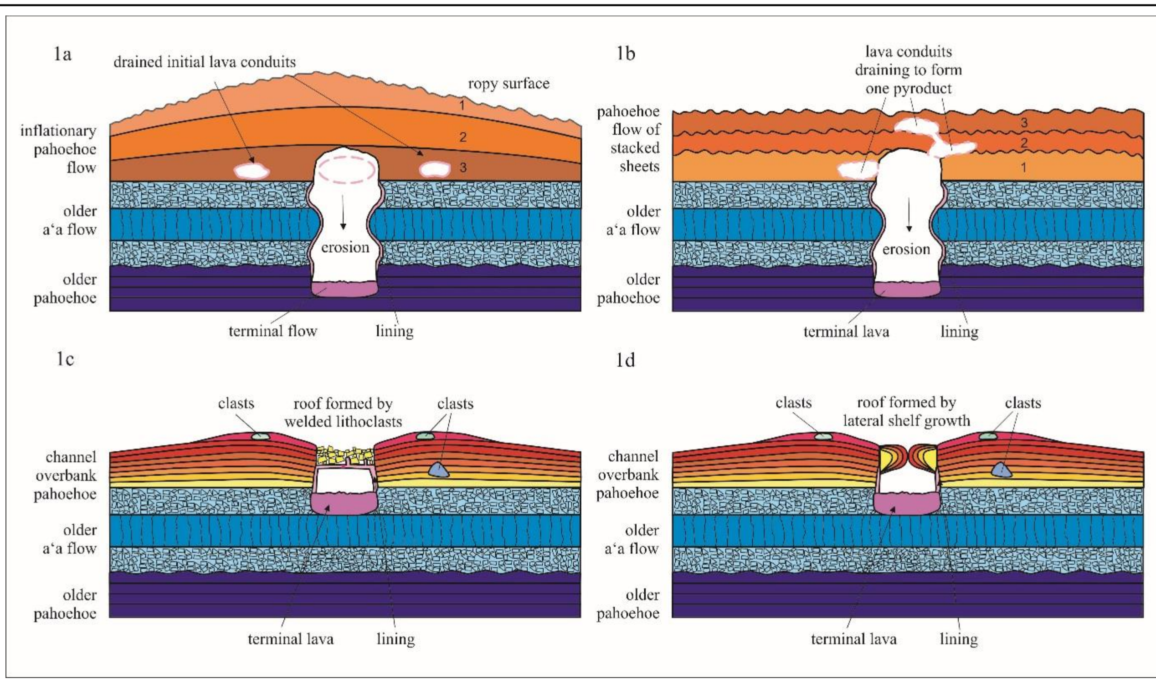

Figure 1. *Within the pyroduct type at least four different formation modes exist: Caves formed by inflation of the lava flow front and later downward erosion (1a), caves formed by coalescence of small ducts and consecutive downward erosion (1b), caves formed by the crusting-over of channels by floating lithoclasts, welded together (1c), and by channels crusted-over by lateral shelf accretion and consecutive closure (1d) (Kempe, 2012a).*

active phase of the pyroduct and not by "evacuating" a "tube" after the eruption ceased. Pyroducts therefore resemble underground canyons with lava rivers at their bottom. They are the most numerous lava caves; the longest being Kazumura Cave (total length of passages 65.5 km) (Hawai'i, Kilauea Volcano) (Allred and Allred, 1997; Allred et al., 1997) and the longest Quaternary duct-supported flow on Earth is the 160 km long Undara flow, Australia (Atkinson, 1993). In Jordan, the Al-Fahda flow may have had pyroducts as long as 25 km (Kempe et al., 2009).

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SPELEO TALK ABSTRACT

John P. Lockwood

An overview of the geology of the Big Island, with particular emphasis on Mauna Loa and the role of pyroducts in forming shield volcanoes

Mauna Loa is not only the largest (most voluminous) volcano on Earth, but is likely also home to more volcanic caves than any other terrestrial volcano. These caves, many unexplored, only form within pahoehoe lavas (smooth-surfaced lava flows that solidify directly from a fluid state). ‘A’a lavas (rough-surfaced flows that continued to move during emplacement after partial solidification) only rarely develop caves, and only ones of limited extent. Pahoehoe lavas comprise 42% (2,150 km^2) of Mauna Loa’s overall surface area, and about 32% of the lava flows ofMauna Loa’s Southwest Rift Zone --- the immediate area of this Conference . The surfaces of molten pahoehoe lava flows cool and solidify quickly during emplacement, and almost all pahoehoe lava is supplied by transport through subsurface conduits. These conduits, which I prefer to call *pyroducts*, following the first-published term coined by Titus Coan, are exceedingly complex in their geometry – ranging from broad sheets to the confined conduits that may ultimately be preserved as caves. Most pyroducts are, however, filled by cooling lava during late eruptive stages, so that only a small proportion are eventually drained of molten material, forming the caves of great interest to speleologists and of benefit to the other animals who call these caves home. Because most volcanologists prefer to study lava flows in the sunlight, understandings of the complex mechanisms responsible for pyroduct formation are only now being revealed by volcanospeleologists like you! Cavers who explore and map the extent and geometry of volcanic caves are making important contributions to volcanology; those who document the processes by which those caves form during their studies are making even more important contributions to our understandings of how basaltic lava flows are emplaced!

Detection of the soil heat flux and its effect on the cave climate in different lava tubes on Big Island

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So far there is little knowledge about the influence of the soil heat flux on the climate conditions of lava tubes and caves in general and what role this belongs to the transmission of the situations of the external atmosphere to what is happening in the cave.

To gain knowledge about these relationships in 2014 we started a research project in different lava tubes on Big Island, HI, where the soil heat flux is detected by temperature measurements with data loggers in different heights of the cave rocks and on the surface.

Those measurements will be supplemented with results of investigations with a thermal camera of selected measurement locations and in future with airflow-measurements as well as measurements of radiation.

Aim of the study is to capture the influencing factors of the soil heat flux and its effect on the cave climate.

In this presentation the issue, the choice of measurement locations, the measurement concept, the measurement methodology and first measurement results will be presented.

AN OVERVIEW OF SIGNIFICANT CAVE-CONTAINING LAVA FLOWS NORTH OF KONA, HAWAI`I

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Abstract

Lava flows in the northwestern part of the island of Hawai`i cover an area of roughly 590 square km and contain nearly 1,000 lava caves. The area is bounded by the town of Kona on the south, the Pacific Ocean on the west, the boundary between Mauna Loa and Mauna Kea flows on the north, and the western flank of Hualalai, a shield volcano above Kona (summit elevation 2521 meters) on the east.

As of late 2015, over 1,500 entrances to 1,049 lava caves containing 208.5 km of surveyed passages have been documented in fifty Hualalai and Mauna Loa flows in this area. The Hualalai flows contain 946 caves with 168.3 km of surveyed passage. The caves are found at all elevations on Hualalai and cave temperatures range from 30° C on the Pacific coast to 20° C on the upper slopes of Hualalai. The Mauna Loa flows contain 103 known caves at elevations from 70 meters above sea level to 690 meters asl. Of these, 55 have been surveyed with a total surveyed length of 40.2 km.

Of these caves, 78.5 percent of the total number and 87.7 percent of surveyed passages are found in only twelve flows: nine in western Hualalai flows and the other three in Mauna Loa flows. The Hualalai flows contain some of the world's longest and most vertically extensive lava caves. The lava caves in these flows range in age from just over 200 years to up to 30,000 years in age and vary greatly in pattern; from simple linear conduits to challenging multi-level braided and branching complexes.

Some, but not all of the major cave complexes that have been documented in this area include:

- the 27.4 km Hualalai Ranch cave complex with 452 meters of vertical extent
- the 19.7 km Delissea Cave System with 661 meters of vertical extent, the second most vertically extensive cave in Hawai`i
- the 10.8 km Hu`ehu`e (Manini`owali) cave in the historic 1801 flow field with 498 meters of vertical extent
- the 10.7 km Lama Lua-Ka`upulehu cave complex extending over a linear distance of 5.4 km and with a vertical extent of 370 meters
- Um`i Manu, extending for a linear distance of 3.4 km with a relief of 570 meters, the third most vertically extensive cave on Hawai`i.
- Manu Nui, a high gradient cave on the upper slope of Hualalai with a surveyed length of 3.7 km and a vertical extent of 352 meters
- The Pueo-Two Owl-Aluminum Ladder cave complex with 15 km of braided passages

Introduction

Over 1,000 lava caves have been found and documented in a 590 square km area on the northwestern side of the island of Hawai`i (Figure 1).

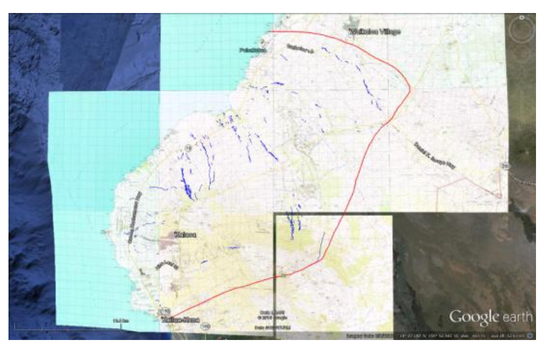

Figure 1. Study Area Showing Major Caves

This area is bounded by the town of Kailua-Kona on the south and the Waikoloa/WaikoloaVillage vicinity 40 km to the north. A majority of these caves are found in flows from Hualalai, a shield volcano reaching an elevation 2521 m (8271 feet) and covering an area of 751 km^2 (290 mi^2).

The remainder of the caves are found in a variety of Mauna Loa flows.

Acknowledgements

The works described in this paper has been carried out on lava flows in a variety of ownership and management settings. This work would have not been possible without the receipt of permits by State and Federal agencies and the granting of permission by private landowners and leaseholders.

For example, work on the Kiholo Flow was carried out under permits granted by the Hawai`i Division of Forestry and Wildlife (DOFAW) and the Hawai`i State Parks Division. Work on the Old Kiholo Road flow, the Mauka Pu`u Wa`awa`a flow, the Umi`i Manu Flow, and the Puu Anahulu flow was done under a series of research permits issued by both DOFAW and the Hawai`i Experimental Tropical Forest of the U.S. Forest Service. Work in the Ka`upulehu ahupua`a (the Hualalai Ranch and West Ka`upulehu flows) was done with permission of the Hualalai Resort and on the South Kohala flow with permission granted by the Waikoloa Village Association and private landowners.

Significant Flow Fields Containing Lava Caves in NW Hawai`i

The lava caves found in NW Hawai`i Island are among the longest and most vertically extensive on earth with five of these caves having a vertical extent of over 300 meters and 34 of them having surveyed lengths of greater than one km. Seventy nine percent of the caves and 86 percent of the surveyed length are in caves found in only 12 of the 38 Hualalai flows and 12 Mauna Loa flows that have been visited. In the remainder of this paper, these flows and their most significant caves will be briefly described. Flow designations and age ranges are those used on the U.S. Geological Survey Geologic Map of the Island of Hawai'i (Wolfe and Morris, 1996). In addition, informal names for the flows are provided in italics. Flow descriptions are provided roughly from south to north.

1. Flow 9313, age group Qh1y (3.0-5.0 ka) *Airport South flow*

Located a few km south of the Kona International airport, the major cave in this flow is a substantial unitary cave (Under the Wall Cave) that extends for a linear distance of 2.5 km and has a vertical range of 125 meters. The upper part of the cave consists of a 10 meter wide and 6 meter high tunnel containing a variety of man-made features including walls, ramps, and platforms. A description and map of the cave are provided in Medville (2002).

2. Flow 9390, age group Qh2 (1.5-3.0 ka) *Airport flow*

This flow, just to the east of the Kona International airport, extends mauka for 7.5 km and contains numerous caves containing cultural materials such as internal walls, platforms, stepping stone trails and ahus. The principal caves in the flow can be found in a line extending from the airport mauka for 5 km and contain 4.4 km of passages.

3. Flow 9410, age group Qh5 (0 to 200 years bp) *1801 flow*

The historic1801 Hu`ehu`e pahoehoe flow field crosses Rt. 19 2.7 km north of the Kona airport. This flow field contains two adjacent flows; the primarily pahoehoe Manini`owali flow and just to the north, the somewhat older channel fed Puhi-a-Pele flow.

Although the most visible cave in this flow is the one having a 5 meter diameter entrance on the mauka side of Rt. 19, 3.5 km north of the Kona International Airport (Puhi-a-Pele flow episode), the major cave is in the Manini`owali flow. This cave, informally called the Hu`ehu`e Cave (also labeled Manini`owali cave in Kauahikaua et. al. 2002), is essentially a single large conduit that extends over a linear distance of 6.17 km and has a vertical extent of 495 meters. Passage dimensions are generally in the range of 5-6 meters in width and 4-5 meters in height. The cave and its geology are documented in Oberwinder (1996), Medville and Medville (1997), and Kempe and Oberwinder (1997). The history of the emplacement of this flow is described in Kauahikaua et. al. (2002).

4. Flow 9395, age group Qh1y (3.0-5.0 ka) *Hualalai Ranch flow*

The source of this 36 square km flow, located 14 km north of Kailua-Kona, is Pu`u Alauawa at 660 meters asl. The flow contains a number of lava caves, the largest of which is the Hualalai Ranch Cave complex, a system that contains over 24 km of passages, the longest surveyed cave in NW Hawai`i (Figure 2).

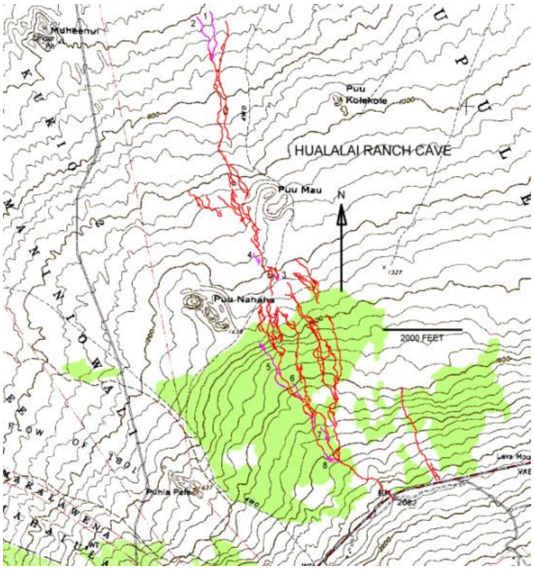

Figure 2: Hualalai Ranch Cave in Flow 9395 (Hualalai Ranch flow)

The cave is located just north of the NW rift zone of Hualalai with passages branching out in a distributary pattern. From its upper (mauka) end, a single passage can be followed makai (toward the ocean) for over 450 vertical meters, branching into a multi-level complex of parallel passages. At its mid-section, the cave contains numerous parallel passages up to 20 meters beneath the flow and extending laterally for 600 meters across the flow. The cave has a linear extent of over 4 km and is described in Rosenfeld (2001) and Davis (2003).

5. Flow 4822, age group Qh2 (1.5-3.0 ka) *West Ka`upulehu flow*

Adjacent to the historic (1800-1801) Ka`upulehu a`a flow and on its western margin, this pahoehoe flow contains another complex of large caves. Although 20.0 km of passages have been surveyed in this flow, half of the total (10.5 km.) is found in two long, aligned caves extending over a linear distance of 5.5 km.

The upper of the caves, Lama Lua, is described in Medville and Davis (2007). The cave has 5.5 km. of passage with the highest entrance being a collapse pit, 10 meters in diameter and 8 meters deep leading to a 15 meter wide and 10 meter high passage nearly 20 meters beneath the surface. This passage can be followed down the flow for nearly 3 km to lower entrances (Figure 3).

Figure 3: Passage in Lama Lua
Photo credit: Nevin Davis

A parallel passage 700 meters below the Lama Lua entrance extends to the ENE for over 2 km before ending at a lava seal beneath the adjacent historic Ka`upulehu a`a flow. The surveyed distance to this point from the Lama Lua entrance is 2.65 km., entirely in darkness. The two parallel passages in Lama Lua are 550-600 meters apart, comparable to the lateral extent of the Hualalai Ranch complex. In addition to its length and depth, the cave is noteworthy for the presence of an olive-green copper-vanadium-silicate mineral of unknown crystal structure. This mineral is in the form of a thin, uniform coating on floor breakdown and along cracks on passage walls. The mineral and the analysis of its composition is described in White (2010).

The lower of the two caves; Ka`upulehu Cave, has 5 km. of surveyed passages, extending over a linear distance of 2.2 km. and is a continuation of the Lama Lua Cave. This cave consists of a unitary passage with occasional braids. It ends at a lava seal 200 meters above Rt. 19 over a linear distance of 2.2 km. Lama Lua and the Ka`upulehu Cave are separated by two shatter rings each of which is about 60 meters in diameter and are 275 meters apart. The rings are a result of filling of the cave passage beneath and a breakout to the surface with subsequent draining of lava back into the cave as described in Kauahikaua et. al. (1998). However, the lower of the rings contains a short cave with 1 meter high passage that lies beneath the perimeter of the ring, forming a single loop.

6. Flow 9334, age group Qh1y (3.0-5.0 ka) *Kiholo flow*

This flow crosses the coastal highway (Route 19) at the Kiholo Bay scenic viewpoint at mile post 82. The flow contains over 215 caves from sea level to its mauka end at an elevation of 480 meters asl, a distance of 7.2 km. Unlike the flows described above, this flow does not contain a single massive conduit but rather numerous shallow caves, 3 to 5 meters beneath the surface, that parallel each other with no apparent overall pattern. Seventeen of the caves in this flow are over 300 meters in length with the longest being 1270 meters in length. The Kiholo Bay State Park Reserve occupies the distal part of this flow, on the makai side of Rt. 19. Many caves in this part of the flow contain significant quantities of cultural materials; e.g., constructed walls and modified entrance areas.

7. Flow 4698, age group Qh1y (3.0-5.0 ka) *Old Kiholo Road flow*

In the vicinity of Pu`u Wa`awa`a and at an elevation of 500 meters asl, this flow extends for nearly 9 km. toward the ocean. The caves in this flow are shallow: only 3-5 meters beneath the surface and contain numerous small entrances. These caves however, are highly braided and complex, perhaps indicating lava flowing in multiple diverging and recombining lobes before the molten cores of these lobes were evacuated with resulting braided caves remaining. The largest of the caves in this flow, Pueo Cave, contains over 6.5 km. of passages in an area less than 0.2 km^2 (Figure 4).

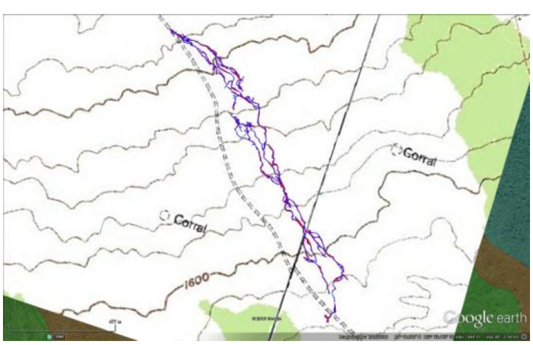

Figure 4: Pueo Cave in Flow 4698 (Old Kiholo Road flow)

The cave contains over 40 loops and is one of the most complex of the Hualalai caves. Pueo Cave is described in Medville (2008). A similar cave (Two Owl Cave) is 150 meters below Pueo Cave but separated from it by a lava seal. It contains over 5 km of similarly braided passage. Aluminum Ladder Cave, 500 meters makai of Two Owl Cave, has the same pattern and has 3.5 km of passage.

8. Flow 5477, age group Qh1y (3.0-5.0 ka) *Umi`i Manu flow*

This small flow contains a single cave extending for nearly the entire length of the flow. The cave, Umi`i Manu, literally Bird Trap, is named after the numerous skeletal remains of the extinct Hawaiian flightless goose (Branta rhuax), collected in this cave by ornithologists from the University of Hawai`i and the Smithsonian Institution. The upper end of the cave is at an elevation of 1890 meters and is only 300 meters below the source vent for the flow. The cave extends for a linear distance of nearly 3.4 km and has a vertical extent of 570 meters, the third most vertically extensive lava cave known, after Kazumura Cave and, as noted below, the Delissea System. Umi`i Manu consists of a single large conduit, generally 5 meters wide and high and follows the steepest gradient of the flow for its entire length. In addition to the fossil goose bones, the cave contains the skeletal remains of other birds, including rails, petrels, and nenes. The cave is a good example of a high gradient conduit with very little meandering or braiding of passages. An outline map and summary are provided in Medville (2003).

9. Flow 4889, age group Qh2 (1.5-3.0 ka) *Mauka Pu`u Wa`awa`a flow*

With over 225 documented caves containing over 40 km of surveyed passages in an area of only 8 sq. km., this flow contains perhaps the greatest concentration of lava caves on Hawai`i. Located above the Pu`u Wa`awa`a Trachyte cone and ranging in elevation from 900 to 1600 meters asl, the area contains numerous entrances leading to a complex of linear and braided caves extending laterally for 1.6 km. The principal documented cave to date is the Delissea Cave System containing nearly 20 km of passages in a large distributary pattern extending over 661 meters in vertical range, the second most vertically extensive lava cave on Earth. Other major caves include Upper Owl Cave with 3.1 km of passage and the Henahena/Bee Flat cave complex with 2.3 km of surveyed passage. Several of these caves contain numerous fossil bird bones including the extinct Hawaiian Goose (Branta rhuax). Ongoing studies in these caves involves documenting their content; e.g., bird bones, roots, and native and invasive flora in entrances as well as recording entrance locations and conducting surveys.

10. Flow 4627, age group Qk1y (3.0-50. ka) *Puu Anahulu flow*

One of the three major Mauna Loa flows in the area, this flow extends from the Mamalahoa highway (Rt. 190) makai nearly to Rt. 19 along the coast, a distance of nearly 9 km with a vertical range of almost 600 meters. The flow is bounded by the Pu`u Pohaku Road on the east and the historic 1859 flow on the west. The flow contains a series of aligned large volume caves, seven of which are over a km. in length. The longest of these is called the West Hawai`i Landfill System and contains over 4.2 km of braided passages up to 8 meters in width and height. The distal end of this cave extends for nearly a half kilometer beneath the adjacent historic 1859 flow before ending in rockfall.

11. Flow 9327, age group Qk7 (11-30 ka) *Paniolo flow*

This is the oldest major cave-containing flow and is also a Mauna Loa flow. Extending from sea level to an elevation of 100 meters asl over a linear distance of 3.7 km, the flow contains several large volume lava caves, the most well known of which is the historic Paniolo Cave. The cave also contains a massive stone wall at one of its entrances. The flow has a low gradient with a smooth surface. Other caves in this flow also contain cultural materials such as rock rings and ahus constructed at entrances. The caves in this flow are only 3-5 meters below the local surface and tend to end in either rockfall or in infilling with unoxidized black lava from the adjacent historic 1859 flow.

12. Flow 4528, age group Qk2 (1.5-3.0 ka) *South Kohala flow*

The northernmost of the flows containing substantial caves in NW Hawai`i is also a Mauna Loa flow, located in the South Kohala District. Extending for 540 vertical meters over a linear distance of 10.5 km., this flow contains over 16 km of passages in a linear series of eight large volume caves (Figure 5).

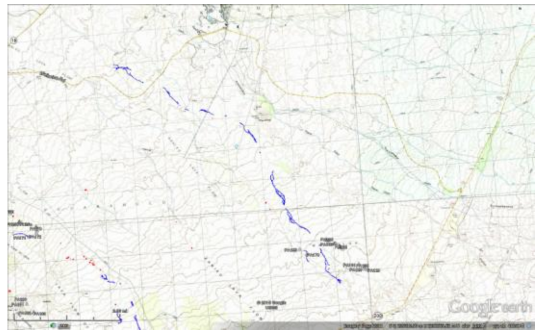

Figure 5: Lava Caves in Mauna Loa Flow 4528 (South Kohala flow)

Several of these caves contain deposits of a fine volcanic ash/mud mixture on the passage floors (Figure 6).

Figure 6: Passage in Pu`u Hinai Dust Cave
Photo credit: Ted Lappin

At its mauka end, the flow and 5 meter diameter passage in its highest cave are terminated by a`a fill from a younger flow, indicating that both the flow and its caves could continue mauka, were it not for the intrusion. Makai, the flow and its lowest elevation cave also end beneath a younger flow.

Summary

A substantial amount of work has been carried out in documenting the lava caves of NW

Hawai`i over the past 25 years. We observe that although there are some variations in the physical nature of caves within a flow, more substantial differences in the lava caves are observed to exist when the caves are compared between flows. Several flows contain single or a linear series of large diameter unitary caves; e.g., flow 9319 (Under the Wall Cave), flow 9410 (the Hu`ehu`e Cave) and flow 4528 in South Kohala. Others contain distributary networks; e.g., flow 9395 (Hualalai Ranch System), 4822 (Lama Lua), and flow 4889 (Delissea Cave System) or multiple lines of parallel caves with no obvious single conduit; e.g., flow 9334 above Kiholo Bay. Yet other flows contain complex braided caves at a single horizon; e.g., flow 4698 (Pueo Cave, Two Owl Cave, Aluminum Ladder Cave).

Although efforts have been made to investigate each flow in order to document every significant entrance and lava cave, much work remains to be done. Many entrances can be seen on aerial imagery, both in the flows discussed above and in other, as yet unvisited flows and it is expected that both the number and variety of lava caves in NW Hawai`i will continue to increase.

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UK SPELEOLOGICAL EXPEDITION TO HAWAI'I ISLAND 1979

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Abstract:

This expedition, which lasted for seven weeks in the summer of 1979, involved seven UK cavers with four other occasional visitors, and had the stated objectives:

- To locate, explore and map as completely as possible the drained segments of the Mauna Ulu (Kilauea) tube system as a basis for morphometic analysis and interpretation of the dynamics on the emplacement of this type of lava flow,

- To investigate generally the occurrences and forms of lava tube systems (as identified in lava tube caves) on the volcanoes Mauna Loa and Kilauea.

under the leadership of the late Dr Chris Wood.

Prior contact/liaison with both the National Park HQ and Hawai'ian Volcano Observatory provided permission to stay and work in the Park throughout the visit, often in areas prohibited as dangerous to normal visitors.

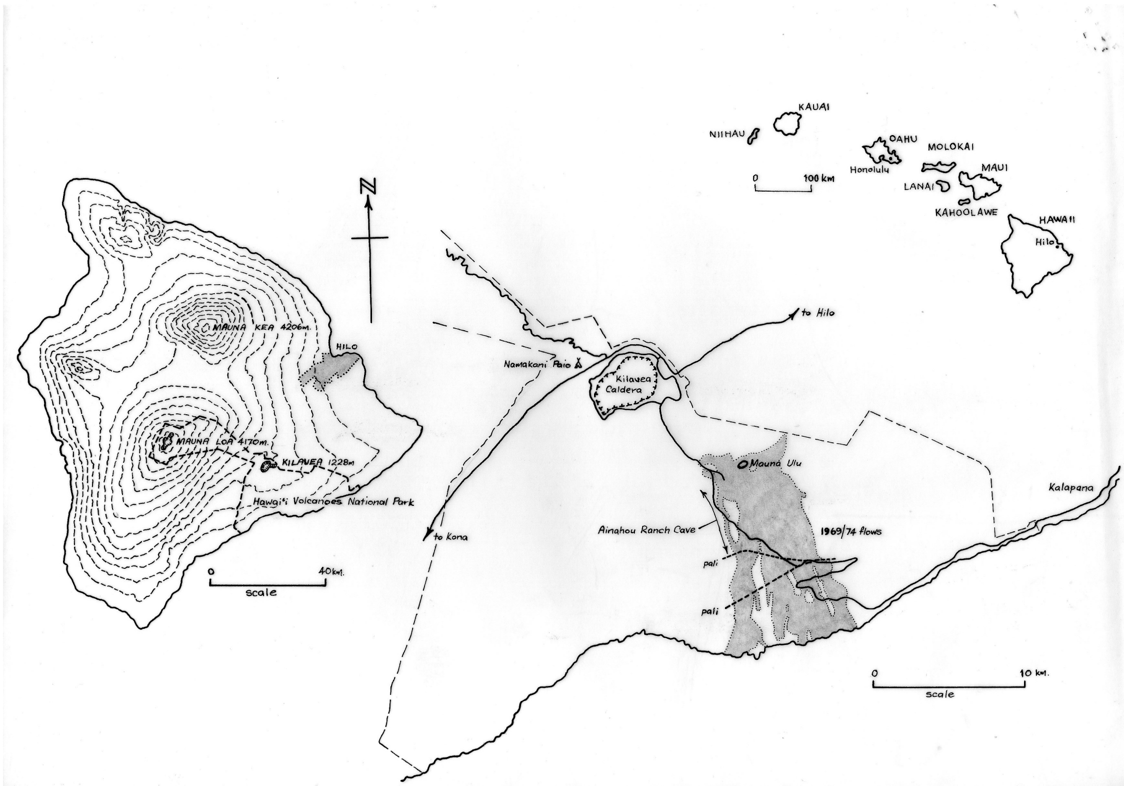
Many days were spent walking the 1972/74 flows from Mauna Ulu crater to the coast and examining its features. Near the coast a large entrance led to 1.3 km of lava tube containing the most spectacular display of lava formations. It was named Apua Cave.

Ainahou Ranch Cave, which had previously been partially explored for about a mile and was still going, was located and extended (including the discovery of a 200 year old human skeleton) and surveyed with 22 entrances/collapses to 7.11 km with a vertical range of 352 meters.

Kazamura Cave was located and surveyed to 11.55 km length and 260 meters vertical range.

In all 20 caves were visited, 22.4 km surveyed and a further 3.9 km visited/checked out.

> "There are persistent rumours of caverns many miles long on the island of Hawaii. There the caves are largely unexplored and almost wholly unmapped because of their veneration as tombs of ancient royalty – and the grand-parents of commoners still living"
>
> (Bill Halliday, 1966)



Location map

INTRODUCTION

Back in 1968 little did I realise when I put the case for the Shepton Mallet Caving Club going to Iceland in 1970 to investigate lava caves as being something “different”, how much I was subsequently to be involved with this other ‘variety’ of caves. Prior to 1979 I had visited more than 45 different lava caves in Iceland, Tenerife, United States and Kenya and surveyed over 15.7klm of lava cave. On Tenerife in 1973 we had extended and surveyed Cueva del Viento from a length of 6181m to 7422m which at that time was reckoned to be the longest known lava cave in the world. Why this interest in caves of which we have none in the UK, I find difficult to explain. However, enduring the trials and rigours that this involved, in 1979 brought an invitation from the late Chis Wood and a just reward of a trip to Hawai’i to investigate yet more lava caves – it has to be said and many will have noticed this – that one of the consolations of lava tube caving is that they are often found in relatively attractive locations. A decade earlier we had learnt there were lava cavers in Hawai’i (Thurston Lava Tube being the most often mentioned) – not for one moment did I ever expect to be going there. Thus much the world had shrunk over the decades. It also satisfactorily resolved the question of a honeymoon, for as Kirsty pointed out not everyone gets a honeymoon in Hawai’i – albeit on a caving expedition!

General

The party comprised (primarily) five Shepton Mallet Caving Club members and two Chelsea Speleological Society members with 4 other visitors joining us at various times, and lasted seven weeks with people there for between three and five weeks (in our case four weeks) apart from Chris Wood who as leader was there throughout. The result was that, except for the final week, we always had at least four cavers present.

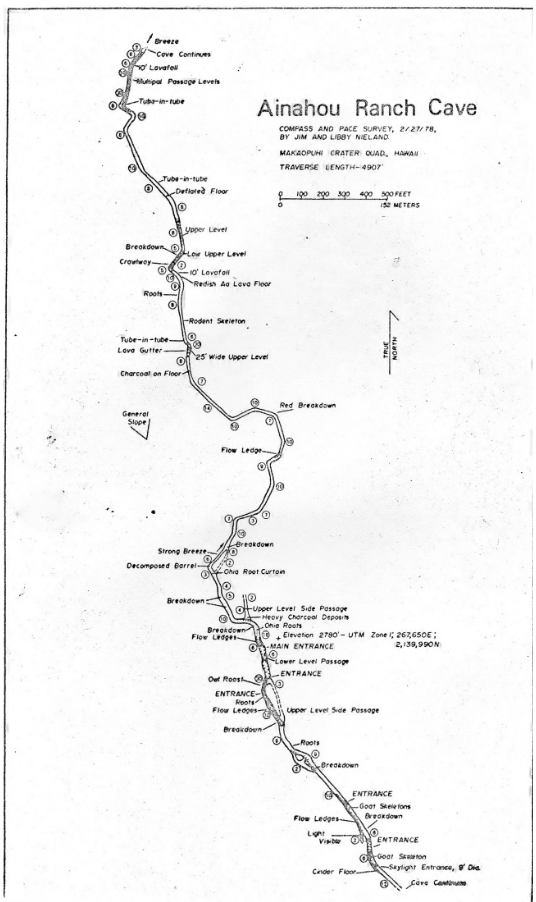
The stated objectives were

(i) to locate, explore and map as completely as possible the drained segments of the Mauna Ulu (Kilauea) tube system as a basis for morphometric analysis and interpretation of the dynamics on the emplacement of this type of lava flow;

(ii) to investigate generally the occurrences and forms of lava tube systems (as identified in lava tube caves) on the volcanoes of Mauna Loa and Kilauea.

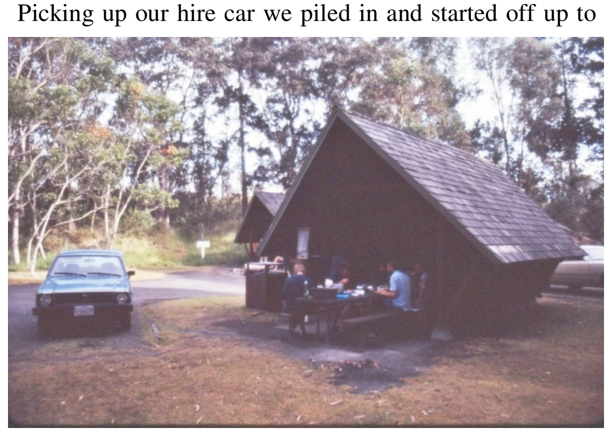
Mark Twain described the islands as “the loveliest fleet of islands that lies anchored in any ocean”. Of the climate Robert Louis Stevenson said it “sweetens one’s bones” and, incidentally, the Hawai’ian language has no word for weather.

Departing on Friday 13th July from Edinburgh, Scotland, by train was asking for trouble and about ten minutes out the train broke down – however this was but a foretaste. Being grant-aided it was felt we should fly the cheapest route rather than direct, thus we were due to fly Heathrow – New York – Seattle – Hilo. Our route being through Seattle enabled us to stay overnight with Bill Halliday at 1117 36th Avenue East(?). He had laid on a reception for us and his Cascade Grotto specialists were there with a view to a firm agreement on measuring lava tube caves. We had always differed with the Americans on this, basically if there is one or more collapses/entrances part way along the length of the cave they regarded each section as a separate cave, irrespective of (as we saw it) the whole cave being formed at the same time with the roof collapsing either at the time of formation or subsequently. The fact that it was also 5.00 am our time probably didn’t help; however WRH did give us a photocopy of an account ‘Visiting Hawaiian Caves’ by Libby and Jim Nieland from the Oregon Speleograph Sept. 1978 of a trip to Hawaii in February 1978, including a description and part survey of Ainahou Ranch Cave which had been explored for just under a mile and was still going both up and down flow. After more adventures, by Royal Hawaiian Airlines, we made Honolulu and then had two additional island ‘hops’ on Aloha airlines to get to Hilo, where after 59 hours travelling we had arrived 48 hours later.



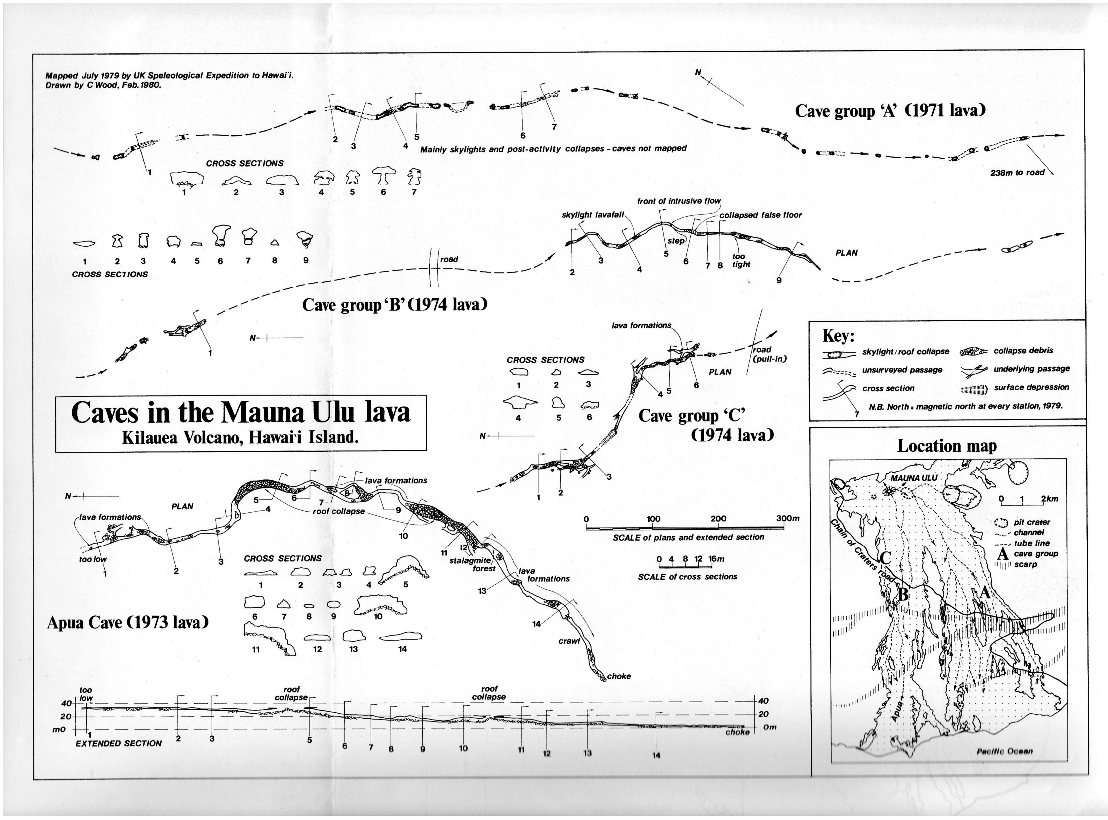
Nieland 1978 survey of part of Ainahou Ranch Cave

Picking up our hire car we piled in and started off up to the Hawaii Volcanoes National Park some 40km distant. We were dismayed to find it was raining (except it was warm rain) and surprised to find when we checked in that we had booked our cabins from the next day, so we had to go off and find a campsite for the first night! After a deep sleep, the following morning we went off to the National Park Headquarters and Hawaiian Volcano Observatory to introduce ourselves as we had permission to stay and work in the Park throughout



Polynesian style camping cabin. Photo M Mills our stay, often in areas prohibited as dangerous to normal visitors. Then we moved into our two Polynesian style camping cabins at Namakani Paio campsite (altitude 1250m) and on one occasion experienced a 4.8 earthquake.

Work on the Flows



Caves in the Mauna Ulu Lava, drawn by C Wood. 1980

An eruption astride the rift zone began on 24 May 1969 and ended in mid-October 1971, creating and building up the parasitic shield volcano at Mauna Ulu (Hawaiian for Growing Mountain) some 2km across, 120m high, the summit being at an altitude of about 1050m. At the height of the volcanic activity, lava was produced at over 200,000m³ a day with a peak of 1,000,000m³ an hour, and resulted in 40.5km² of bush and forest being covered by lava flows up to 90m thick. Tubes are a primary means of volcanoes transporting lava long distances from the vent to the extremities of the advancing flow, in this case in September 1970 some 12 km to the Pacific Ocean to extend the area of the island by 0.8km². The Halina fault system produces scarps (called pali) 120 – 180m high between the vent and the ocean, lava tubes even extended down these at an inclination of 60^0. Volcanic activity resumed in February 1972 until 1974. The whole of the activity was the first long-term duration flank eruption to be witnessed in detail, and was observed by Peterson & Swanson who in 1974 published in "Science of Speleology" their findings, which at the time was the best account and certainly the finest illustrations to date of lava tube formation. Through skylights in the roof of tubes they were able to measure the temperature of the molten lava flowing in tubes at 1150^0C, its speed of flow at varying between 1 and 6km per hour, and temperature drop of the molten

Tony Jennings and Chris Wood inspecting the lava flows. Photo M Mills lava as only 10 – 20 ^{0}/c in over 10km travel distance. New plant life was observed on the lava flows within three months.

Our first week was spent walking down the flows, from the vast smoking crater nearly 200m deep above the perched lava pond on the volcano's flanks, looking for anything we could get into. Although the tube system were only 6 to 8 years old and had not been examined since they were formed, we quickly found that the 1972/4 flows had covered the 1969/72 flows, no doubt obscuring many of the caves. In our searching of the flows we were greatly assisted by the Chain of Craters Road, which runs across the flows, having been re-opened just two weeks before our visit – it had been closed when invaded by flows in 1969 and had since been reconstructed.

John Cooper on surface below Poli o Keawe Pali.

The first day we walked from the Chain of Craters Road like veritable mad dogs and Englishmen the 10km or so to the coast, descending two pali (like petrified coke heaps) en route. Walking on the fragile glassy surface of pahoehoe flows in temperatures of 85^{0}F (29.5^{0}C) in the shade (except there was none) fanned by a strong Trade Wind was rather like walking in an ungreased frying pan. Near the coast we found some very large entrance collapses that necessitated a further visit. At the coast we then faced a walk of similar distance to the nearest point on the road. Meanwhile Kirsty, who had turned back at the head of the upper pali to take the car down to the coast, fared even worse as we had the water bottle! Walking in from the road she was slightly ahead of us in time, failed to find us, and so returned to the car and was reduced to drinking the only available water in the car windscreen washer bottle! Pahoehoe flows which we had been walking over are relatively smooth, however these were frequently interspersed by Aa flows which are like clinker, and much more difficult (and painful) to cross. The natives used to weave ti leaves into sandals for crossing Aa flows, and leave a stone wrapped in a ti-leaf at the entrance of any caves they visited as a symbolic "thank you" to the volcano goddess Pele. The ti plant was a symbol of divine power to the people of old, and was considered a charm against evil spirits.

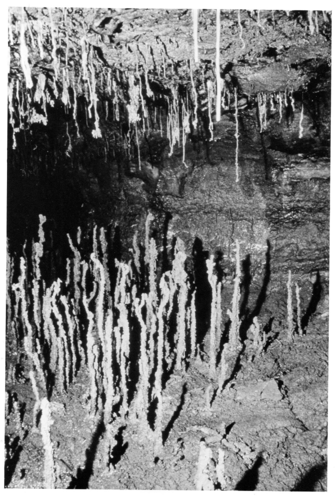
Walking across lava features on the flow. Photo M Mills

Descending Holei Pali. Photo M Mills

After our somewhat epic first experience on the flows, especially our reactions to heat/water (or the lack of it) we were rather more careful and left our return visit to the very large entrance collapses found near the coast until we had adjusted/acclimatised slightly better. Apart from these the longest cave found was only 275m long, although there was a remarkable line of 27 surface features/entrance collapses over a distance of 1.5km.

On Puna Coast Trail walking towards Apua Cave with Don Peterson of USGS in the rear. Photo M Mills

When the day came for our return to the very large entrance collapses found near the coast we were joined by Don Peterson, former Chief Scientist at the Volcano Observatory (part of the U.S Geological Survey). Upflow of the upper collapse the cave rapidly became too low, but downflow and beyond a second entrance collapse we encountered a 'forest' of about a hundred 1m high lava 'mites, thought to be the most spectacular display of lava formations yet found in any lava cave. In addition, there were straight and erratic rod and straw lava 'tites up to 50cm long, lava 'mites up to 30cm high and lava "roses" on the floor. This cave, which we named Apua Cave, because of its proximity to Apua Point, ended in a choke after 1.3km. Apart from the protection afforded it by being situated in the National Park, this cave also has the natural protection provided by its distance from the road. The entrance collapses do not appear on aerial photos taken in 1974 and it is believed they were opened by a subsequent earthquake – more could reveal themselves.

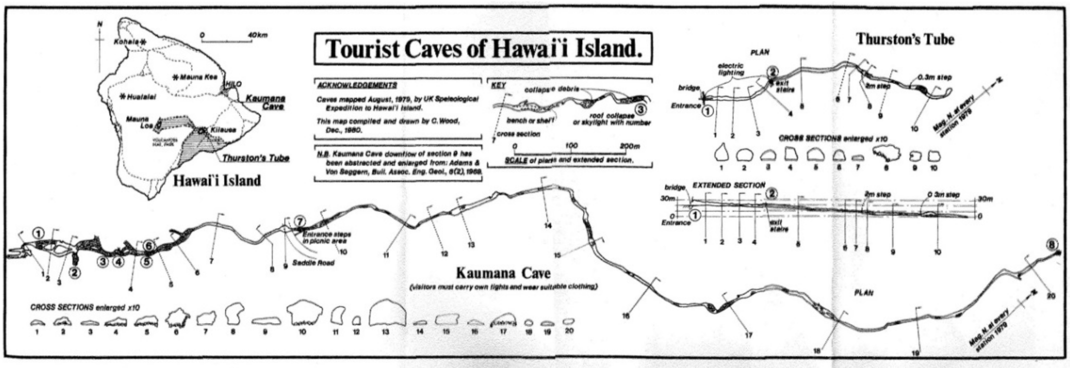


Examples of lava 'mites in Apua Cave. Photo A C Waltham

Party relaxing outside Apua Cave. Don Peterson USGS sitting at the back. Photo M Mills

After a warm day's caving we invariably took ourselves to either the Queen's Bath near Kalapana, a natural basalt rift filled with fresh water; the black sand beach at Kalapana which will disappear through erosion in 2 – 3 centuries; or Volcano Store for a hamburger and iced coke, and perhaps in the evening to Volcano House, the only hotel in the National Park, for an iced beer. The hotel maintained 'perpetual fire' in the fireplace to remind visitors of the possibility of an eruption, and commands an unrivalled view into Kilauea Caldera which had last erupted in 1974.

Other Caving



Tourist Caves of Hawaii Island, drawn by C Wood, 1980

On the outskirts of Hilo city we found Kaumana Caves County Park which comprised a parking lot, a couple of picnic tables and the cave. We did a rapid 45 minutes through trip downflow from the main entrance to a lower entrance, which is virtually the trade route. Appetites whetted, this cave was later visited and upflow from the main entrance nearly 1km of passage was surveyed, ending in a complex network of low, rubbish-filled crawls which appear to sump in wet weather.

The next time the prospect of a spare day from work on the flows loomed, Ainahou Ranch Cave came to mind, so armed with the photocopy of the article Bill Halliday had given us, we set off to locate the cave in an area covered by forest and scrub in Kampua'a flow about 350 – 500 years old and mentioned in Hawaiian legends. After an hour or so thrashing about in the bush two entrances were found simultaneously. Dumping the 'sacs we set off down the cave, surveying as we went, it was predominantly large passage of at least 8m diameter with long sections of breakdown boulder piles which made for slow precarious going, apart from the surveying hazard of thick curtains of tree roots; however, 85 stations and 1.7km later towards late afternoon hunger got the better of us (we had left the lunch in the 'sacs) so surveying was abandoned for the day. To ensure that the cave did not close down just round the corner form the final station, we had a quick recce and found within a short distance a lava fall that required a hand line to descend. With enthusiasm for the cave running high, we returned the following day and divided into two parties. The first retraced steps to the terminal point of the previous day and continued downflow, descending two lava falls and passing several more entrances (one being a roost of Pueo, Hawaiian short-eared owl) after a further 770m the cave terminated at Poli o Keawe Pali from which entrance could be plainly seen on the flow at the foot of the pali, further entrance collapses – these await further investigation. The second party commenced surveying upflow and after finding some water calabashes were

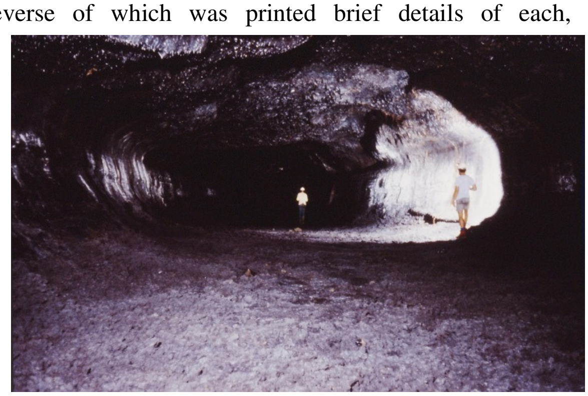
View from lowest entrance of Ainahou Ranch Cave looking down over the pali. Note chain of collapses on next level. Photo M Mills

Lowest entrance of Ainahou Ranch Cave looking out over Poli o Keawe Pali. Photo M Mills startled when Kirsty came upon a human skeleton; however they had surveyed a further 1.78km that day. As in the UK the finding of human remains should be reported to the law enforcement authority, so the skeleton was reported in the evening to the Chief National Park Ranger, who detailed a Ranger, Brian Goring, to accompany us on the 'morrow to check out the remains. He concluded that the skeleton was possibly 200 years old and may have crawled into the cave to die or been killed for disobeying Kapu (sacred laws), but warned us of booby-traps in caves protecting important burial chambers, such as precariously perched boulder piles with a tripping mechanism, hopefully now set off by earth tremors. The cave was undoubtedly used as a hidden routeway through which warriors could move unnoticed by the enemy as was indicated by the amount of torch charcoal on the floor throughout the cave. The same day a further 1.65km of passage was surveyed as far as the top entrance. When the remaining side and upper level passages were completed, the cave had 16 entrances (one containing outstanding petroglyphs), a length of 7.11 km and a vertical range of 352m, making it at that time the second deepest lava cave in the world.

Petroglyphs in Entrance 6, Ainahou Ranch Cave. Photo M Mills

Kazamura Cave was first reported in 1972 at 6km length, and in 1975 at 10km with 15 known collapse holes and sections reported, as yet unexplored. As no subsequent reports had appeared we were anxious to visit the cave and so wrote to Frank Howarth, at that time the only resident caver in the islands (though he lived in Honolulu) and source the original reports. However, he was doing continuing fauna studies in the cave and declined to tell us its location, but offered to join us from 9th – 21st August during which he would show us the cave. At Kaumana Cave we had noted outside the entrance a nuclear fall-out shelter sign, and subsequently several others during our travels around the island. From the Civil Defence Office in Hilo a map showing the location of all the shelters on the island was obtained, on the reverse of which was printed brief details of each, including whether it was a cave or other form of shelter. Amongst which were details of Kazamura Cave. After a preliminary recce where we walked over 5km down this unitary tube of about 10m diameter, passed 4 entrances and 2 or 3 boulder chokes, it was surveyed following our departure by those remaining to 11.55km with a vertical range of 260m to make it the longest lava tube cave in the world at that time known. It had very few side passages, extensive breakdown in the lower section, ends in a draughting choke, had

Chris Wood in Kazamura Cave. Photographer unknown



Kazamura Cave passage Photo unknown.

been used by ancient Hawaiians as a burial site with two burial chambers, several complete skeletons present, and the lowest entrance contained the remains of a great stone structure interpreted to be a heiau (temple platform) – a religious tradition of old timers has it that if these are photographed, spirits will fog the film.

Kirsty Mills at Thurston Lava Tube with warning sign. Photo M Mills

Thurston Lava Tube which was open as a self-guided cave, the first 120m lit by electricity and at the entrance had a sign stating "Caution: Reduced Light, Low Ceiling Ahead, Remove Dark Glasses". This was surveyed on our last evening to 539m length in just 20 minutes, using two survey teams.

Conclusion

The total cave consumption of the trip was over 20 caves visited, nearly 22.4km of passage surveyed, including Kazamura Cave at 11.55km, longest in the world, and Ainahou Ranch Cave at 7.11km (now the fifth longest and second deepest in the world), and a further 3.9km visited/checked out, including Blair Cave, Dr. Bellou Cave, Hawaiian Acres No. 1 Cave, Bird Park Cave and Ainahou Ranch No. 2 Cave. Ten years later in 1989 the Hawaii Speleological Survey was founded.

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MICROBIAL COMMUNITIES OF ICELANDIC LAVA CAVES

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Abstract

Iceland is a country with many great Holocene lava caves that contain a diversity of microbial deposits. Our study examined a variety of microbial communities that included microbial mats, snottites, organic ooze, mineral deposits, and surface soils above the caves. The samples varied in color from white to tan, yellow/gold, orange, to the brown of surface soils. Four caves were sampled: Þríhnúkagígur, Leiðarendi, Raufarhólshellir, and Vatnshellir. Scanning electron microscopy (SEM) revealed the presence of biofilm, filaments, rods, and clusters of coccoid shapes, plus evidence of iron and sulfur minerals. DNA analysis demonstrated that the surface soils above the two of the caves are more diverse and substantially different from cave samples. All samples contained Acidobacteria and Proteobacteria, but surface soils were the only samples to contain a new candidate phylum, AD3. The snottites were more similar to microbial mats than expected and were not acidic as the snottites are in sulfur caves around the world. While the microbial mats were fairly similar in composition at the phylum level, the mineral deposits varied from sample to sample. Overall, the type of sample (mat versus mineral versus surface soil) made the greatest difference in composition.

Methods

Site descriptions and sample collection:

In 2013, we have sampled four lava caves (Þríhnúkagígur, Leiðarendi, Raufarhólshellir, and Vatnshellir) for microbial communities for scanning electron microscopy (SEM) analysis and DNA sequencing. Þríhnúkagígur is a 4000 years old (tephrochronological dating) open vertical volcanic conduit (OVVC). The crater reaches down to a depth of 201 m and is descended on a platform (Fig. 1). Samples were taken at 120-130 m depth from a 20-30.000 years old tuya base. Leiðarendi is a little over 1000 m long and 2000 years old (tephrochronological dating). Leiðarendi has become the most frequented cave in Iceland with 50-100 visitors per day on the average. Raufarhólshellir is 5600 years old lava cave (carbon dating), 1360 m long, wide (10 m on average). Vatnshellir is 8-10,000 years old (sea level 15-20 m lower than present). Vatnshellir is special because it is on three levels. The cave reaches down to a depth of -36 m, with a total length of 200 m.

Figure 1: Overview of the descending platform used to enter Þríhnúkagígur. Photo by K. Ingham.

Figure 2: Gunnhildur in Leiðarendi. Photo by K. Ingham.

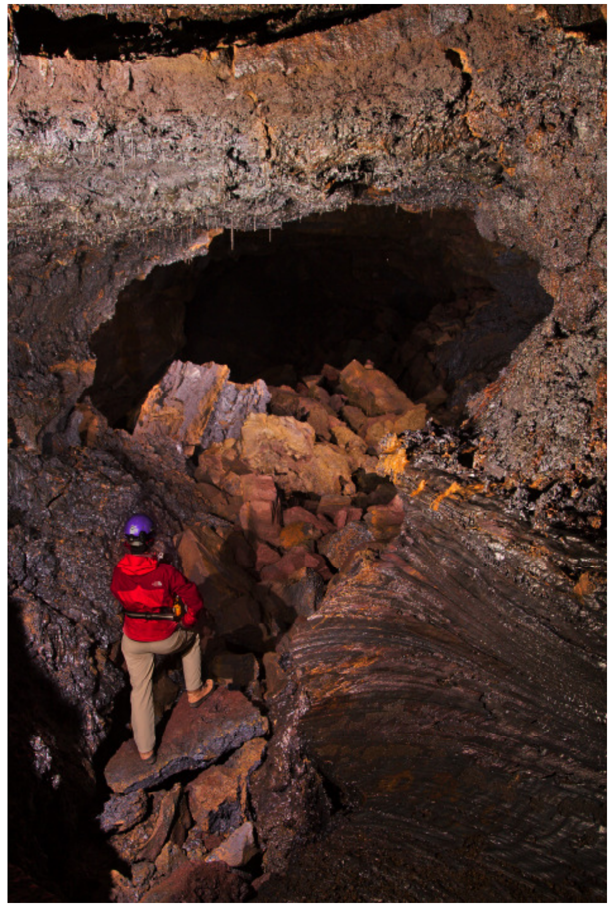

Figure 3: Gunnhildur in Raufarhólshellir. Photo by K. Ingham.

Figure 4: Gunnhildur in Vatnshellir. Photo by K. Ingham.

Samples were taken aseptically using a flame-sterilized cold chisel, and were immediately covered with sucrose lysis buffer to preserve the DNA (Giovannoni et al. 1990). Rock chips with microbial mats or mineral deposits sampled for SEM were mounted directly on SEM sample stubs in the field.

Scanning electron microscopy

Samples were air dried, and coated with Au-Pd metal for imaging in the laboratory. They were then examined on a JEOL 5800 SEM equipped with an energy dispersive X-ray analyzer (EDX), at high vacuum with an accelerating voltage of 15KeV with a beam current between 0.1 to 0.01 ηA.

Results and Discussion

SEM

Scanning electron microscopy (SEM) revealed that the yellow crumbly mineral deposit of Þríhnúkagígur contained abundant biofilm with a plethora of extruding filaments (Fig. 5) and clusters of round, coccoid shapes with short hair-like extensions. The white microbial mat from Leidarendi contained an abundance of fuzzy coccid shaped morphologies (Fig. 6), biofilm, some of which had many rod-shaped morphologies embedded in it, and some filaments. The hard, gold-colored mineral deposit from Raufarhólshellir showed biofilm covering mineral crystals, some of which contained iron oxides and sulfur minerals. The sulfur deposit from Vatnshellir contained some beautifully folded biofilm (Fig. 7).

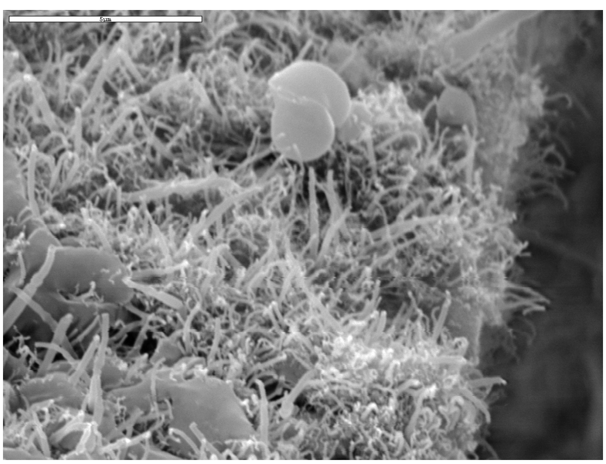

Figure 5: Overview of filament like structures on a sample of yellow, crumbly mineral deposit in Þríhnúkagígur.

DNA sequencing

The Actinobacteria, which give caves their musty odor, were more abundant in microbial mats, with the exception of one white microbial mat, and surprisingly were not very abundant in surface soils. Actinobacteria were also not very abundant in mineral deposits, or in the snottite or ooze samples (Fig. 8). Another abundant

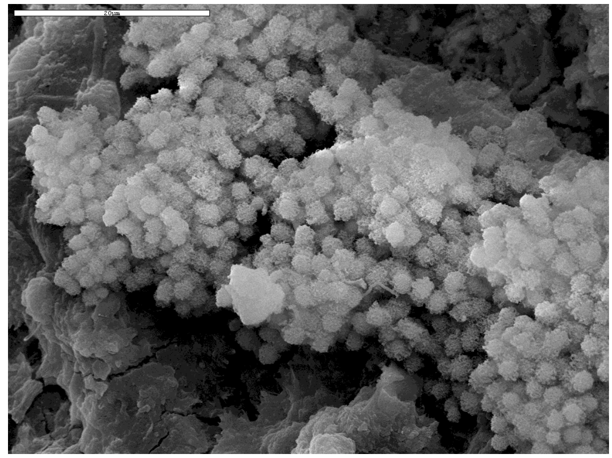

Figure 6: Clusters of coccoid shapes with short hair-like extensions from the white microbial mat in Leidarendi.

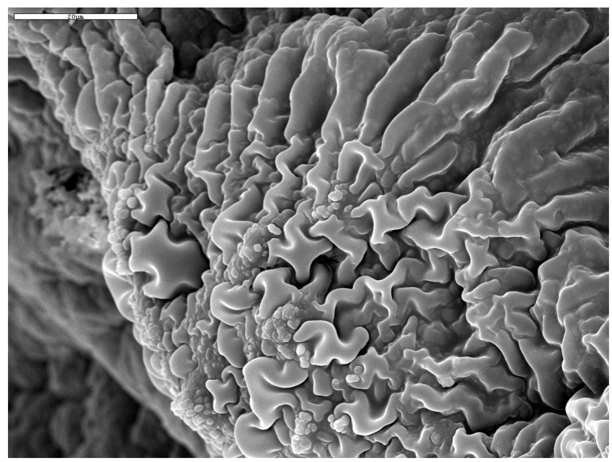

Figure 7: Folded biofilm from a sulfur deposit in Vatnshellir.

group in most samples was the Acidobacteria, most of which were undescribed, uncultured bacteria. Gammaproteobacteria, a class that contains some of the acidophilic bacteria found in snottites in sulfur caves, was not very abundant in the snottite found in Leidarendi, or in the ooze sample or in surface soil samples. Also interesting was the occurrence of the candidate phylum NC10, which was discovered in the Nullarbor Plain caves of Australia. NC10, a methanotroph that reduces nitrite (Ettwig et al. 2009), was mostly found in the mineral deposits sampled.

This parallels several of the findings of Hathaway et al. 2014, who studied Hawaiian and Azorean lava cave microbial mats. A notable exception is the lack of Nitrospirae in the Icelandic lava caves.

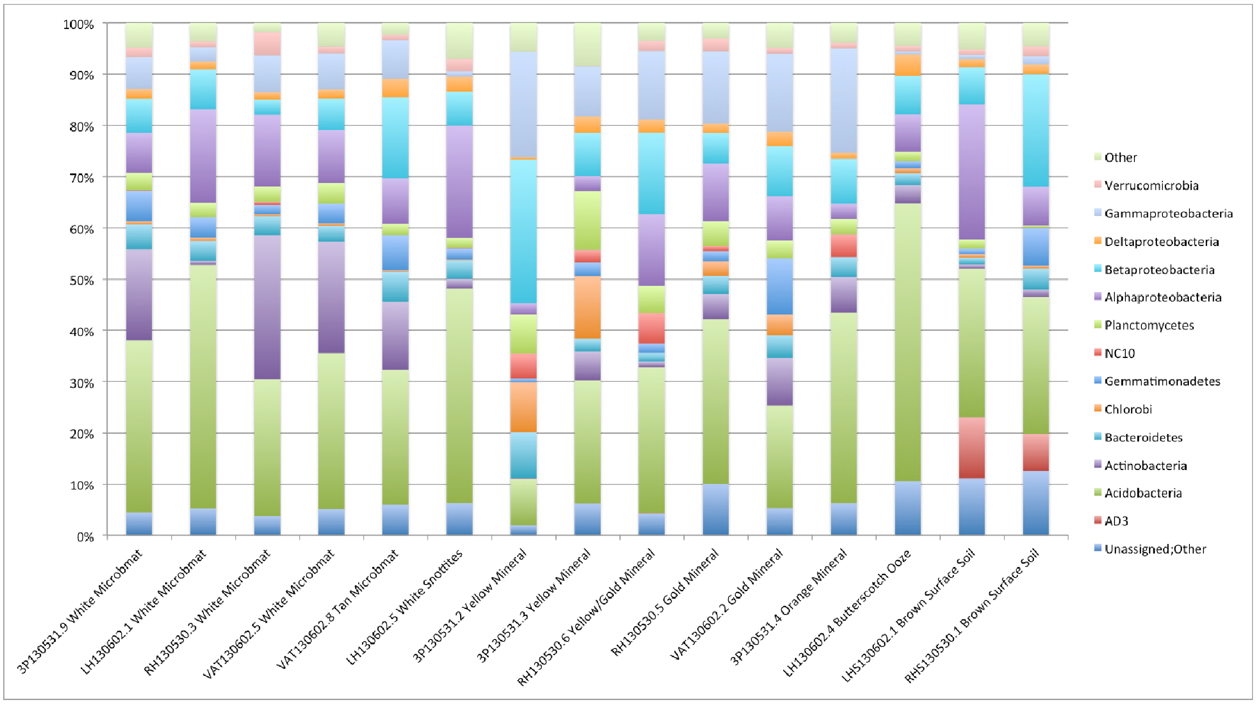

Figure 8: Bacterial phyla composition arranged by sample type, color, and cave.

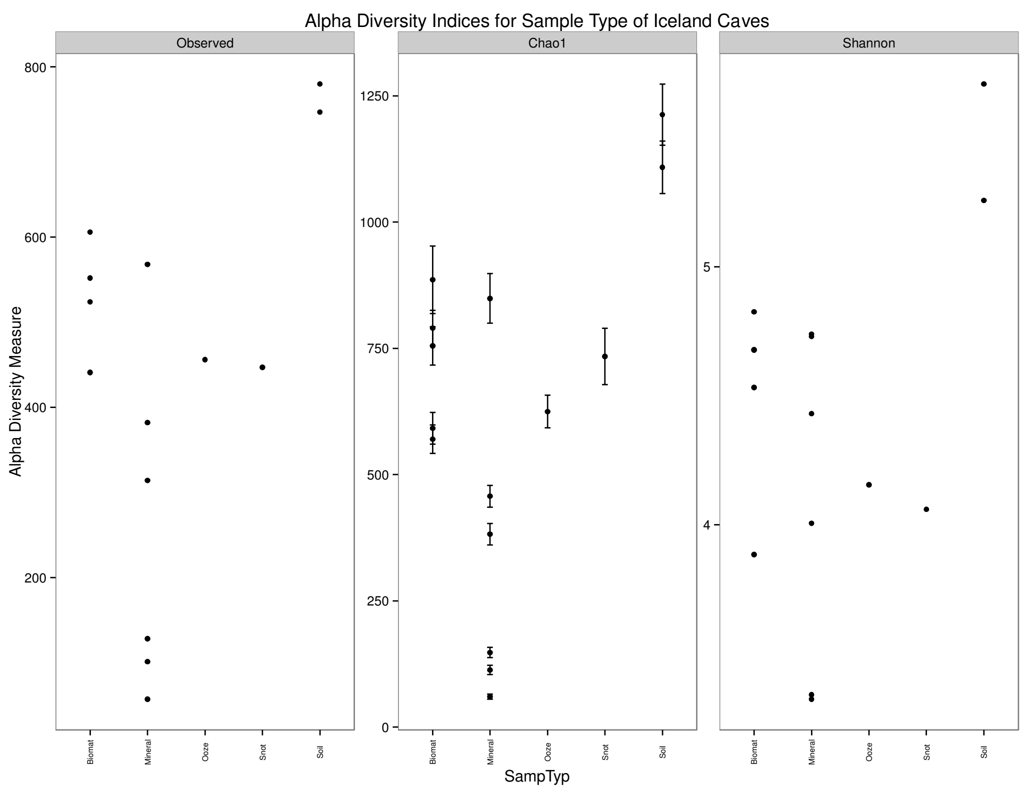

Figure 9: Alpha diversity by sample type: left to right on the x axis for each plot: biomat (microbial mat), mineral, ooze, snottite, surface soil.

Alpha diversity (the number of different operational taxonomic units (OTUs or "species") present in any given sample) varied within and across sample types. Surface soils were the most diverse, while half of the mineral samples were the least diverse. Snottites and ooze were at the bottom end of the diversity observed in microbial mats (Fig. 9). The non-metric multidimensional scaling (NMDS) observed in Fig. 10 reveals that the two surface soil samples were substantially different from the cave samples (biomat, mineral, ooze, and snot). The mineral and microbial mat (biomat) samples are mostly intermixed, revealing similarities in their makeup. Both the snottite and organic ooze samples were substantially different from the other cave samples.

NMDS plots by cave, color, surface versus cave, and by cave type were also done, but the most revealing was the substrate type, which appeared to be the most important factor so far studied in determining what controls diversity.

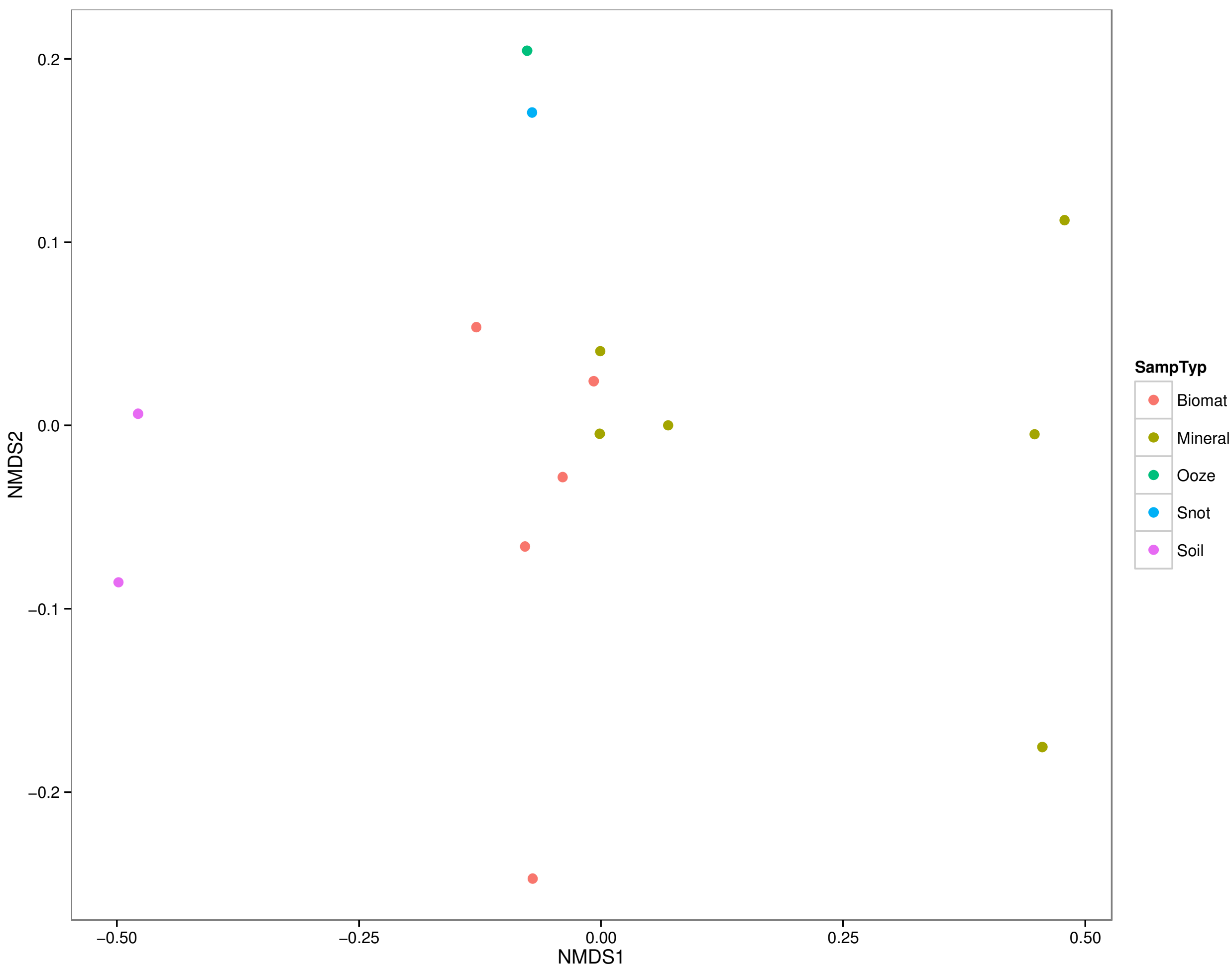

Figure 10: NMDS plot of diversity by sample type.

Conclusions

Samples of microbial mats, mineral deposits, a snottite, an organic ooze, and overlying surface soils were analyzed by SEM and DNA sequencing. SEM imaging revealed filamentous and coccoid morphologies, with biofilm present in some samples. DNA analysis demonstrated that the most abundant bacterial phyla present were the Actinobacteria, Acidobacteria and the Alpha-, Beta-, and Gammproteobacteria. Surface soils were the most diverse, followed by microbial mat samples. The mineral samples varied from not very diverse to some being comparable to some of the microbial mats. Organic ooze and snottites were moderately diverse. Icelandic lava caves offer a new and exciting frontier for investigating microbial diverse in la caves.

Acknowledgements

We are very grateful to Björn Olafsson and 3H Travel for providing air travel from Denver to Iceland for Northup and Ingham and for the funding to conduct the DNA sequencing. Gunnhildur Stefánsdóttir was very helpful with fieldwork and photography. We greatly appreciate the wonderful accommodations that she and Árni provided, as well as the transportation around Iceland.

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Mapping Volcanic Fissures at Kilauea

Keywords

Fissure eruptions, Volcanic Vents, Robotics, 3D Mapping

Authors:

Carolyn Parcheta, Jet Propulsion Laboratory, California Institute of Technology

Abstract

Volcanic fissure vents are a narrow, sub-vertical ground cracks that erupt magma. They are difficult to quantify due to their inherent danger and their extremely narrow size. Additionally, lava flows, lava drain back, or collapsed rampart blocks typically conceal a fissure's surface expression. When a fissure remains exposed, documenting the non-uniform distribution of wall irregularities, drain back textures, and the larger scale sinuosity of the whole fissure system can be done with our developed robotic mapping device: VolcanoBot. VolcanoBot maps the fissures from the **inside** after an eruption ends and the fissure cools off to <50 C. The robot uses a near-IR structured light sensor that can reproduce the 3d structure to cm-scale accuracy. Here we present a portion of our 3D model within the Mauna Ulu fissure system. We see a self-similar pattern of irregularities on the fissure walls throughout the entire shallow subsurface, implying a fracture mechanical origin similar to faults. These irregularities are typically 1 m across, protrude 30 cm into the drained fissure, and have a vertical spacing of 2 m. A horizontal spacing has yet to be determined. Irregularities are larger than the maximum 10% wall roughness used in engineering fluid dynamic studies, indicating that magma fluid dynamics during fissure eruptions are probably not as passive nor as simple as previously thought. Where piercing points are present, we infer the dike broke the wall rock in order to propagate upwards; where they are not, we infer that syn-eruptive mechanical erosion has taken place.

This work is funded by a NASA Postdoctoral fellowship through Oak Ridge Associated Universities.

Ice cave research in the Ice Caves on Mauna Loa (HI)

Andreas Pflitsch, Norbert Schorghöfer, Steve Smith, David Holmgren

Abstract

The Mauna Loa shield volcano (19 ºN 156 ºW), one of two summits over 4000 m a.s.l. on the Island of Hawaii, has a high density of lava tubes. The Hawaiian chain, the most isolated islands on earth with the highest summits in the North Pacific, is located in the northern tropics, and air temperatures inside lava tubes near sea level are well above 20 °C. At high elevations, the climate is alpine in character and snowfall and freezing temperature are possible any time of the year. Heavy storms occasionally bring snow to the tallest summits of Hawaii, but at elevations below 3,350 m any snow vanishes quickly. Mean annual temperatures are well above freezing, even on the summit. Many of the high altitude lava tubes on Mauna Loa have icy floors during winter months or seasonal icicles, but perennial ice has rarely ever been reported in Hawaii. Patches of buried permafrost were once documented near the summit of the other tall volcano on the island, Mauna Kea.

We provide the first detailed documentation of a lava tube cave with permanent ice on the Hawaiian Islands. "Mauna Loa Icecave" had been surveyed in 1978; we periodically visited the cave and monitored temperature, humidity, and ice levels from 2011 to 2015. Perennial ice still blocks the lava tube at the terminal end, but a previously present large ice floor (estimated 260 m^2) has disappeared. Airflow measurements, scallop patterns in the ice, strong temperature and humidity variations, and ice volume fluctuations indicate ventilation of the cave, which suggests that additional ice loss could occur rapidly. But the last year showed us some interesting changes.

Andreas Pflitsch, Steve Smith, David Holmgren, Michael Killing Heinze, Katharina Scherink

Climatologic research in the lava tubes on Big Island (HI)

Abstract

Cave ecology is the main reason to investigate cave climatology inside lava tubes (pyroducts). Organisms living there are highly specialized and adapted to the conditions, which is why even small changes (for example induced by anthropogenic interventions) can decimate entire species. In this context, the insularity of Hawai'i is especially important since it allows isolated observations of fauna and flora. Hawaiian pyroducts now provide a research area for numerous sciences. Lacking solar radiation and the relatively constant temperatures underground create conditions well suited to preserving archaeological findings over a long time. The same is true for cave deposits (e.g., cave ice) which can be used in paleo-climatological studies since they can be found inside Hawaiian pyroducts as well.

However, only little is known about the climatic conditions inside lava caves – distinctly less than about similar processes in karst caves. The speleo-climatological research done in Hawai'i addresses this deficit.

As classic primary caves with a comparably short genesis, lava tubes differ clearly from caves developing slowly through dissolution processes. Both types show further distinctive features, e.g., the surrounding bedrock, the covering and entrance structures. Therefore, it is to be expected that there is a notable difference between both the short-term meteorological processes and the climatic characteristics of both cave types.

Presumably, the available results of climate measurements in karst caves can only partly be transferred to lava caves. To close this gap, the research center 'AKEAKAMAI' was founded in 2013 on Big Island, Hawai'i, in order to investigate the meteorological and climatic conditions inside lava caves.

First measurements, however, started as early as 2011 on the Mauna Loa – meanwhile, a measurement series is available for the last four years. During the following years, further measurements were added to the program. Within the scope of the presentation, the different measurements will be presented as well as some first results.

Technical Report HCSU-068

WINTER DISTRIBUTION AND USE OF HIGH ELEVATION CAVES AS FORAGING SITES BY THE ENDANGERED HAWAIIAN HOARY BAT, LASIURUS CINEREUS SEMOTIS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract

We examine altitudinal movements involving unusual use of caves by Hawaiian hoary bats, *Lasiurus cinereus semotus*, during winter and spring in the Mauna Loa Forest Reserve (MLFR), Hawai'i Island. Acoustic detection of hoary bat vocalizations, were recorded with regularity outside 13 lava tube cave entrances situated between 2,200 to 3,600 m asl from November 2012 to April 2013. Vocalizations were most numerous in November and December with the number of call events and echolocation pulses decreasing through the following months. Bat activity was positively correlated with air temperature and negatively correlated with wind speed. Visual searches found no evidence of hibernacula nor do Hawaiian hoary bats appear to shelter by day in these caves. Nevertheless, bats fly deep into caves as evidenced by numerous carcasses found in cave interiors. The occurrence of feeding buzzes around cave entrances and visual observations of bats flying in acrobatic fashion in cave interiors point to the use of these spaces as foraging sites. *Peridroma* moth species (Noctuidae), the only abundant nocturnal, flying insect sheltering in large numbers in rock rubble and on cave walls in the MLFR, apparently serve as the principal prey attracting hoary bats during winter to lava tube caves in the upper MLFR. Caves above 3,000 m on Mauna Loa harbor temperatures suitable for *Pseudogymnoascus destructans* fungi, the causative agent of White-nose Syndrome that is highly lethal to some species of North American cave-dwelling bats. We discuss the potential for White-nose Syndrome to establish and affect Hawaiian hoary bats.

Introduction

Altitudinal migration of an animal population infers an annual return movement of all or part of the population between breeding and non-breeding areas that differ in elevation (Dixon and Gilbert 1964; Rabenold and Rabenold 1985). Altitudinal migration occurs in at least 61 species of bats (McGuire and Boyle 2013). The underlying reasons for most of these migrations usually are driven by seasonal roosting requirements including those involving hibernation or by seasonal segregation of males and females as occurs in North American hoary bats, *Lasiurus cinereus cinereus* (Cryan *et al*. 2014).

First documentation of a potential altitudinal migration by Hawaiian hoary bats, *Lasiurus cinereus semotus,* was made by Menard (2001) based on historical museum specimen collection records and substantiated by acoustical monitoring in Todd (2012) and Gorresen *et al*. (2013). The extensive 5-year acoustic data set of Gorresen *et al*. (2013) describes this bat species as breeding in lowlands at or below 1,000 m with much of the population active in montane regions during winter through early spring on Hawai'i Island. However, the latter data set did not sample above 2,000 m asl, whereas, Hawaiian hoary bats historically are known to have a distributional range from sea level to near 4,000 m elevation (Hawai'i Natural Heritage Program 2001). Thus a notable part of the species' behavior and ecology, that taking place above 2,000 m, has not been investigated and the ecological reasons for its annual altitudinal movement patterns remain poorly understood.

The association of Hawaiian hoary bat carcasses present deep inside lava tube caves on the north east flank of Mauna Loa and occasional observations of live bats roosting in rock crevices elsewhere has been reported by Tomich (1974 and 1986). Tomich attributed all bat carcasses found in caves of Hawai'i as "appear to have entered the caves accidentally". Tomich (1986) also reported fat deposits of 20–25% of total body mass during early winter for Hawaiian hoary bats as possible preparation for "lesser activity during cooler months"; however he cautioned that "winter torpor or colonial occupancy of deep cave shelters is yet to be demonstrated" (Tomich 1974).

Understanding the use of high elevation habitats by the Hawaiian hoary bat is an important management issue for this endangered subspecies because 1) these habitats are used to an unknown extent during the poorly documented winter portion of the bat's annual cycle and 2) high elevation habitats on Hawai'i Island include numerous caves with microclimates that potentially could harbor *Pseudogymnoascus destructans*, the fungus that is the causative agent of White-nose Syndrome (WNS). WNS has caused fatalities leading to population declines for several species of bats in eastern continental North America (Lorch *et al*. 2011, Blehert *et al*. 2009). The fungus infects the skin of bats while they hibernate leading to physiological and energetic disruption of hibernation such that fatality rates can be enormous in infected populations (Lorch *et al*. 2011, Warnecke *et al*. 2012, Minnis and Lindner 2013). It recently has been found that *Lasiurus borealis* and *Lasionycteris noctivagans*, two tree-roosting, migratory bats, can be carriers of *P. destructans* (USFWS 2014, Bernard *et al*. 2015); thus locating the wintering grounds of hoary bats as well as learning about the possible use of winter torpor are important steps in learning if there is potential vulnerability to WNS by hoary bats (Cryan *et al.* 2014).

Our current study examines the winter ecology and movement patterns of Hawaiian hoary bats at elevations between 2,200 and 3,600 m in the Mauna Loa Forest Reserve (MLFR). We surveyed the airspace surrounding 13 cave entrances as well as the cave interiors with the following objectives: 1) document monthly patterns of bat presence in the vicinity of cave entrances by quantifying acoustic activity with ultrasonic recording detectors; 2) survey cave interiors to visually look for evidence of hibernacula; and 3) assess if there is a potential risk of White-nose Syndrome effecting Hawaiian hoary bats in caves of the MLFR. Finally, we examine the hypothesis that Hawaiian hoary bat flight activity and foraging in the MLFR is influenced by local weather conditions.

METHODS

Study Area

Our study was conducted in the MLFR, Hawai'i Island (Figure 1). The MLFR spans elevations from approximately 2,000 m to the summit of Mauna Loa Volcano at 4,169 m asl. We placed acoustic recording stations in the immediate vicinity of 13 lava tube cave entrances at elevations between 2,261 and 3,562 m (Table 1). Many additional lava tubes occur in the reserve; however, we selected lava tubes for acoustic sampling to provide a large gradient of elevation and with a known presence of bat remains. The lava tubes in our study formed from eruptions of Mauna Loa Volcano, some as recently as 172 years before present (ybp) with the oldest dated as 3,000 ybp (Wolfe and Morris 1996). The lava fields of MLFR consist almost exclusively of tholeitic basalt forming two principle types of lava flows: a'a and pāho'eho'e (Wolfe and Morris 1996). Younger lava fields around our study caves are barren lava with almost no vegetation present (Figure 2). Older lava fields support scattered low shrubs (Figure 3) that include pūkiawe (*Styphelia tameiameiae*), 'a'ali'i (*Dodonaea viscosa*), 'ōhelo 'ai (*Vaccinium reticulatum*) and the dwarf trees of 'ōhi'a lehua (*Metrosideros polymorpha*). Some habitat islands of dwarf forest consisting primarily of 'ōhi'a lehua also occur in the reserve, but are not a common landscape feature above 2,000 m. Precise lava tube cave coordinates are withheld by agreement with the Hawai'i Division of Forestry and Wildlife due to the sensitive ecological and cultural attributes of these caves. We list the 13 caves (Table 1) by numerical codes (1–13) with increasing elevation.

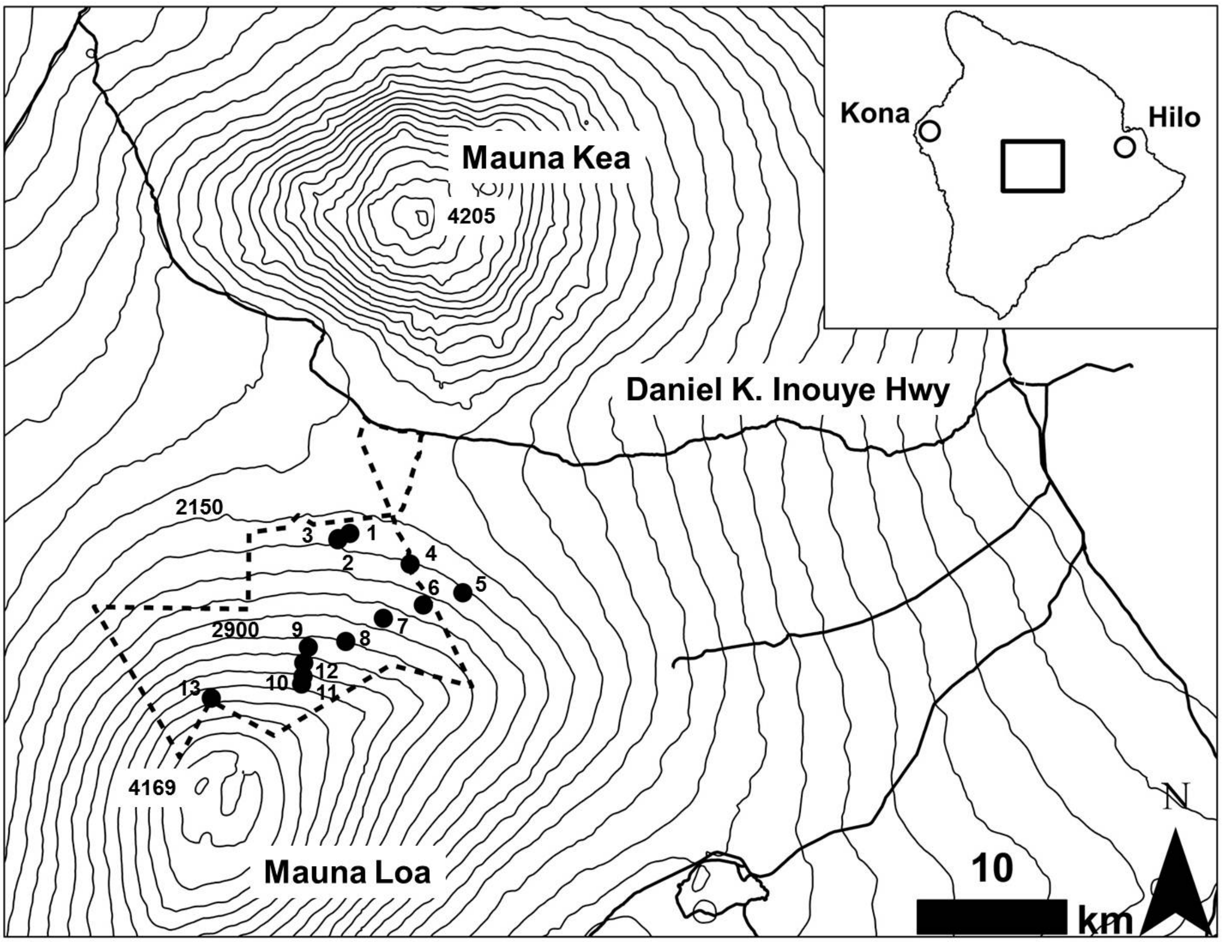

Figure 1. Hawai'i Island with the study area (rectangle of inset map) in the Mauna Loa Forest Reserve. Reserve boundaries are indicated by dashed lines, principle roads by heavy black lines, and contours of elevation in m asl by concentric thin black lines. The 13 lava tube cave entrances are numbered dots (caves 2 and 3 are superimposed).

Table 1. Cave number, elevation, substrate age, and nights sampled for bat activity at 13 lava tube caves in the Mauna Loa Forest Reserve.

Cave Number	Elevation (m)	Substrate Age*	Nights Sampled
1	2,261	1	111
2	2,277	4	27
3	2,286	4	154
4	2,341	3	104
5	2,341	4	129
6	2,533	4	131
7	2,725	3	129
8	2,979	3	157
9	3,045	2	76
10	3,191	2	96
11	3,338	2	114
12	3,393	2	111
13	3,562	3	56

*Substrate age classes (Wolfe and Morris 1996) in years before present: 1 = 172, 2 = 200–750, 3 = 750–1,500, 4 = 1,500–3,000.

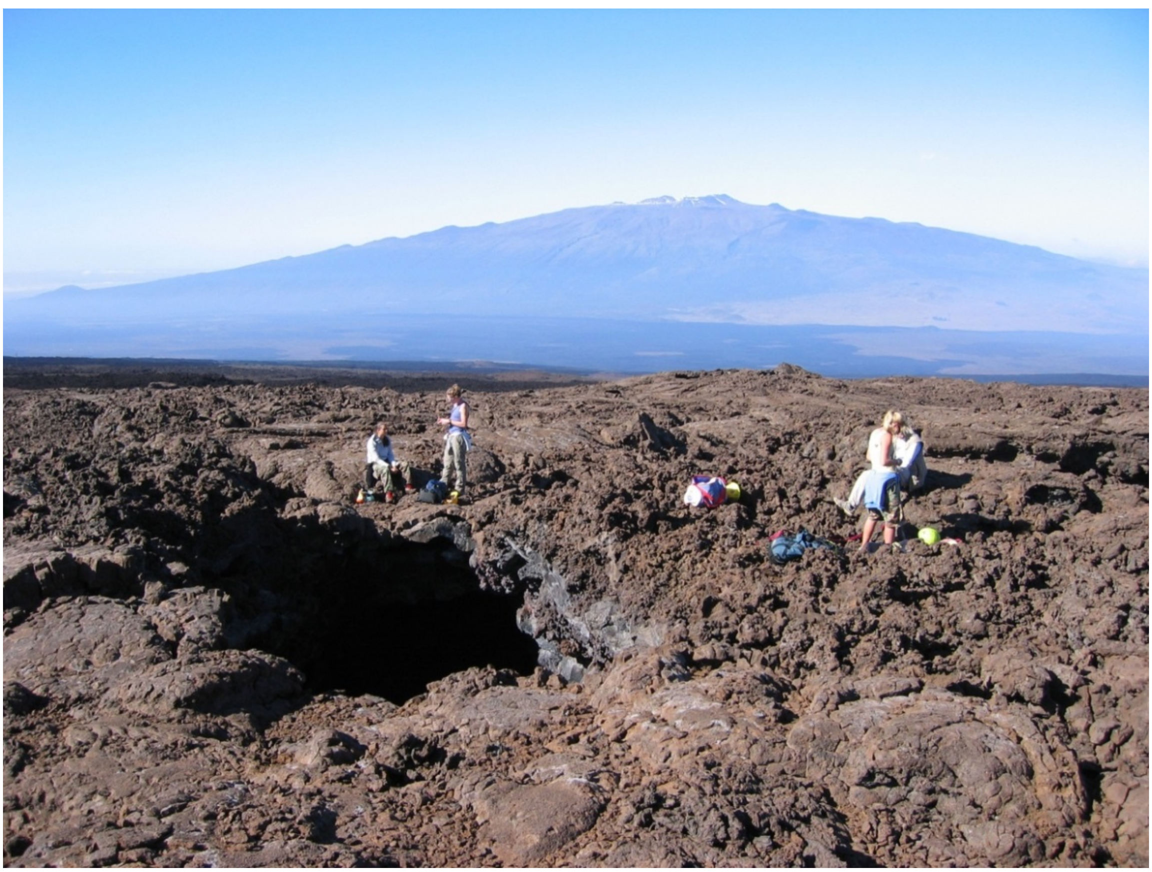

Figure 2. Entrance to cave 8 showing barren a'a lava. Mauna Kea is the volcanic peak in the background.

Figure 3. Pāho'eho'e lava flow (1,500 to 3,000 ybp) at the entrance to cave 3 and co-author, K. Montoya-Aiona.

Annual rainfall in the MLFR averages approximately 200 mm (Giambelluca *et al.* 2013). Although heavy fogs add some moisture in addition to rainfall, the reserve is situated above the usual cloud inversion layer (ca 1,700 m; Giambelluca and Schroeder 1998) and many nights are clear.

Acoustic Detection Protocols

Ultrasonic vocalizations of Hawaiian hoary bats, including search phase and terminal phase calls (Griffin 1970) hereafter referred to as "feeding buzzes", were recorded from November 2012 through April 2013. SM2Bat+ (SM2Bat) Song Meter Digital Field Recorders (Wildlife Acoustics, Concord, MA) capable of recording ultrasound between 20 and 100 kHz were deployed at each of 13 cave entrances in our study area. Cave 2 was dropped from further recordings in December 2012. Our recording stations ranged between 2,261 and 3,562 m asl. Each SM2Bat was programmed to record from one hour before local sunset until one hour after local sunrise. Recordings were made a total of 1,395 site specific recording-nights. SM2Bat units consisted of a waterproof housing, an external temperature sensor, 4 D-cell batteries, and each was attached by a wood mount onto a 3-meter galvanized steel pole (Figure 4). High frequency SMX-US microphones (Wildlife Acoustics) were placed approximately 2 to 3 m above the lava substrate and connected by cable to the SM2Bat microphone port.

Figure 4. An acoustic recording station with SM2Bat recording unit (green box) attached to a galvanized steel pole. An extension cable connected to a high frequency microphone is wrapped around the pole to secure it from high winds.

High frequency microphones are capable of recording bats at distances up to 100 m under ideal conditions; however, the range of call detection varies with weather conditions and orientation of the bat's head relative to the microphone. Upon detection of a vocalizing bat a sound file is generated with the appropriate date and time.

We set SM2Bats to record in zero-crossings mode. Sequences of ultrasonic pulses from a bat, defined as a "call event", were filtered to remove background noise, and counted for each sampling night using Kaleidoscope (Wildlife Acoustics, version 1.1.0). Individual echolocation "pulses", including those from search and feeding buzz calls, also were counted within each call event using AnalookW (version 3.8; Corbin 2012). We visually inspected call events to count feeding buzzes indicative of attacks on prey (Britton and Jones, 1999 and Griffen at al. 1960). Feeding buzzes are recognized by a rapid increase in pulse repetition rate and decrease in inter-pulse interval.

Statistical Analysis

All statistical analyses were conducted using the program R (version 3.1.2, R Development Core Team, 2014) except where other programs are noted. Detection probability values, henceforth referred to as "detectability" from occupancy analysis (MacKenzie *et al*. 2006) represent the probability of detecting a bat at a microphone on a given sampling night. Detectability was calculated during each sampling month using Presence (version 6.4: J. Hines 2006). Detectability of 1.0 was equivalent to recording bat calls at all detectors every sampling night. A threshold of at least one confirmed call event with ≥ 3 echolocation pulses/night was applied to all data. Zero detectability represented no verifiable bat calls during an entire sampling period. Monthly differences in activity parameters and detectability were analyzed for significance using ANOVA.

A spatial distribution analysis of monthly mean bat activity across 12 lava tube entrances was calculated and mapped using the weighted standard deviational ellipse tool in ArcGIS (version 10.2.1, ESRI, 2013). We used a one standard deviation ellipse polygon for each month weighted by the number of echolocation pulses recorded. Each monthly ellipse illustrates central tendency of distribution of bat activity across the 12 caves. Smaller ellipses represent more concentrated areas of bat activity.

We compiled hourly measurements of wind speed, barometric pressure, and precipitation from the Global Monitoring Division at the Mauna Loa Observatory located adjacent to cave 6 in Figure 1 (NOAA Earth Systems Research Laboratory 2014) to test if these variables influence bat activity. Mean hourly temperature was recorded from external sensors on SM2Bat units at five minute intervals.

We used both multiple regression and quantile regression to examine potential patterns between bat echolocation activity and temperature, wind speed, and barometric pressure. Because measureable precipitation occurred only on two nights during our study, we removed it from the analysis. We restricted these analyses to data from caves 11 and 12 because bat activity was greatest at these caves and expected to be strongly weather dependent due to the extreme conditions at the high elevations represented. Additionally, we examined the relationship between bat echolocation activity and wind speed with a t-test to compare the means of hourly bat activity above and below wind speeds of 6 m/sec.

Linear quantile regression of bat activity with temperature, wind speed, and barometric pressure were examined using quantiles 0.10, 0.25, 0.50 (median), 0.75, and 0.90 (Cade and Noon 2003). For example, the 0.10 quantile examines the relationship between 90% of bat echolocation activity and a weather variable such as temperature while the 0.90 quantile examines the relationship between the upper 10% of the bat echolocation activity and a weather variable. Statistics for quantile regression including slope coefficients, standard errors, 95% CIs, t-statistics, and p-values were calculated using the rank inversion method and default settings in the package "quantreg" (Koenker 2001, Koenker and Hallock 2007).

Visual Searches for Hibernacula

Each of the 13 caves in our study was examined one to three times between November 2012 and February 2013 by visual searches of all substrates from floor to ceiling. Searches were conducted by at least two persons slowly walking the length of the cave. We looked for signs of bats including live animals flying or roosting, mummified or skeletonized carcasses, guano, or substrate staining caused by roosting bats. All signs of bats were noted in detail and mapped.

RESULTS

Seasonal Acoustic Patterns

Hawaiian hoary bats were detected vocalizing in the airspace around all of our 13 monitored cave entrances. During 1,395 detector nights, vocalizations were recorded at a mean of 46.6% ± 16.2% of the nights sampled (Table 2). The numbers of recorded vocalizations (Figure 5) at caves 11 and 12 far exceed those of all other caves. In December 2012, cave 2 was dropped from further sampling. Pooled monthly mean detectability from the remaining 12 caves over the entire survey (Figure 6.) was significantly higher during November and December ($F_{5,59} = 7.8$, $p < 0.001$); however, there was no significant difference in pulse number recorded between months ($F_{5,55} = 1.71$, $p = 0.15$).

Table 2. Call event and echolocation pulse summary at caves in the Mauna Loa Forest Reserve from November 2012 to April 2013.

Cave Number	Nights with Bat Calls	Call Events	Pulses	Call Events /Night ± SD	Pulses/Night ± SD	% Nights with Calls/Month ± SD
1.	71	161	684	1.74 ± 1.01	9.80 ± 10.53	51 ± 0.14
2.	17	28	104	1.64 ± 0.99	6.88 ± 5.51	58 ± 0.00
3.	56	86	415	1.53 ± 0.85	7.94 ± 10.19	37 ± 0.17
4.	48	125	444	2.60 ± 1.65	9.41 ± 7.57	42 ± 0.40
5.	75	264	1,656	3.52 ± 2.96	22.0 ± 28.50	59 ± 0.42
6.	65	163	857	2.29 ± 1.59	12.07 ± 13.00	54 ± 0.22
7.	73	238	1,216	3.26 ± 2.63	16.65 ± 21.72	59 ± 0.36
8.	45	77	568	1.65 ± 0.92	12.60 ± 15.39	29 ± 0.19
9.	44	86	616	2.00 ± 1.24	13.62 ± 14.67	38 ± 0.13
10.	54	310	2,822	4.68 ± 4.61	50.11 ± 65.40	60 ± 0.33
11.	55	1032	10,370	18.10 ± 40.54	181.00 ± 459.63	52 ± 0.25
12.	67	1334	15,215	19.91 ± 26.35	227.08 ± 408.82	62 ± 0.26
13.	2	10	116	5.00 ± 0.00	58.00 ± 56.57	5 ± 0.08
Total	672	3,914	35,083	5.22 ± 6.23	48.24 ± 78.58	47 ± 16

In November, echolocation activity as shown by mean ellipses (Figure 7) was concentrated below 3,000 m around caves 1, 3, 4, 7, and 8. In December and January, activity ellipses were located above 2,900 m around caves 8, 9, 10, 11, and 12. In February and March, bat activity was distributed over a large range of elevations and caves from 2,300 to 3400 m. The highest cave sampled, cave 13 (3,562 m), as well as cave 5 (2,341 m) generally had little bat activity throughout our study.

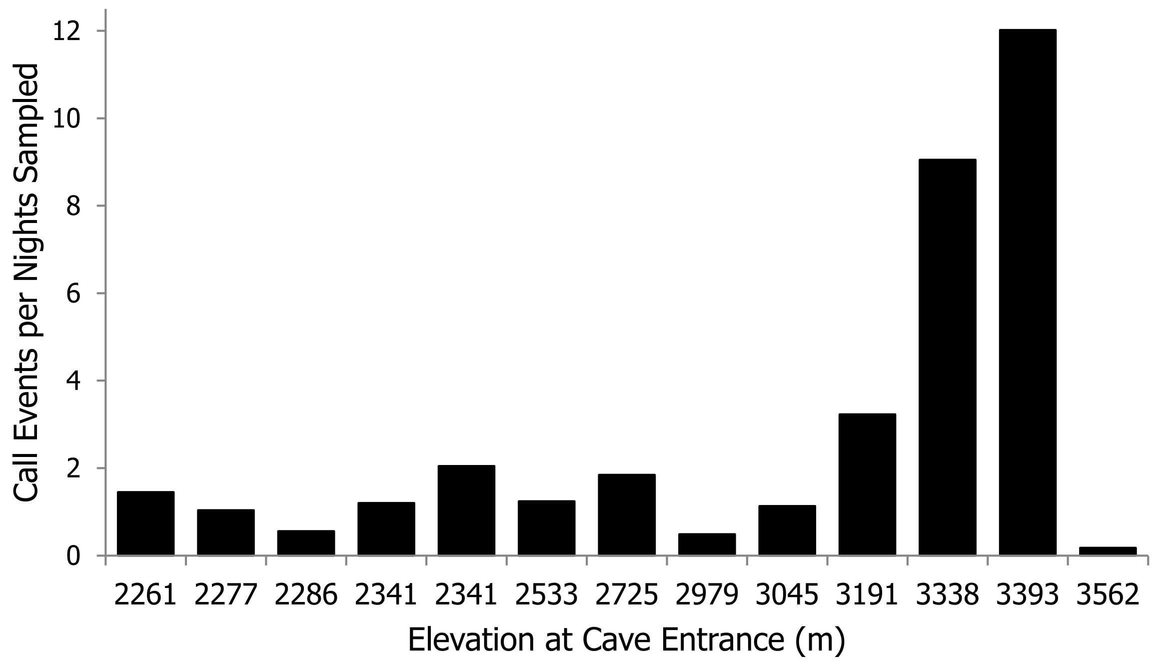

Figure 5. Cumulative call events recorded at 12 cave entrances from November 2012 to April 2013. Call events are standardized to number of sample nights for each cave. Caves are listed by increasing elevation.

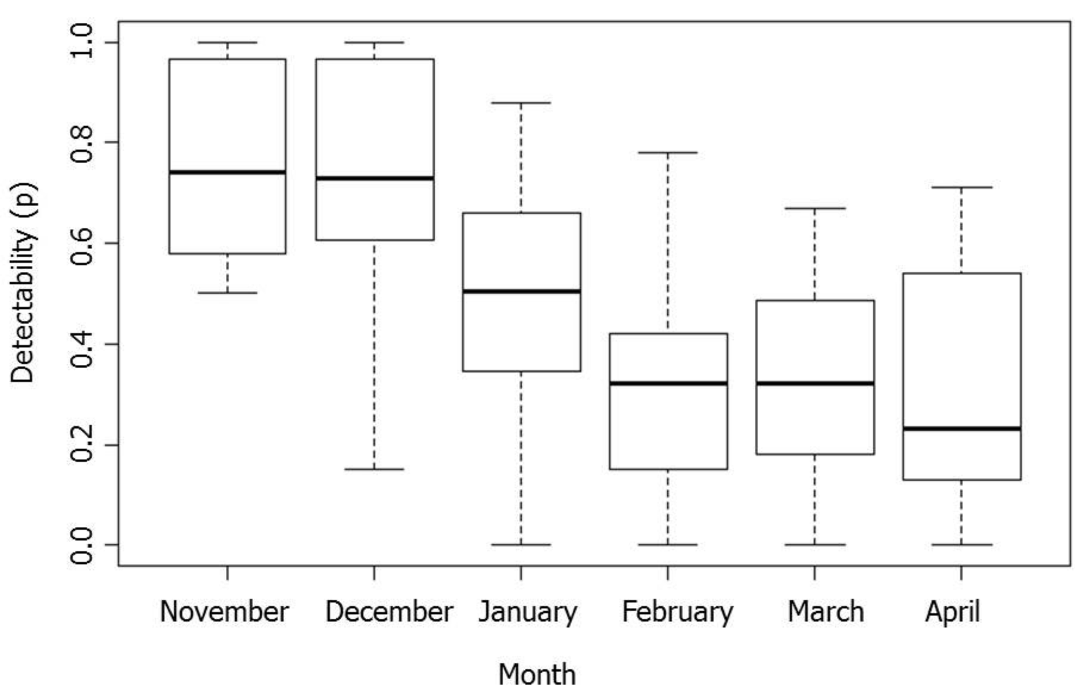

Figure 6. Pooled monthly detectability of bat echolocation calls from all caves. Boxes are interquartile ranges, bold black lines are medians, and dashed lines are minima and maxima.

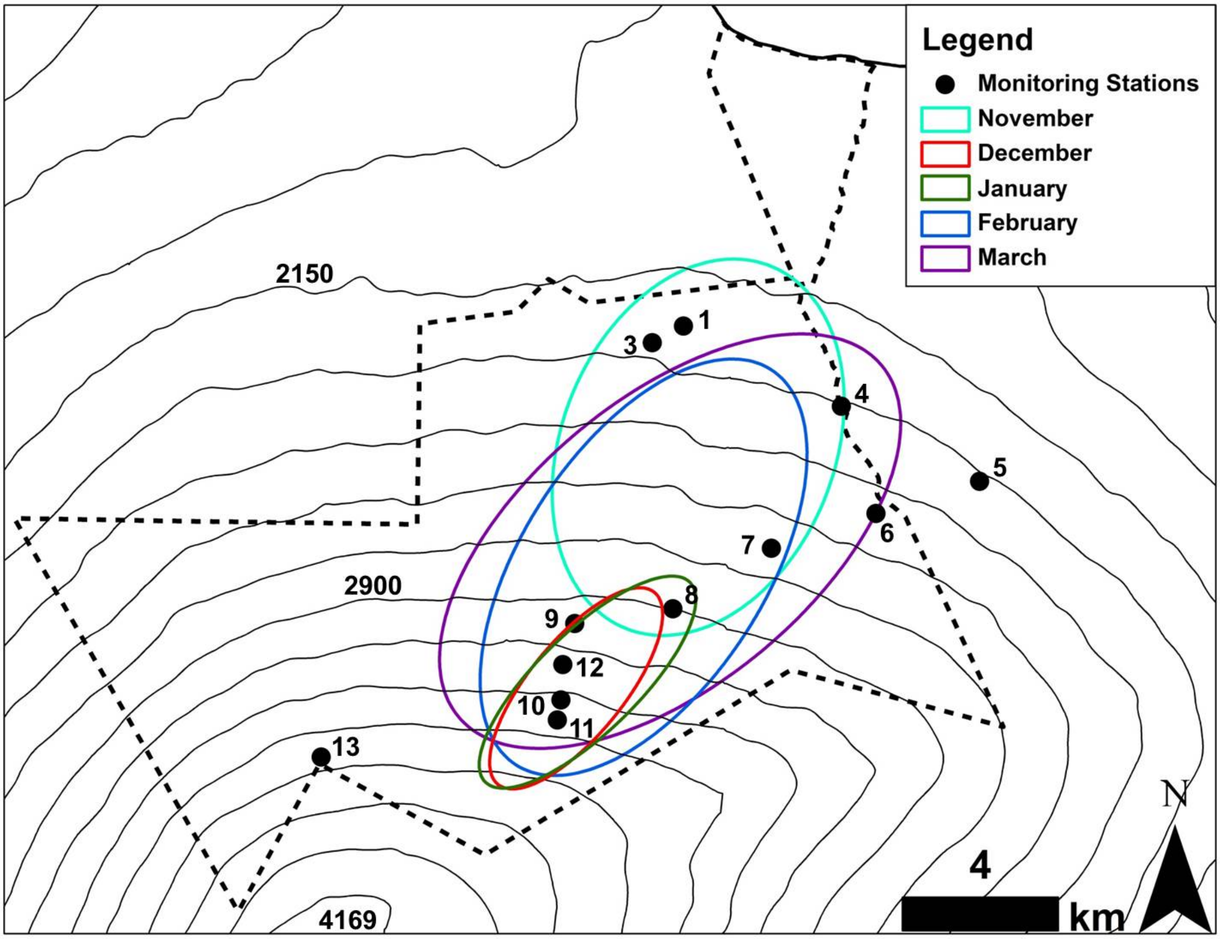

Figure 7. Ellipses of mean echolocation pulse number at cave entrances in the Mauna Loa Forest Reserve, November 2012 to March 2013. Cave numbers and elevations are listed in Table 1.

Hourly Within Night Bat Activity

Echolocation calls often were recorded through prolonged portions of the night at caves situated below 3,000 m asl. For example, during December 2012, bat calls were recorded at cave 5 (2,340 m asl) from about 1700 (sunset) until 0400 hr when air temperatures fell to about 8 °C, the minimum air temperature recorded at this cave entrance during that month (upper graph, Figure 8). The maximum number of echolocation pulses/hr recorded was 145. Throughout January average nightly temperatures approached 5 °C by 2300 hr at cave 5 and bat calling sharply decreased coinciding with this temperature (lower graph, Figure 8).

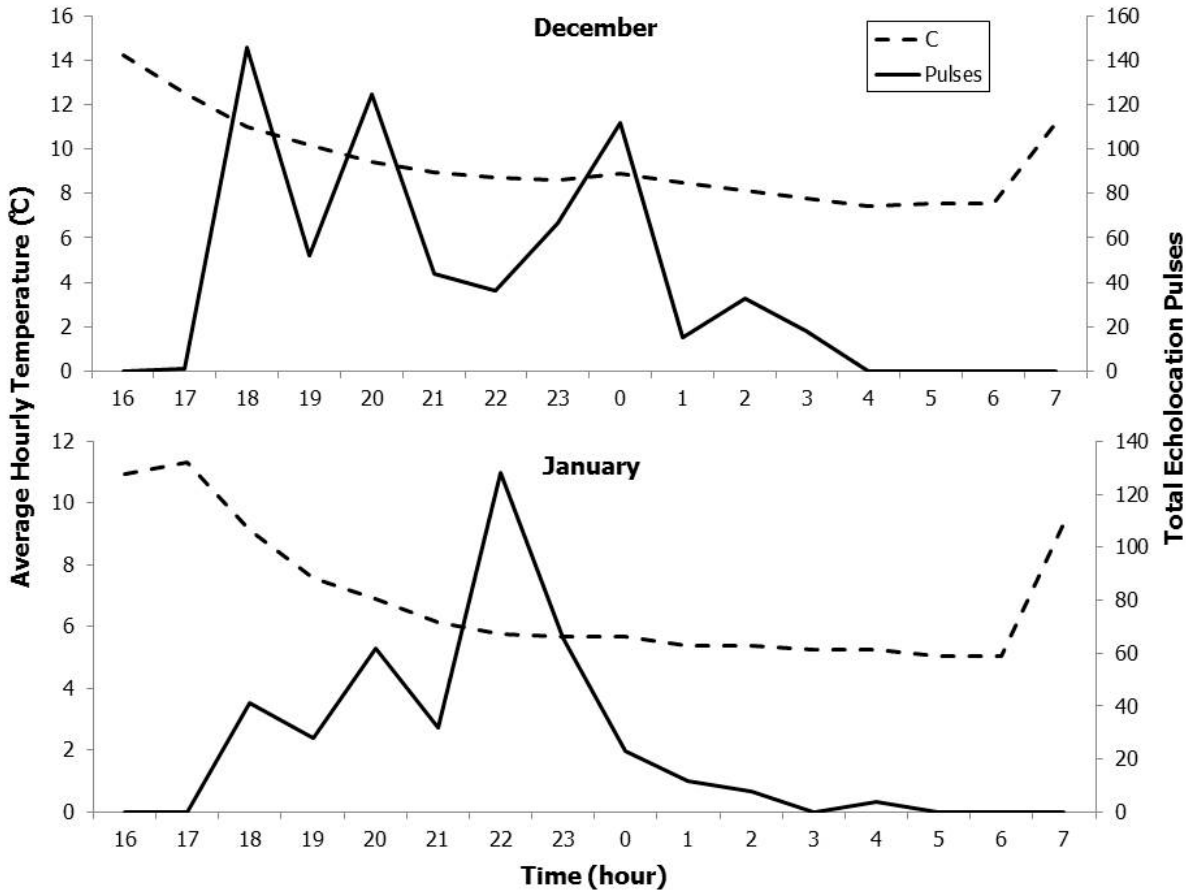

Figure 8. Hourly mean air temperature (°C) and bat echolocation pulse number during December 2012 and January 2013 at cave 5; 2,340 meters asl.

Bat calling peaked in the first two hours of darkness at all cave entrances above 3,000 m asl during December through February with little subsequent calling in subsequent hours as air temperatures fell below 8 °C (see example for cave 12 in Figure 9). Even with a narrow temporal window of activity early in the night, the total number of call pulses recorded at caves 11 and 12 were an order of magnitude greater than at any other caves during winter months (Table 2).

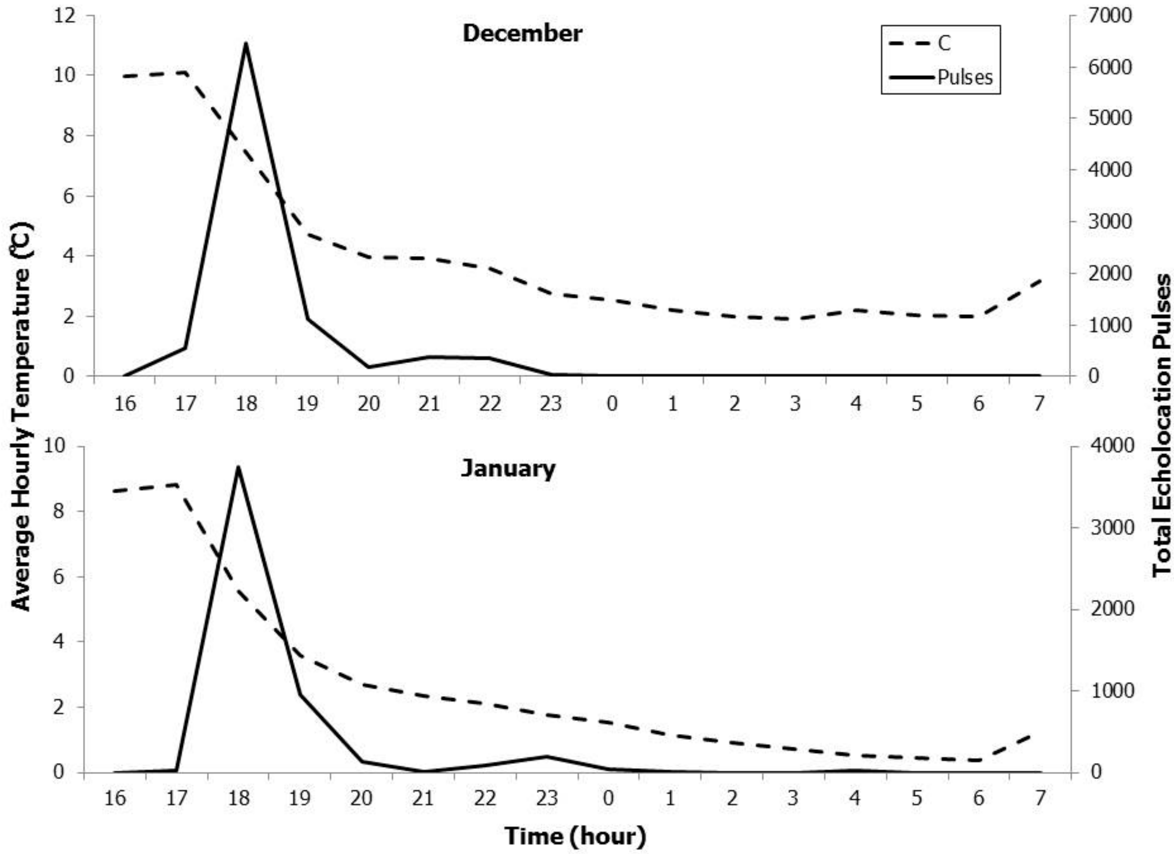

Figure 9. Hourly mean air temperature and bat echolocation pulse number during December 2012 and January 2013 for cave 12; 3,400 meters asl.

Influence of Weather on Bat Activity

Our analysis of the influence of weather variables on bat echolocation activity is focused around two high elevation caves, 11 and 12, where calling activity was most frequent. We sampled 1,470 hourly periods, 203 of which had bats present and thus were used in multiple regression and quantile regression analyses. Bats were not detected during 1,267 of the hourly observations.

Multiple regression of mean hourly echolocation activity greater than zero against temperature, wind speed, and barometric pressure measured at caves 11 and 12 (Figure 10) indicated that these variables had a significant influence on bat activity ($F_{3,175} = 5.8$, $p = 0.0008$, $R^2 = 0.0905$, $R^2_{Adjusted} = 0.0749$). Although the linear model was significant these weather variables explained only 9% of the variation observed in activity. Temperature, the most significant predictor, was positively correlated with echolocation activity ($\beta = 0.29$, $t = 3.7$, $p = 0.0002$, $R^2 = 0.07$; Figure 10a). Wind speed was almost significant and negatively correlated with echolocation activity ($\beta = -0.15$, $t = -1.9$, $p = 0.0530$, $R^2 = 0.01$; Figure 10b). Barometric pressure was not a significant predictor of echolocation activity ($\beta = -0.0004$, $t = -0.005$, $p = 0.9960$, $R^2 = -1.55e05$; Figure 10c). No significant interactions were found between any of these variables when tested in the linear model.

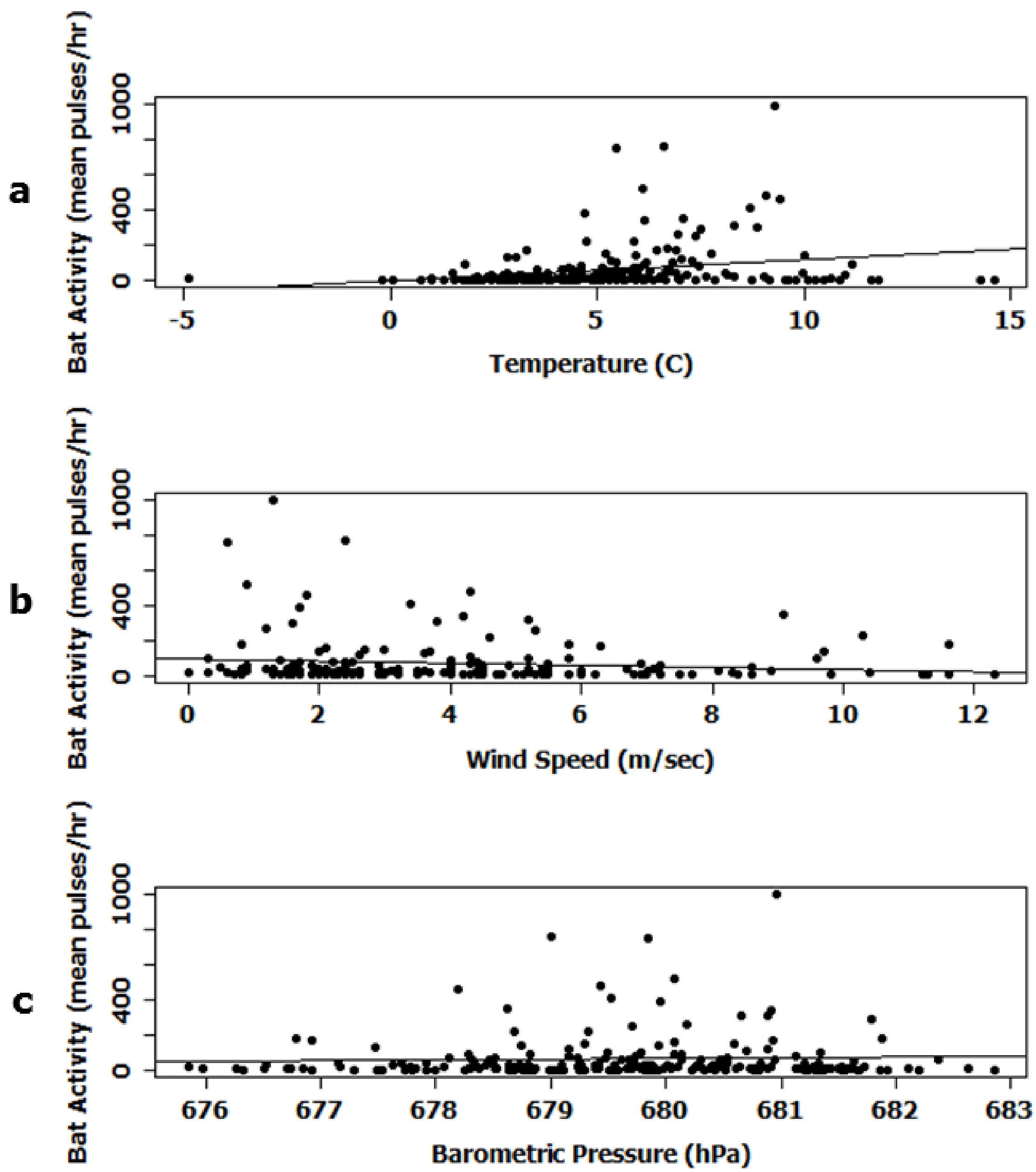

Figure 10. Relationship between mean hourly echolocation activity at caves 11 and 12 and a) temperature, b) wind speed, c) barometric pressure. Solid black circles represent hourly calling events. Regression lines represent the best fit line.

Quantile regression showed a significant positive relationship between hourly activity and temperature at the 75th and 90th quantiles (Figure 11a and Table 3). This relation with echolocation activity varies across the temperature scale and was strongest at the 90th quantile. Comparisons between the temperature slope coefficients at all quantiles 0.10, 0.25, 0.50, 0.75, 0.90 ($F_{4,1011} = 3.26$, $p < 0.05$) were significant.

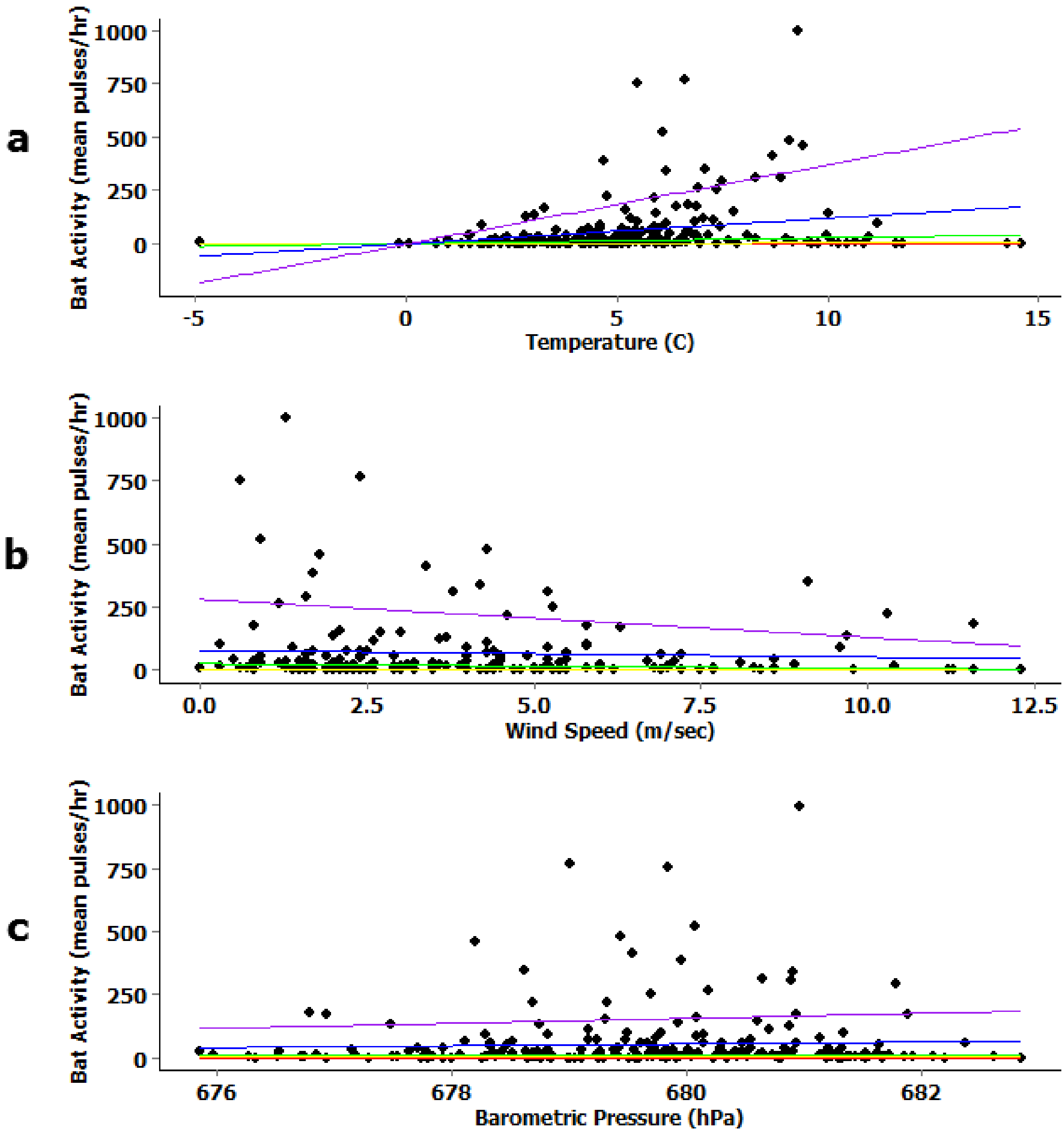

Figure 11. Relationship between mean hourly echolocation activity at caves 11 and 12 and a) temperature, b) wind speed, c) barometric pressure. Black diamonds represent hourly calling periods. Regression lines represent quantiles of 0.10 (red), 0.25 (yellow), 0.50 median (green), 0.75 (blue), and 0.90 (purple).

Table 3. Quantile regression of temperature, wind speed, and barometric pressure with echolocation activity.

Temperature						
Quantile	**Estimate**	**SE**	**Lower 95% CI**	**Upper 95% CI**	**t-value**	**p-value**
0.10	0.44	0.11	-0.09	0.09	0.38	0.70
0.25	0.27	0.32	-0.17	0.69	0.86	0.38
0.50	2.72	1.67	0.39	4.32	1.62	0.10
0.75	11.91	6.17	5.75	17.77	1.93	0.05
0.90	37.11	10.44	21.01	42.22	3.55	0.0004

Wind Speed						
Quantile	**Estimate**	**SE**	**Lower 95% CI**	**Upper 95% CI**	**t-value**	**p-value**
0.10	-0.20	0.06	-0.43	-0.04	-2.99	0.003
0.25	-0.32	0.24	-0.81	-0.07	-1.30	0.19
0.50	-1.80	5.56	-2.88	0.79	-1.70	0.09
0.75	-2.60	5.56	-7.91	9.42	-0.46	0.64
0.90	-15.11	13.38	-26.32	7.10	-1.09	0.27

Barometric Pressure						
Quantile	**Estimate**	**SE**	**Lower 95% CI**	**Upper 95% CI**	**t-value**	**p-value**
0.10	0.10	0.18	-0.23	0.23	0.57	0.56
0.25	-0.11	0.55	-0.47	0.69	-0.19	0.84
0.50	0.00	1.88	-3.22	2.20	0.00	1.00
0.75	3.75	7.86	-12.58	11.98	0.47	0.63
0.90	9.88	31.33	-4.47e01	4.6e01	0.31	0.75

Quantile regression showed a negative significant relationship between hourly echolocation activity and wind speed at the 10th quantile (Table 3 and Figure 11b). Overall, there was a negative trend, suggesting reduced bat activity at higher wind speeds (Figure 11b). Wind speed slope coefficients at all quantiles, including 0.10 vs 0.25 did not significantly differ. An unpaired t-test found no significant differences between the means of bat activity below or above wind speeds of 6 m/sec. Finally, there were no significant relationships between echolocation activity and barometric pressure using the quantile analysis (Table 3 and Figure 11c).

Foraging Activity

The percentage of nights having feeding buzzes pooled for all caves peaked during December and January and again during April (Figure 12). Feeding buzzes usually were observed only at air temperatures > 6 °C. Feeding buzzes were observed at all 12 caves that were monitored the entire study (Table 4); however, only cave 12 had > 50 feeding buzzes/month recorded. In December, multiple echolocating bats were observed in single call files at Cave 11 (n = 10) and at Cave 12 (n = 27).

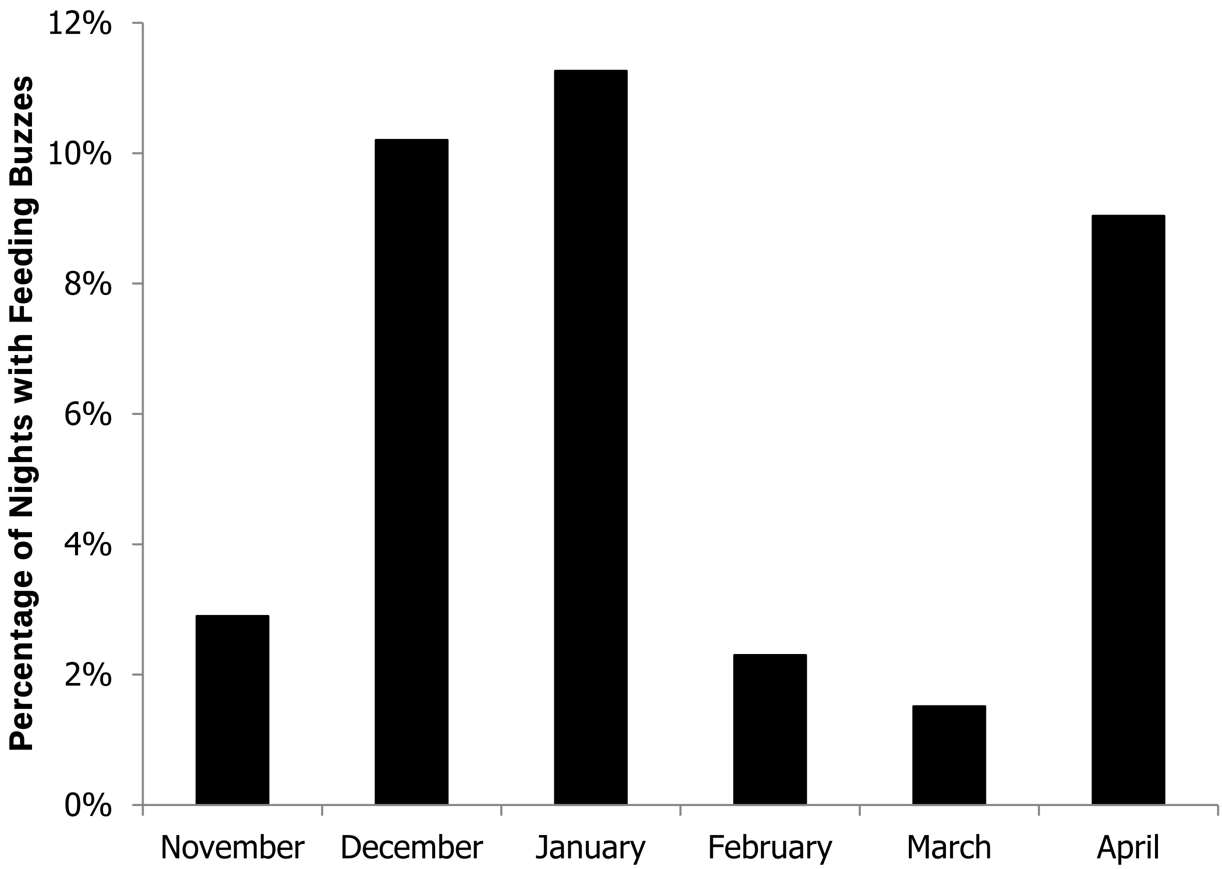

Figure 12. Percentage of nights having feeding buzzes pooled from 12 Mauna Loa Forest Reserve caves.

Table 4. Number of feeding buzzes recorded at cave entrances from November 2012 to April 2013 in the Mauna Loa Forest Reserve.

Cave Number	November	December	January	February	March	April
1	-	0	0	2	0	4
3	2	0	2	0	0	1
4	0	0	1	0	0	0
5	2	1	1	1	0	0
6	0	1	2	2	0	1
7	0	0	1	0	0	0
8	1	0	2	0	0	0
9	-	-	4	0	1	1
10	1	4	11	0	0	3
11	-	9	0	0	11	6
12	-	66	58	1	1	5
13	-	0	0	-	0	-

Visual Surveys of Cave Interiors

We visually searched for signs of bat use within caves during winter months, looking for living animals, carcasses, guano deposits, or wall staining. No signs of hibernacula or day roosts present or past were found in any Mauna Loa Caves. We did find skeletal remains (Figure 13), partially decomposed mummies with fur (Figure 14), and one fresh carcass (cave 11) perhaps only several days old (Figure 14). Twenty carcasses were found in cave 2, ~100 in cave 3, ~200 in cave 8, and seven in cave 12.

We also found living and dead cutworm moths of the genus *Peridroma* (Noctuidae) in all caves. The genus *Peridroma* is broadly distributed in Eurasia, Northern Africa, the Middle East, and North America in addition to Hawai'i and other Pacific islands. Several endemic species have been described for Hawai'i and additional species are likely to be described in the future. Peridroma occurring in the MLFR (Figure 15) have a body length of about 20 mm representing a prey size suitable for Hawaiian hoary bats (Jacobs 1999). Populations in MLFR now mostly live in rock rubble on the floors of the lava tubes although immense populations of these moths covered walls and ceilings of many lava tubes on the Island of Hawai'i in historic times (F. Howarth, personal communication). *Peridroma* populations declined severely early in the 20th Century as a result of biological controls released to protect sugar cane from the larvae of this grass feeding genus.

Figure 13. Skeleton of a Hawaiian hoary bat on a cave floor. Photo by F. Bonaccorso.

Figure 14. Partially decomposed and mummified Hawaiian hoary bat on rubble of a cave floor (Left Photo: F. Bonaccorso) and a few day old Hawaiian Hoary Bat carcass with a fungal infestation on a cave floor (Right Photo: C. Todd).

Figure 15. A *Peridroma* sp. moth on an ice flow covering the floor of cave 13 (Photo: S. Smith).

DISCUSSION

Echolocation Activity

Hawaiian hoary bats echolocation calls were recorded at high elevation cave entrances and surrounding environs in the MLFR during each month from November 2012 through April 2013. The detectability indeces and the total number of call events were relatively high in November and December, intermediate in January, and low but consistently representing bat presence in February through April. Caves 11 and 12, both located above 3,000 m asl, together accounted for 60.4% of all call events and 72.9% of all echolocation pulses recorded. Caves 11 and 12 also currently shelter the two largest known populations of cutter moths (*Peridroma*) among our study caves (S. Smith, personal communication). All other nocturnal flying insects found inside and out of caves in our study were uncommon in a one-night qualitative comparison of night-time insect activity around an ultraviolet light source.

Foraging behavior was demonstrated by recordings of "feeding buzzes" at all cave entrances that we monitored. The low numbers of feeding buzzes detected relative to search calls in our study is typical of many acoustic surveys. Recognizable feeding buzzes often are detected only under excellent recording conditions when bats are near a microphone with the head oriented toward the microphone.

Cave 12 was associated with most of the feeding buzz activity in our study and shelters the largest population of *Peridroma* moths, the only important prey group in the area. The absence of any observation of roosting activity resulting from our visual cave inspections supports the conclusion that feeding on *Peridroma* moths may be the key reason that Hawaiian hoary bats are active in and around the high elevation caves in the MLFR.

During December and January, Hawaiian hoary bats foraged until approximately 0100 hr around cave entrances located at lower elevations in our study area; whereas at elevations above 3,000 m asl bat foraging was restricted to the first two hours of the night. Foraging activity was positively correlated with air temperature and negatively with wind speed. Temperatures below 6 °C had almost no associated bat activity. For example, during December and January at cave 12 (3,393 m asl), air temperatures fell below 6 °C around 1900 hr and virtually all bat echolocation recordings were observed before 1900 hr (most heavily concentrated between 1800 and 1900 hr).

Our study area generally has low occurrence of fog and rain due to the effects of the cloud inversion layer which hovers at approximately 1,700 m asl in this region (Giambelucca et al. 1998 and 2013). The rarity of measureable precipitation (n = 2 nights) in the MLFR during our five month study eliminated rainfall as a variable in our analysis. We surmise that individual Hawaiian hoary bats may be particularly likely to travel to the MLFR to forage on *Peridroma* moths during times when unfavorable localized climatic conditions, particularly common in winter months, render foraging at lower elevations ineffective (Bonaccorso *et al.* 2015).

We conclude that high elevation caves on Mauna Loa, as a result of providing sheltering sites for populations of *Peridroma* moths, offer Hawaiian hoary bats a food source that is particularly important during winter months. Bat foraging activity evidenced by the amount of search and feeding buzz calls in the MLFP is correlated with relatively low wind speeds, air temperatures above 6 °C, and although we could not assemble enough local data to provide statistical rigor, probably with conditions free of heavy fog and rain. Low temperatures, high wind speeds, fog, and rain all are reported to interfere with hoary bat foraging efficiency and/or insect activity elsewhere (Belwood and Fullard 1984, Arnett et al. 2008, Gorresen *et al.* 2015) and in general increase metabolic costs (Voigt *et al*. 2011), thus causing bats either to retreat into night roosting sites or to opportunistically move to areas of clear, calm weather.

Winds above six m/sec generally reduce vespertilionid flight activity (Arnett et al. 2008, Schuster et al. 2015). Hawaiian hoary bat echolocation activity in the MLFR also was negatively correlated with wind speed and little activity occurred during periods of wind speed > 6 m/sec.

One possible way for bats in Hawaiʻi to avoid inclement weather conditions while hunting for aerial nocturnal insects is to fly to elevations above the cloud inversion layer, a condition frequently occurring above 1,700 m asl in the MLFR (Giambelluca and Schroeder 1998). Our data show that Hawaiian hoary bats make particularly heavy use of the high elevation caves in the MLFP during December and January, thus the MLFP and other areas of similar elevation with lava tube caves may be particularly important as winter foraging areas.

Potential Use of Caves as Roosting Hibernacula by Hawaiian Hoary Bats

No hibernacula, nor any sign of cave use by Hawaiian hoary bats for the purpose of roosting, were found in any of the caves visually searched by our staff. The more than 300 bat skeletons and mummies in the five caves having bat carcasses are likely to have resulted over time from bats that became disoriented and unable to leave a cave after entering to forage on cave-sheltering moths. The majority of all carcasses were found within large chambers with restricted exit spaces (crawl spaces for humans) leading to the cave entrance, thus creating a “fish trap funnel” condition.

Previous authors have hypothesized that Hawaiian hoary bats most likely undergo altitudinal migration in order to seek microclimates to facilitate winter torpor (Menard 1999, Gorresen *et al*. 2013). Although we have not excluded winter torpor as possibly being part of the life cycle of Hawaiian hoary bats, our observations suggest that the use of high elevation lava tubes for this purpose is not likely. We conclude that Hawaiian hoary bats approach and enter caves in the MLFR for the pursuit of nocturnal flying moths as prey items during foraging flights.

Given that there are no suitable trees to serve as roosts in the upper portion of the MLFR and very few in the lower portion of this reserve it is likely that bats commute to the reserve only for foraging and return to forested areas at lower elevations surrounding the MLFR for daily roosting. Thus the movements by Hawaiian hoary bats into and out of the MLFR are not a "seasonal migration" but a seasonal use of a unique foraging area that offers an attractive food resource in tolerable climatic conditions above the usual cloud inversion layer found in this region. We suggest that individual bats will make optimal foraging decisions on a nightly basis about whether to commute to the MLFR or not based on local weather conditions in the portions of their respective winter foraging ranges at lower elevations and closer to roosting sites.

Assessing the Potential Risk of White-nose Syndrome in Hawaii

Because extensive winter searches of caves with and without bat carcasses present in the MLFR have not been found to have bat hibernacula or any form of day-roosting behavior by bats, the risk of White-nose Syndrome (WNS) to Hawaiian Hoary Bats is perhaps low. Bats of several species in North America are highly susceptible to WNS as they hibernate in caves with air temperatures below 14°C. There may yet be a risk for Hawaiian hoary bats from temporary "night roosting" within foraging caves if the *Pseudogymnoascus destructans* fungus is present in the MLFR. The microclimates, in terms of temperatures and humidity in caves on Mauna Loa, are suitable for *P. destructans* and other fungi for growth/survival. One fresh bat carcass found on a cave floor during our surveys had the facial region covered by a fungus (Figure 15); however, from this photo it has been determined that the fungus was not *P. destructans* (D. Blehart, personal communication).

The recent findings of *P. destructans* spores in the fur of eastern red bats and silver-haired bats, two species of foliage roosting bats that rarely enter caves, suggest that hoary bats may also carry spores if exposured to the fungus (USFSW 2013, Bernard *et al.* 2015). If Hawaiian hoary bats make short "night roosts" on cave substrates in the midst of foraging activity inside caves, there is a possibility bats may come in contact with the fungus should it be present in Hawai'i. As yet, no studies have attempted to identify the presence/absence of *P. destructans* in Hawai'i. Given the frequent winter/spring use of caves by Hawaiian Hoary Bats as demonstrated by large numbers of bat carcasses within caves, our visual observations of bats flying at night in caves, the high volume of vocal activity at cave entrances, as well as the movement of visiting humans between North American and Hawai'i, prudence may warrant that surveys for the presence of *P. destructans* (Lindner *et al.* 2011, Turner *et al.* 2014) be conducted to further explore possible exposure of hoary bats to this fungus.

Although no evidence of roosting behavior associated with caves was found in our study, Hawaiian hoary bats frequently enter caves and sometimes die in caves. These bats are likely to encounter cave substrates either in collisions during prey capture or for the purpose of short duration "night roosting". There is certain to be some contact between bats and cave substrates. The air temperatures found inside caves above 2,500 m asl are suitable for growth of *P. destructans*, thus there is at least some possibility of risk for Hawaiian hoary bats to come in contact with this fungus if present. At this time it is not known if the fungus is present in Hawaiian cave ecosystems; however given that visitation of recreational cavers from North American is a common occurrence, introduction from contaminated clothing and equipment does bear a risk that the fungus if not already present in Hawaiʽi will become established. Whether the behavior and immunology of Hawaiian hoary bats would render disease risk from WNS moot or not is simply not known.

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Sunday 23 July until Saturday 29 July 2017

David Butler and Cathie Plowman

The congress venue is Panthers, a sports and entertainment club in the western Sydney city of Penrith. The congress facilities are modern and away from other activities of the club. There are a number of bars and eating areas within the club. Congress registrants will be made members of the club for the week, so as to be able to purchase meals at the discounted member prices.

Outside the main building is a 1875 square metre exhibition area, which will serve as the trade area, display area, speleo sports venue and will also provide an area where registrants can mingle informally.

There are two motels located close by, one immediately adjacent to the congress venue, the other is a 10-15 minute walk away. There is bunk-room accommodation available at a nearby sports facility which is a 10 minute walk from the congress venue. A camping site will be developed in the grounds of the nearby Museum of Fire, also a 10 minute walk from the congress venue.

The presentation at the Vulcanospeleology Symposium will include details of the congress field excursion and the pre and post-congress excursions. Pre and/or post-congress excursions are being held in all six Australian states and New Zealand.

Full congress details, including the call for presentations will be available in the Second Circular which will be released in April and also on the congress website. Registrations open in July 2016.

Please visit the congress website: http://speleo2017.com

THE "CUEVA DEL VIENTO" ON THE CANARIES, SPAIN

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Abstract

The processes of pyroduct (i.e. lava tube) formation are well investigated, primarily for examples of the Hawaiian volcanoes. This study examines a section of the "Cueva del Viento" a complex pyroduct system on Tenerife, the largest island of the Canaries, Spain. It was established during an eruption of the "Pico Viejo" (3103 m), a stratovolcano with steep flanks. It consists of several levels. The second and third levels are compared here. The characteristics are principally comparable to those of the Hawaiian volcanoes, with specific differences probably due to the steeper flanks of the volcano. Pronounced longitudinal structures are observed, such as ridges, ledges and shelves. Lava stalactites are also common. Analysis of the chemical composition showed, that the petrography of all levels is that of tephritic lava. Therefore, the two levels were likely formed during one eruption event. Further, the lack of detectable ceiling material on the bottom of the third (lower) level suggests that lava was still flowing in this pyroduct at the time the superimposed flow was active. The steepness of the terrain appears an important factor shaping this complex pyroduct system.

Introduction

Volcanoes attracted public and scientific interest early on as they can alter the landscape dramatically and rapidly. Volcanoes occur world-wide and mark the plate boundaries of the Earth's crust as mid ocean ridges or along subduction zones. Others rise above Hot Spots, long-term stationary mantle plumes. Well-known examples are the Hawaiian, Galapagos, Azores and Canary Islands. As plates move over the Hot Spots chains of volcanic edifices are formed with time stretching away from the resident mantle plume.

The Canary Islands are situated in the eastern Atlantic, west of Morocco. They form an age-dependent chain from East to West (Lanzarote >Fuerteventura >Gran Canaria >Tenerife >La Gomera >La Palma >El Hierro) (Olzem, 2015). Tenerife is the largest island of the volcanic Canaries and is topped by a complex formed by the two stratovolcanoes Teide and Pico Viejo. Special features of the volcanic formations are pyroducts, also called lava tubes. Lava pyroducts are an important feature for the formation of shield volcanoes. They allow for a steady lava flow through subterranean conduits over several tens of kilometers with little heat loss (e.g., Kempe, 2010, Lockwood and Hazlett, 2010). Current knowledge of pyroduct formation derives mainly from studies of Hawaiian shield volcanoes, i.e., on examples developed on gentle slopes of 1.5°-5° (e.g., Kempe, 2009; Lockwood and Hazlett, 2010). Most of the pyroducts occur in tholeiitic or alkaline basalts (e.g., Kempe, 2009). These lavas are very hot and have a low viscosity when erupting. After forming pyroducts they can continue to flow rapidly underground; the temperature drops as little as about half a degree centigrade per kilometer (e.g., Lockwood and Hazlett, 2010). The mobility of the lava depends on the maintenance of high temperature; therefore, the faster the flow (for example the steeper the terrain), the lower the heat loss is for a given distance (Wood, 1974). Heat loss inside the tunnel and at its lower boundary is conductive, while the lava flow surface loses heat convectively (e.g., Kempe, 2009). Thus heat and fluidity of the lava can be maintained over long distances. The fluid lava starts to erode its bed, leaving a gas-filled space above. When the eruption terminates, a cave is already existing regardless if the terminal lava drains the pyroduct or not (Kempe, 2002).

The process of roof-forming most commonly is related to buoyancy and built-up by repeated cycles of inflation and advance. Roofing begins at the distal tip of the lava flow, where it freezes fast to thin sheets, due to the contact with the colder underground. As it chills quickly, the contained gas exsolves, aggregates and forms vesicles which de-crease the density of the sheets. The following advance of lava lifts (inflates) the frozen sheets up due to buoyancy. Often, a number of cycles of advance and inflation establish a primary roof composed of a stack of sheets, separated by shear interfaces (Fig. 1). From this follows that the oldest lava is situated at the top of the stack showing the corded lava surface, typical for pāhoehoe surfaces. Below this primary roof the lava keeps flowing.

Although pyroduct-generated cave systems are typical features of shield volcanoes, they also occur on the stratovolcanoes such as the Cueva del Viento on the Pico Viejo. This cave is not only singular because of its occurrence on a stratovolcano, but also due to its complexity of superimposed passages.

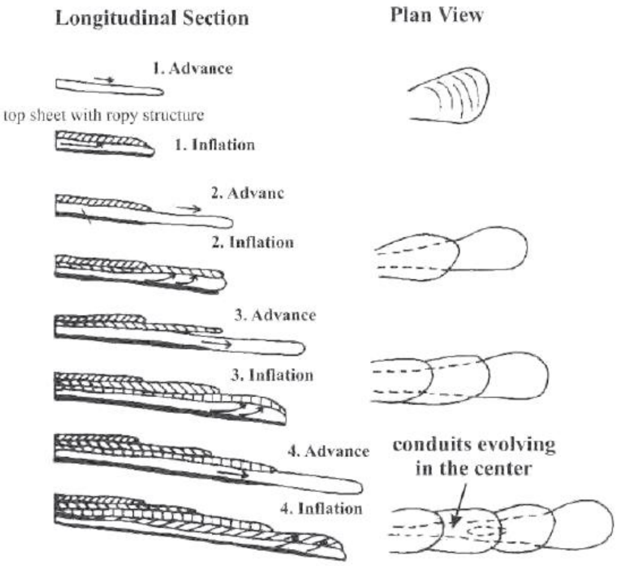

Figure 1: *Many cycles of advance and inflation establish the primary pyroduct roof (Kempe, 2009).*

Study Site

The Cueva del Viento is part of a mazy subterranean lava pyroduct system, with diverse branches. It is located on the northeast flank of the Pico Viejo, in the vicinity of the small town Icod de los Vinos, Tenerife, Spain. Pico Viejo is the older volcano of the two volcanoes in the complex which is fed by a giant magma chamber characterized by the enrichment of incompatible micro-elements and the growth of phenocrysts such as plagioclase and pyroxenes. These could emerge because of the long intervals between the eruptions, which allowed the magma to cool and crystallize eventually. Furthermore, there is a production of highly differentiated magma, because of a scarce supply of basaltic magma (Schmincke, 2010). Diversely differentiated types of lava, evolving from basaltic to phonolitic composition, were ejected at this complex. The Pico Viejo, a circular volcano, whose flanks have a gradient of 12° (bottom) to 33° (near the summit), is 3103 m high (basal diameter about 44.5 km) and topped with a 110 m deep and 800 m wide Caldera (Ablay and Martí, 2000). It is fed by a very large and deep-seated basaltic magma chamber (Martí, 2008; Socorro, 2013), from where the intermediate lava, containing potassium-poor plagioclase as well as kaersutitic amphibole, is supplied (Ablay and Martí, 2000); it reaches the surface predominantly through effusive eruptions at the Pico Viejo.

As a consequence of these effusive eruptions and low viscosity lava flows, a huge pyroduct system was established with many entrances and sections. The longest sections are the Cueva del Viento, Cueva de San Marcos and the Cueva de Felipe Reventón (Wood, 1977). It is assumed that the caves are all interconnected. The Cueva de San Marco is located at the coast, thus representing the end of the flow.

The Cueva del Viento was formed by basaltic, plagioclase-rich pāhoehoe lava, during an eruption 27,030 ± 430 years ago, which is one of the very first eruptions of Pico Viejo (C^{14} dated by Carracedo, 2008). This extraordinary subterranean system is the 5th longest volcano pyroduct on Earth (Gulden, 2015).

Figure 2: *The cliff line at the San Marco beach shows at least five cave entrances. These, together with the interlayers, indicate superimposed levels (photograph taken in September 2014).*

A very special and exceptional characteristic of the cave is its complex, superimposed and sinuous construction. The speleology group of G.E.T. Benisahare surveyed a total of 17,032 m up to now (Cueva del Viento, Visitor Center, 2014) and estimated the total length to about 75 km. The end of the subterranean complex appears to be at the Cueva de San Marco. At the beach of San Marcos, five different lava flow levels are visible, so there may be more cave levels than known as yet (see Figure 2). It should be noted that it is not always obvious how to distinguish the different levels and how to number them. The speleology group G.E.T. Benisahare counted 18 different levels, including some smaller or intermediate levels. Determining a number depends on the chosen approach and thus, providing an exact number of levels is impossible currently.

It generally is assumed that the Cueva del Viento consists of three main levels: the first, upper level is the lowest one just 0.4-1 m high, the second, intermediate level - also called "Sobrado Superior"-, has an average height of 3 m, and the third, the lowest one - also called "Sobrado Inferior"- is the deepest and highest one (up to about 13 m high). In this study the Sobrado Superior and the Sobrado Inferior were inspected and compared.

Methods

Since pyroducts cannot be observed directly during their formation, the development of the Cueva del Viento and its specifics can only be reconstructed by studying its morphology, dimensions and rock formations. While observing the different structures at diverse sites it is possible to obtain an idea of the principles of the flow originating from Pico Viejo. Therefore, the characterization is a result of the observations in addition to information of the caving group at the Cueva del Viento and the publication of Díaz and Socorro (1984).

In order to compare the chemical composition of the two main levels, X-Ray Fluorescence (XRF) analyses were conducted (Prohl, 2014) on samples collected at the ceilings of the levels. One gram of the sample was prepared as an orodispersible tablet and analyzed.

By using the CIPW-norm (Hollocher, 2014) the weight-percentage of the nominal minerals plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$), orthoclase ($KAlSi_3O_8$), hematite (Fe_2O_3), nepheline $(Na,K)AlSiO_4$, diopside ($CaMgSi_2O_6$), perovskite ($CaTiO_3$) and olivine ($(Mg,Fe)_2SiO_4$) were calculated. The complete data for the chemical composition and CIPW-norm are provided in Rein, 2015.

Results

The cave´s internal structures

The cave´s interior is shaped by the characteristics of the flowing lava forming the conduit. The internal structures depend on temperature, viscosity, velocity and stabilization time, all in relation to the width and height of the pyroduct, as well as to slope, curvature and potential obstructions. Therefore, the internal surface structures may give an idea of the friction, force and sinking or refilling processes of the flow. Particularly informative are the structures, which are established at the walls as they indicate the height of the lava flow and by their extent the changing of the flow´s level. Here we present the structures observed in the Cueva del Viento along with an outline of the underlying principles.

The wall formations are called bancos or grados (ridges), terrazas (ledges) and cornisas (shelves). Since they are created at the top and at the edges of the flow as an accumulation of material due to adherence, they represent the changing levels, mostly decreasing, and therefore the volumes of the flow at different times. The material adheres on both side of the flow, establishing longitudinal structures thereby also narrowing the cross-section of the channel. Ideally, one can follow the lines of these features down the conduit. The ridges which are formed first represent a transient level, whereas the ledges and shelves are built up during a phase of more or less constant flux. Ledges and shelves are established when there is a stable flow at moderate velocity that lets the material adhere to the internal walls. Their heights and widths depend on the steadiness, velocity, viscosity and temperature of the flow. Ledges differ from shelves because of their internal structure. Shelves are established by many overlaps of concentric layers, covering a nucleon of accreted clasts (Diaz and Socorro, 1984). As the flow carries a lot of clasts and fragments, the clasts adhere at several points at the edge of the lava flow (Fig. 3).

The deposition of the lava follows several principles, contingent on the impacts of centrifugal force, meandering and inertia (Díaz and Socorro, 1984). All these are forming láminas, or larger accumulations such as terrazas and cornisas.

In a gently dipping, wide curves the centrifugal force causes accumulation of the cooler lava, scoria and fragments at the convex side while possibly eroding at the concave side. Above the critical velocity, the process of meandering dominates the deposition and works opposite to the centrifugal force. At high velocity, there is little aggregation, but rather erosion at the convex side. As the flow follows the principles of meandering, like rivers do, there is thickening at the concave side because of lower velocity. When wide curves follow each other, inertia comes into force and causes the same character of deposition as meandering does. Fig. 3 shows a summary sketch of these processes. Typically, one can observe more accumulation in the convex side than in the concave side, but the inertia and meandering processes can cause the opposite in some cases (Diaz and Socorro, 1984).

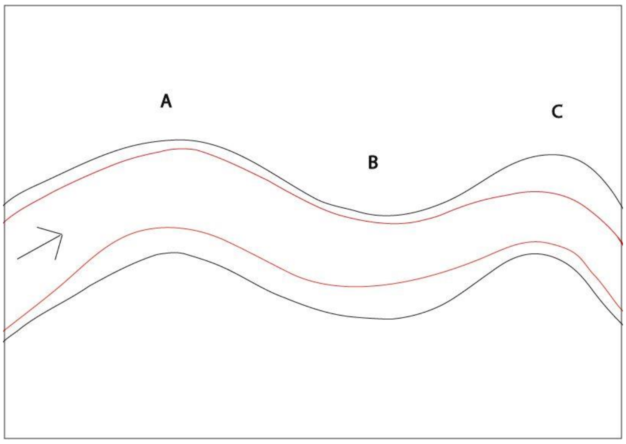

Figure 3: *Accretion due to centrifugal force (A), inertia (B) and meandering (C). The red line shows the line of lava accumulation. At A, in a wide curve, the lava aggregates in the convex side and erodes the concave side. In B, when wide curves follow each other, inertia dominates the accretion processes, wherefore the concave curve thickens. In C the meandering process leads to an accumulation on the concave side (modified from Diaz and Socorro, 1984).*

The more viscous the flow is, the thicker the structure grows. At bifurcations, the láminas adhering to the walls are continuing, but since the highest velocity is at the vertexes, ridges do not form there. They rather start to accumulate behind the fork, where they may be thickening as soon as the velocity is low enough to let the láminas built up. In cases of increased velocity (due to incline or narrowing) thinner and lower ledges and shelves are formed.

Ledges and shelves are not only shaping walls, but also the ceiling when joining their edges and therefore creating a secondary ceiling. A further mechanism for establishing a secondary level may be by blockages which pond the lava behind leaving a horizontal ridge (for an example, see Fig. 4). During the impounding, the carried fragments, scoria and chilled material floating on the surface of the dammed flow consolidate and as soon as the level sinks again, the welded clasts remain and separate the passage into two levels.

Figure 4: *Secondary ceiling in the Sobrado Inferior of the Cueva del Viento caused by damming of the flow because of blockages (Photo provided by Láinez, 2014).*

Figure 5: *"Gota de lava" at the ceiling of the Sobrado Inferior. The yellowish color is due to bacterial colonies (photograph taken by Láinez, 2014).*

Lava stalactites occur at the ceiling of the Cueva del Viento. Even though they are shaped like stalactites, they did not originate by chemical precipitation. They are also called "gota de lava" which means lava-drop and describes their formation vividly (Fig. 5).

These stalactites can be formed when hot lava splashes at the ceiling causing it to drip down. But other possibilities exist also causing irregular and conic ones and those created by re-melting, like vesicular and sinuous forms (Diaz and Socorro, 1984). Because of a high anthropogenic contamination through effluents, the water drops hanging from the stalactites may be colored differently fueling varicolored bacterial colonies.

Sometimes the results of degassing of the flowing lava can be observed. When the hot lava chills, gases can be released. They accumulate below the already highly viscous surface layer until they are finally released but a rupturing explosion (see Fig. 6 at ceiling).

As the lava cools, it becomes more and more viscous causing the terminal flow in the conduits to form loose clasts (scoria) like on an ‘a‘ā -flow. Since the material chills first along the sides while the interior remains semi-liquid, the flow becomes rough at the edges first and keeps flowing down in the middle, narrowing the channel.

The ‘a‘ā-textured lava essentially cannot flow any further, so that still moving viscous lava presses forward from behind piling up low dams of clasts in form of "lenguas" (tongues, up to 0.5 m high) or "escalderas" (stairs, more than 0.5 m high) (cf. Fig. 6).

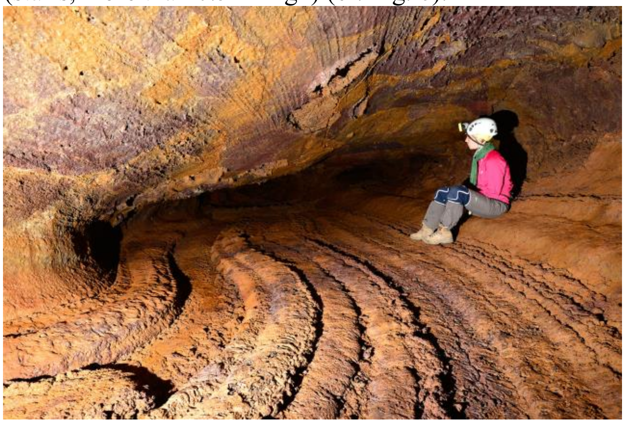

Figure 6: *This view depicts several features: the cooling flow left a series of low levees on the floor (right and left) and the last moving lava formed a low lava tongue (a"lengua"; lower left). At the ceiling small eruptive rings are seen caused by gas that accumulated behind the viscous glazing until it burst (photograph provided by Socorro, 2014).*

Petrographical composition

Previous studies report that the cave developed in basaltic and plagioclase-rich pāhoehoe lava. This lava, called "Basaltos Plagioclásicos" (plagioclase-rich basalts), formed the Cueva del Viento. The basalts contain idiomorphic and twinned phenocrysts of calcium-rich feldspars (i.e., anorthite). It also contains pale, sub-idiomporhic mesocrysts of clinopyroxenes as well as mesocrysts of olivine, which are idiomorphic to subidiomorphic, not showing alteration processes. The opaque minerals are often a mafic hypocrystalline to vitreous matrix with spherical vesicles (Carracedo, 2008). As the “Basaltos Plagioclásicos” contain, according to the TAS-diagram (Total Alkalinity versus Silica Diagram), a SiO_2-concentration between 49-51 wt.% and a Na_2O plus K_2O concentration of around 7-8 wt.%, the lava can be classified as alkaline tephritic (close to phonotephritic, SiO_2: 45-52 wt.%) (Elsanovski, 2014).

Sobrado Superior	
Mineral	**Weight %**
NaAlSi3O8-CaAl2Si2O8	53.42
KALSI3O8	15.40
Fe2O3	9.49
CaMgSi2O6	5.24
(Na,K)AlSiO4	5.07
CaTiO3	4.41
(Mg, Fe)2SiO4	4.01

Sobrado Inferior	
Mineral	**Weight %**
NaAlSi3O8-CaAl2Si2O8	54.08
KALSI3O8	14.63
Fe2O3	9.94
CaMgSi2O6	4.42
(Na,K)AlSiO4	5.13
CaTiO3	4.59
(Mg, Fe)2SiO4	4.20

Figure 7: *Petrographical composition calculated according to CIPW-norm showing presence of plagioclase, orthoclase, hematite, diopside, nepheline, ilmenite and olivine. The high plagioclase and the olivine contents are highlighted (from Rein, 2014).*

Similarly, the analysis of the XRF composition of the basalts of the Cueva del Viento presented here (comparing the Sobrado Inferior and Sobrado Superior) revealed an average SiO_2 content of 48.52 wt.% and an average alkalinity of 7.87 wt.% (Fig. 7). Plotting this composition in the TAS diagram (Fig. 8), these lavas are placed in the field of tephrite and basanite, again very close to a phonotephritic composition (Rein, 2014). The chemical analysis corroborates the high content of plagioclase, as described by Carracedo (2008). As it contains less than 10 % olivine (4.1 %), the classification can be narrowed down to tephrite (Braeunlich, 2009).

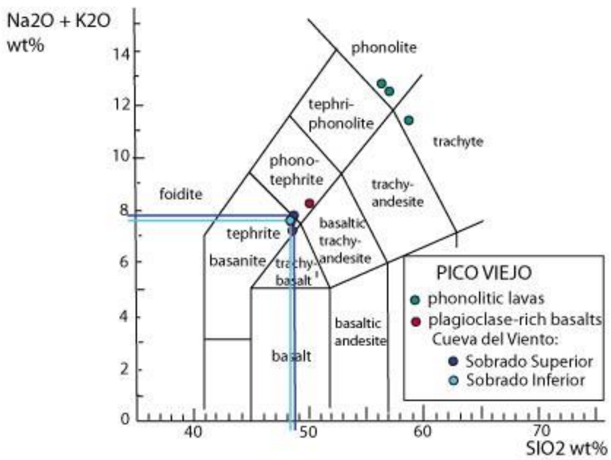

Figure 8: *Position of the Sobrado Superior and Inferior samples in the TAS diagram in comparison to the determination by Carracedo (modified after Carracedo, 2008).*

The high Fe and Ti contents (on average: 9.62 %, and 2.82 % respectively) may be due to the conditions of the magma genesis. Because of the thick lithosphere near the Canaries of about 100 km, very high pressures (>30 kbar) modulate the evolution of the magma (Schmincke, 2010).

The long-lasting intervals between the eruptions facilitated the crystallization of minerals in the magma which began to chill because of inactivity. This favored the enrichment of incompatible micro-elements and the growth of inclusions/phenocrysts such as plagioclase and pyroxenes (Schmincke, 2010).
The chemical compositions of the Sobrado Superior and Inferior do not differ a lot and there is no notable evolution of the magma, indicating that they could very likely have been formed by lava flows of the same eruptive event.

Discussion

The complexity of the Cueva del Viento is probably linked to the steep gradients of the flanks of Pico Viejo and to a constant flux with high effusion rates spreading over a wide area (Wood and Mills, 1977). Several shape-forming mechanisms delineated from observations of other volcanoes also appear to have been operative here.

The Cueva del Viento is a superimposed system which was established by stacking several, individually advancing pyroducts. Their formation follows the generally well-described process of advance and inflation. While the lava flows downhill, the very first “advance” solidifies when contacting the cooler underground and forms an about 30 cm thick sheet. Due to its lower density, caused by degassing and consecutive vesicle formation, it lifts up, “inflates”, while the still hot and fluid material keeps flowing underneath. The primary roof is composed by various sheets, formed at each advance and inflation.

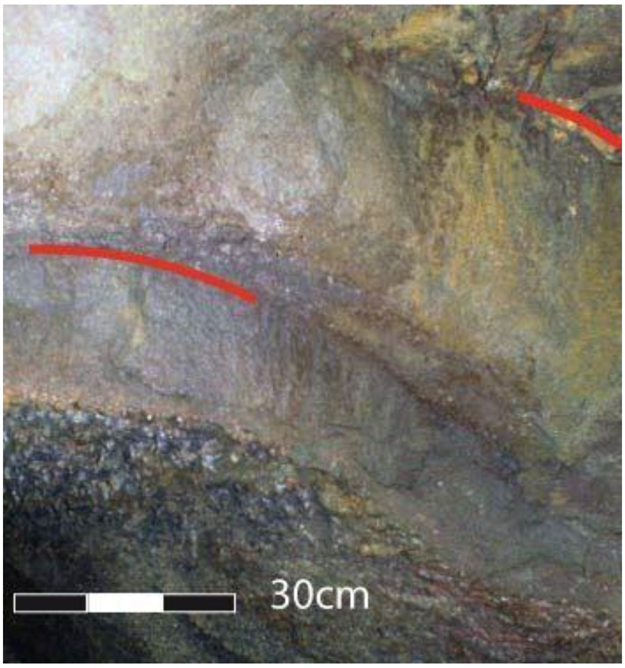

Figure 9: *View of the primary roof exposed by breakdown. Visible are the three lowest sheets of an inflationary primary roof. The sheets are separated by shear planes. (photograph taken in September 2014).*

This conclusion is based on observations at the cave’s ceiling at places of breakdown. The roof there is composed of various sheets, separated by shear interfaces as is typical for inflationary primary pyroduct roofs (Fig. 9).

Presumably, the Sobrado Superior and Inferior were established during the same event and interacting with each other because the different levels are connected by pits, where the lava which was flowing in the Sobrado Superior seems to have been flowing down into the Sobrado Inferior. Breakdown material of the ceiling of the lower level was removed by the final activity in the lower level, thus showing that this level was also the final one to be drained.

The tephritic lava has a higher viscosity than the basaltic lava of Hawaii. This should have led to a slower movement and thus can be the reason why a pyroduct system is found on the steep flanks of a stratovolcano.

Perspective

Only a very small part (about 400 m) of the huge Cueva del Viento on Tenerife was investigated, featuring just two of the many existing levels. Since the Cueva del Viento appears to be the largest example of a superimposed system on a stratovolcano (in contrast to the even longer Kulakai System on Hawaii that exemplifies the situation on a low-slope shield volcano) it would be very interesting to finally find out how many levels of superimposed pyroducts make up the system and how these levels have been interacting with each other.

The cave is also unique for its fauna. According to Martín et al., 1995, about 100 species have been recorded in the Cueva del Viento, 38 of which are troglobites and 15 troglophiles among them spiders, pseudo-scorpions, millipedes, beetles and lepidoptera. Their food basis are bacterial colonies and plant debris. Thus not only geological reasons mandate a conservation concept for this cave but also biological ones. Unfortunately the cave is not protected and is impacted by sewage from households and banana plantations (Fig. 10; Láinez and Socorro, 2012).

Figure 10: *"Pozo negro" (Spanish for "sewage pit") inside the Cueva de San Marco, possibly the result of sewage from a banana plantations (photograph provided by Lainez, 2014).*

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MAUI CAVE PROJECT

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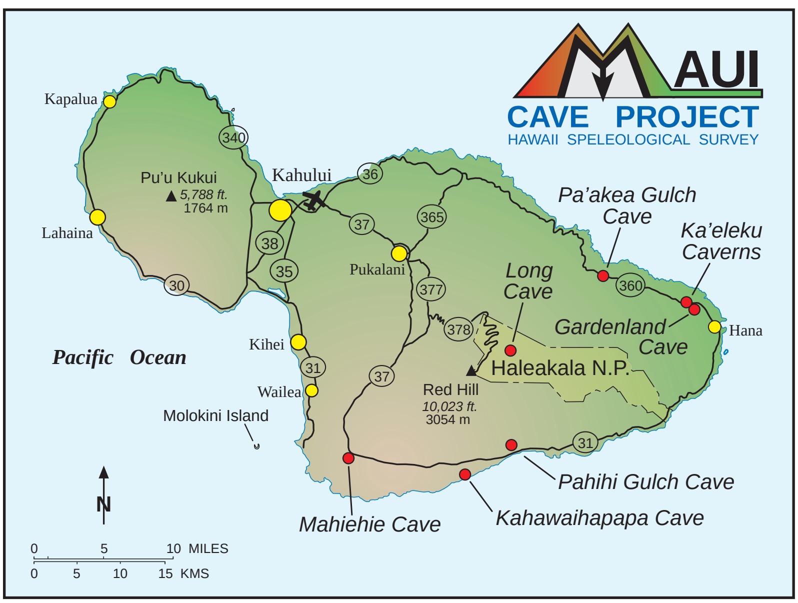
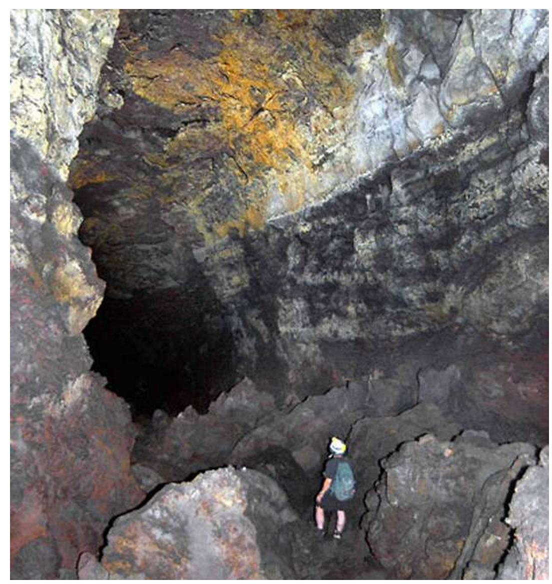
Abstract

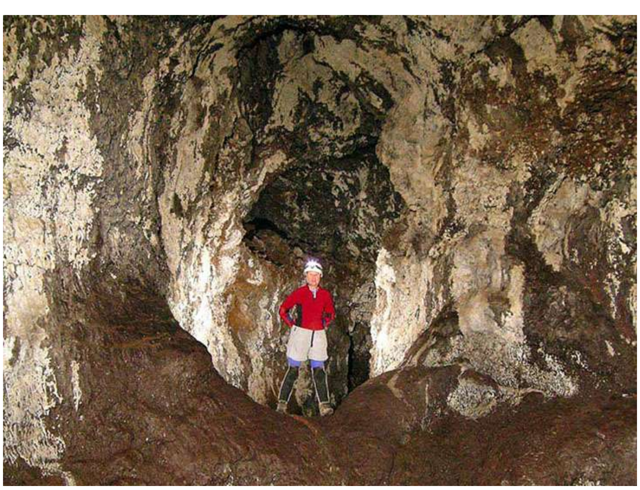
This presentation will highlight some of the cave discoveries on the island of Maui. Haleakala Volcano is home to several lava caves that the Maui Cave Project has been exploring since 1998. The last eruption is thought to have been in the 17th century along the SW rift zone down along the south coast. Haleakala is a massive shield volcano 3055 meters high known as "house of the sun". From the summit one looks down into a large crater some 12 km across, 3 km wide, and nearly 800 meters deep. Down on the floor of this crater project cavers mapped Long Cave a relative young cave in a 1000 year old flow Near Hana along the East Rift zone is Ka'eleku Caverns that is found in a 1500 year old flow and is Maui longest cave at 3 kilometers. The oldest caves that have been mapped are located on the dry south slopes of Haleakala. Pahihi Gulch Cave is thought to be the oldest at 750,000 years, while Kahawaihapapa Cave down on this barren coast is in a 140,000 year old flow. Some of the largest cave passages found on the island is along SW rift zone as seen in Mahiehie Cave. These are just some of the discoveries that the Maui Cave Project have made. The goal of this project is to establish an island-wide cave survey to catalogue, inventory data, as well as to protect the resources for further exploration and research on the island of Maui.



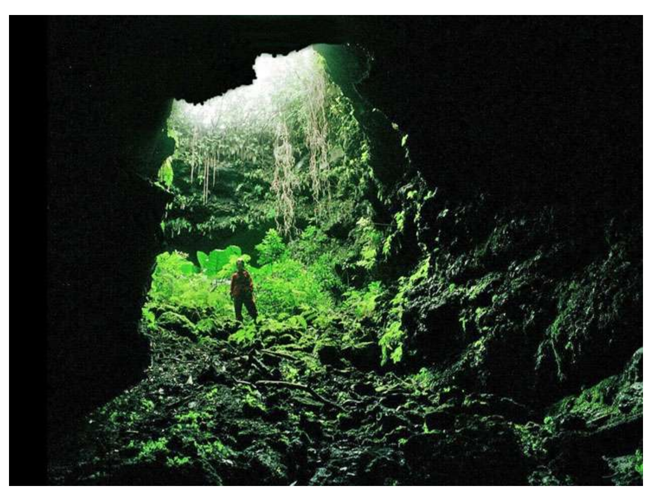
Index map of the surveyed caves on the island of Maui



Mahiehie Cave has some of the largest cave passages known on the island. Photo by R. Ratkowski.



Secondary mineral growth on the walls and ceiling in Long Cave on the crater floor of Haleakala. Photo by B. Szukalski



In the rain forest near Hana is the Ape' Entrance to Ka'eleku Caverns. Photo by D. Bunnell

The Exploration of Hualalai Ranch Cave

John Rosenfeld and John M. Wilson

Hualalai Ranch Cave is the third longest lava cave in the world at 17.256 miles or 27785 meters long and 441.7 meters deep. It is also the third longest lava cave system. The cave is located in the North Kona District of Hawaii County and is owned by the Hualalai Resort. The cave is not open to the public; however, the Resort will give permission under for responsible cavers to enter under certain conditions.

Our talk with discuss some of the scientific interests in the cave as well as a brief history of the exploration which lasted over ten years. Most of the mapping occurred from 1995 to 2005. John Rosenfeld was the expedition leader, and he relied heavily upon Butler Cave Conservation Society members which included many of the twenty-five people who helped with the mapping and others who did some of the scientific work. The paper map was drawn by Nevin Davis in 2005. HRC provided some data for the William White article in "Secondary Minerals in Volcanic Caves: Data from Hawai'i," William B. White. Journal of Cave and Karst Studies, v. 72, no. 2, p. 75–85.

MICROBIAL MAT COMMUNITIES IN HAWAIIAN LAVA CAVES

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Abstract

Microbial mats are a prominent feature in many Hawaiian lava caves, but little research has been done on these communities. Since 2008, we have sampled 16 lava caves on the Big Island of Hawai`i for microbial communities for scanning electron microscopy (SEM) analysis, cultivation, and DNA sequencing. These caves occurred in areas of Hawai`i that varied in rainfall from 47—401 cm per year. Sampled communities included microbial mats of various colors from white to tan, yellow, and orange; white mats floating on puddles in the floor; and butterscotch-colored organic ooze. We also sampled “microbes that masquerade as minerals” to determine whether mineral deposits contained substantial microorganisms. SEM studies revealed diverse morphologies across the lava caves, with coccoid and filamentous shapes predominating. Culture media inoculated with microbial mat or mineral deposits on site in Hawaiian lava caves revealed morphologies consistent with Actinobacteria and many cultures demonstrated the presence of fugitive dyes that were aqueously soluble. DNA analysis revealed that the white wall microbial mats differed from the yellow, pink, and orange mats, which were more similar to each other. Actinobacteria dominated the latter deposits. Overall, the type of sample (mat versus mineral versus surface soil) made the greatest composition difference.

Introduction

Hawaiian lava caves are rich in colorful microbial mats such as the yellow mats in Fig. 1. Yellow and white microbial mats predominate in most lava caves in areas with higher rainfall, with occasional pink, orange, and shades in between occurring in some mats. In more arid areas, such as those found in the vicinity of Ocean View, HI, white mats dominate the caves in the deeper, more humid regions. Microbial mats can consist of individual colonies (Fig. 2A), thick mats of microorganisms (Fig. 2C), organic ooze (Fig. 2B), or floating colonies on pools (Fig. 2D). In areas nearer the entrances of these semi-arid regions, mineral deposits that contain abundant microorganisms dominate, including some moonmilk deposits. More rare and unusual, are the copper containing deposits (Fig. 3).

Figure 1: Yellow microbial mats line walls of this Hawaiian lava cave. Photo by K. Ingham.

Studies by Hathaway et al. (2014) of lava cave microbial communities previously have revealed diverse communities using an older sequencing technique (Sanger sequencing). Our goal was to use next generation 454 sequencing to do a more comprehensive survey of the microbial communities in Hawaiian lava caves.

Methods

Beginning in 2008, we have sampled 16 lava caves for microbial communities for scanning electron microscopy (SEM) analysis, cultivation, or DNA sequencing. Rainfall on the surface above these caves varied from 47—401 cm per year, with the least amount being above the caves in the Kipuka Kanohina System and the greatest amount being in caves in the vicinity of Hilo, HI. Microbial mats varied in color from white to tan, yellow, orange and pink. Other samples included white mats floating on puddles in the floor and butterscotch-colored organic ooze. Samples were taken aseptically using a flame-sterilized cold chisel, and were immediately covered with sucrose lysis buffer to preserve the DNA (Giovannoni et al. 1990). Rock chips with microbial mats sampled for scanning electron microscopy (SEM) were mounted directly on SEM sample stubs in the field.

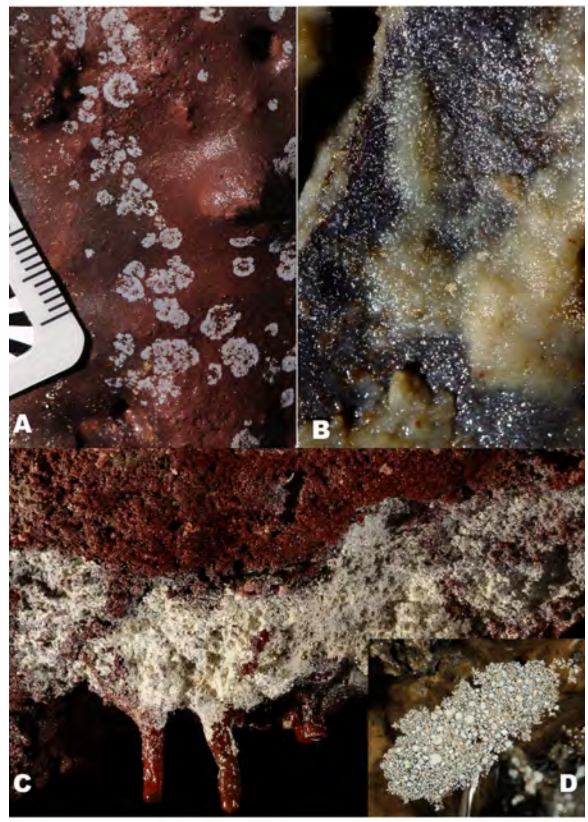

Figure 2: Macroscopic images of microbial colonies and deposits in Hawaiian lava caves. Photos by K. Ingham.

Scanning Electron Microscopy

Samples were air dried, and coated with Au-Pd metal for imaging in the laboratory. They were then examined on a JEOL 5800 SEM equipped with an energy dispersive X-ray analyzer (EDX), at high vacuum with an accelerating voltage of 15 keV with a beam current between 0.1 to 0.01 nA.

Cultivation

Microbial colonies were inoculated into a variety of culture media, optimized for lower nutrient, mineral-rich environments, on site in the caves and allowed to grow for months to years to encourage the growth of more slow-growing cave-adapted microorganisms. Cultures that revealed the presence of fugitive dyes had portions of the agar excised from the cultures, dissolved in pH 7 phosphate buffer and measured with a Nanodrop 1000 UV/Vis spectrophotometer. Long-term incubations of some Hawaiian cultures from 2008 collections were grown in calcite-containing media (10, 35, and 50 mg/L $CaCO_3$ where saturation at 20oC is ~350 mg/L, Donor & Pratt, 1969). Cultures were also grown on silica containing media, using sodium silicate (a.k.a. waterglass) as silica source at concentrations of 10 and 60 mg/L, which are representative of natural waters (e.g. Miretzky et al 2001; Asano et al 2003)

DNA extraction and sequencing

DNA was extracted and purified using the MoBio PowerSoilTM DNA Isolation Kit using the manufacturer's protocol (MoBio, Carlsbad, CA), with exception of using beat beating instead of vortexing. Extracted DNA was sent to MR DNA (**http://mrdnalab.com/**) for next gen 454 sequencing. Returned sequences were processed and analyzed used Qiime (**qiime.org**).

Figure 3: Copper-containing stalactite from a Hawaiian lava cave near Hilo. Photo by K. Ingham.

Results and Discussion

Scanning Electron Microscopy

SEM studies revealed diverse morphologies including beads-on-a-string (Fig. 4A, white line with a solid white ball), filaments (Fig. 4B, C, D), reticulated filaments (Fig. 4E, F), rows of rods embedded in biofilm (Fig. 4C, leftmost black line with solid black square), and cocci (Fig. 4A with white line with open white circle, B), some with extensive hair-like or knobby extensions. Biofilm was extensive in many samples (Fig. 4C, black lines with solid squares on ends). Some of the mineral deposits contained more unusual minerals, such as copper silicates and vanadium oxides. Moonmilk deposits revealed calcite ("lublinite") crystals, microbial filaments, beads-on-a-string, and possible opal deposits (not shown). Reticulated filaments are relatively rare in lava cave microbial mats, with the exceptions of a white mat (Fig. 4E) and copper silicate speleothems from the Kipuka Kanohina System and in Blair Cave (Fig. 4F).

Cultivation

Culture media inoculated on site in Hawaiian lava caves revealed morphologies consistent with Actinobacteria and many cultures demonstrated the presence of fugitive pigments that were aqueously soluble and sensitive to light. Pigment colors range from pink and red to orange and disappear in cultures exposed to light after they are initially incubated in the dark. The spectra from portions of the agar excised and analyzed with a spectrophotometer, closely resemble index spectra of beta-carotene (Miller et al 1935 and many subsequent studies), with a number of additional peaks not yet identified that may be due to other pigment components or to other adsorptive materials in the agar.

Some cultures demonstrated significant ability to precipitate calcite and silica if provided in the media. Precipitate halos of microcrystalline calcite primarily on the growing margins were observed. This material coated the entire colony after several years of growth and the colony eventually slowed its growth to undetectable, which may be due to a combination of aging of the cells or to the growth kinetics of calcium carbonate crystallization (e.g. Nancollas & Reddy, 1971). Cultures grown in the presence of a small concentration of sodium silicate to mimic typical silica concentrations in natural waters (e.g. Correll et al 2000) have a different precipitation pattern and simply appear to coat themselves in a silica gel that then hardens. The cultures are being maintained to determine whether such amorphous silica will eventually crystallize.

DNA sequencing

Hawaiian lava caves contain a wealth of microbial colony morphologies and bacterial phyla that vary by color of microbial mat, by cave, and by type of

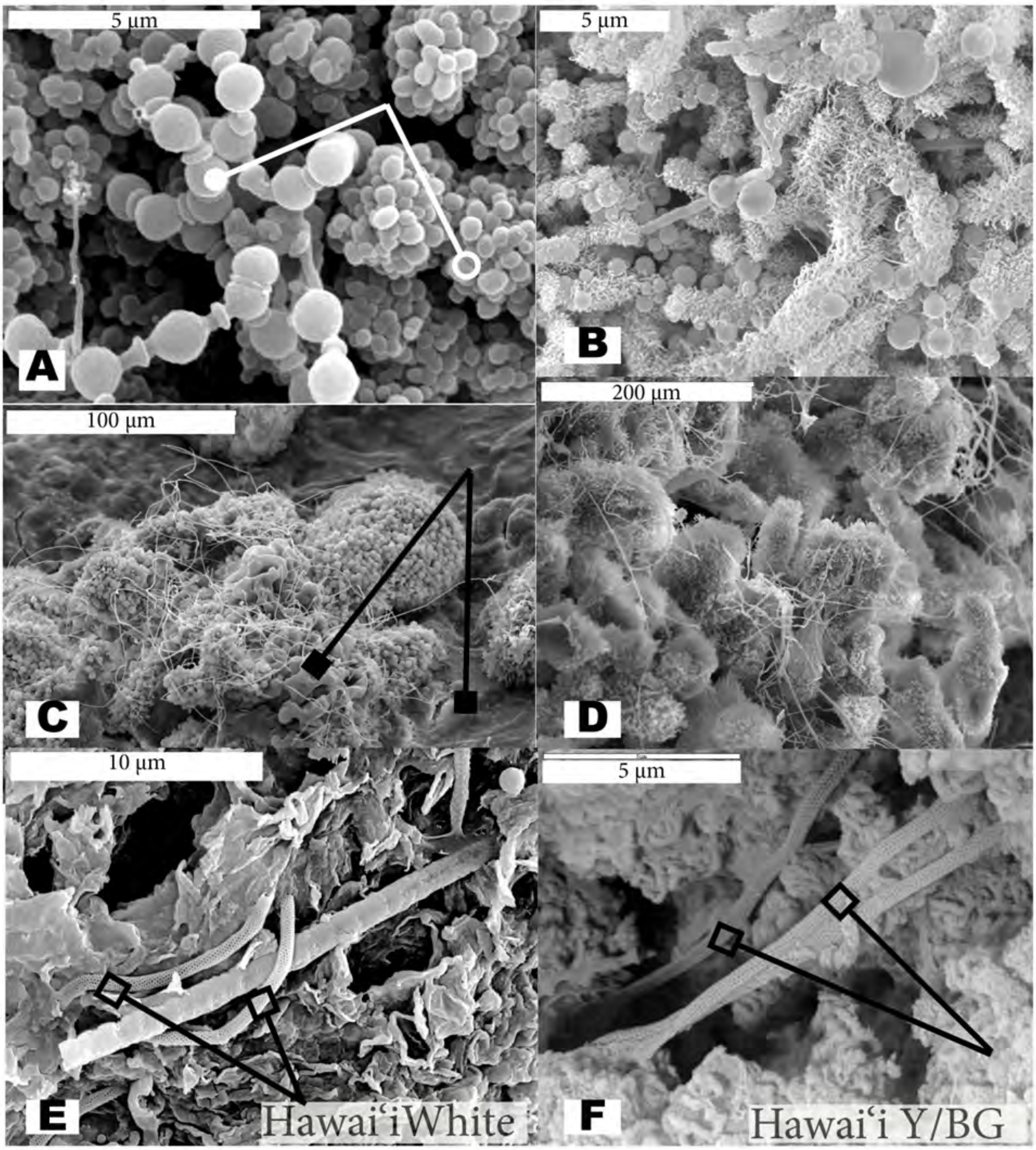

Figure 4: Scanning electron micrographs of white (A, C, E) and yellow (B, D) microbial mats, and a blue-green speleothem (F).

microbial deposit. Common bacterial phyla present in the communities included Alpha-, Beta-, and Gammaproteobacteria, Actinobacteria, Acidobacteria, and Nitrospirae (Fig. 5).

The Actinobacteria, which give caves their musty odor, were more abundant in microbial mats. Looking at the overall patterns observed in the phyla plot, it's apparent that the yellow and pink-orange microbial mats are very similar, while the white microbial mats are more varied and substantially different from the other colors. White floating mats were much less diverse than wall microbial mats and were very different in composition from microbial mats. Organic ooze varied from sample to sample, but usually contained a moderate number of Nitrospirae sequences and was very different in composition from wall microbial mats. The organic ooze from Kula Kai Caverns in the Kipuka Kanohina System had abundant Firmicutes and Gammproteobacteria (Fig. 5).

Common genera present included *Bacillus, Nitrospira, Crossiella,* and *Euzebya* (Fig. 6). The latter two genera are recently described Actinobacteria genera that have been found in several cave culture-independent studies. *Crossiella* sequences were present in large numbers in some of the cave microbial mats. *Nitrospira* is a genus of bacteria that is known for its oxidation of nitrite to nitrate. Recently a new member of the *Nitrospira* genus has been shown to be able to execute the entire nitrification cycle, taking ammonia all the way to nitrate (Daims et al. 2015). The genus *Chloracidobacterium,* first identified in 2007 (Bryant et al. 2007), is currently only known for its photosynthetic lifestyle. The identification of this genus in all of the caves studied, and in particular in Kazumura and Textbook Tunnel Caves, raises the possibility that other, non-photosynthetic species exist in this genus. Alternatively, the *Chloracidobacterium* in the cave could employ a mixotrophic metabolism in which they use heterotrophy when in the dark. Or, their presence could be evidence of re-inoculation of the lava caves from surface microorganisms entering the cave by being lofted on air masses or fluid-borne by infiltration of waters from the surface.

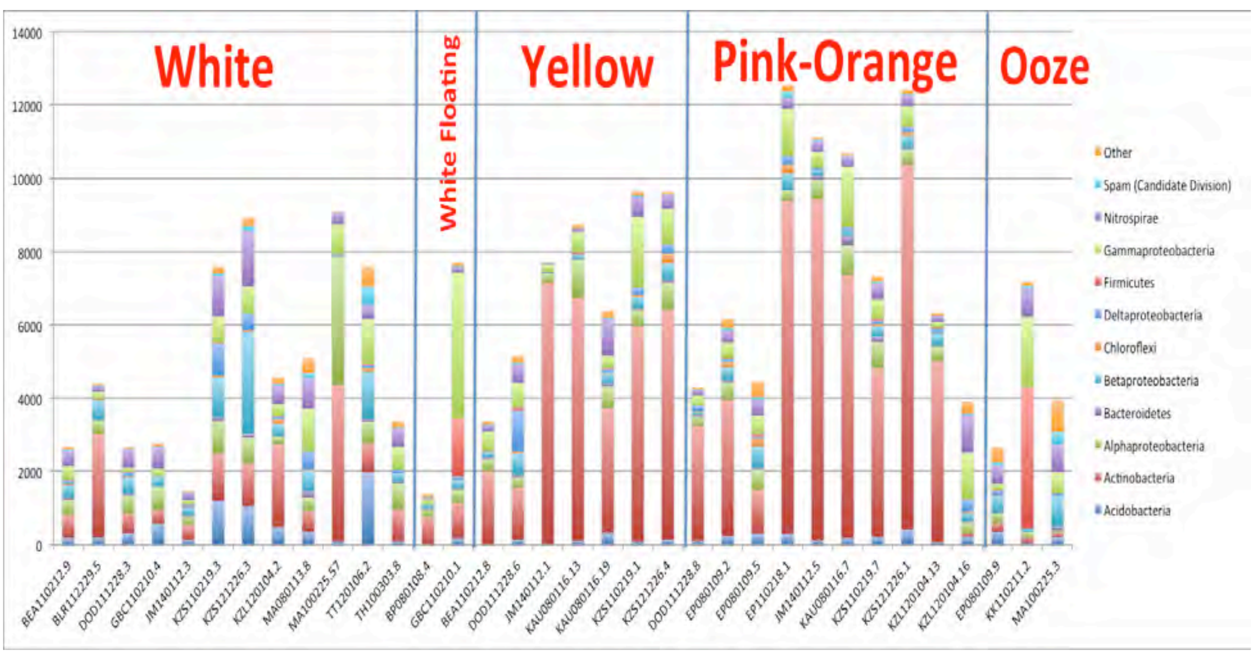

Figure 5: Phyla of bacteria present in white wall microbial mats, white floating colonies, yellow and pink to orange wall microbial mats, and organic ooze deposits.

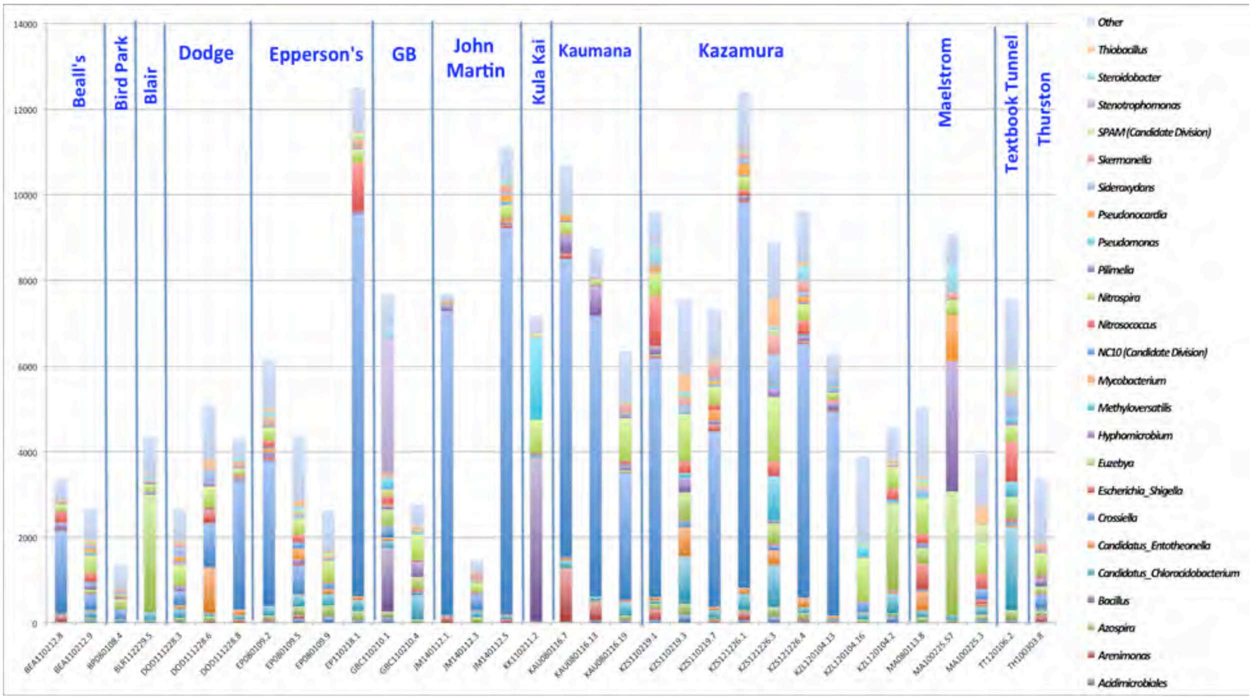

Figure 6: Bacterial genera present in Hawaiian lava caves by cave sampled.

Conclusions

Hawaiian lava cave microbial mats, floating microbial colonies, and organic ooze deposits contain a wealth of microbial diversity with eight major bacterial phyla and many less abundant bacterial phyla present. Scanning electron microscopy has provided us with an intimate look at the microbial morphology diversity present. Most notable are the extensive rods, cocci, and filaments with hair-like and knobby extensions from their cells. Also of interest is the presence of reticulated filaments found in many carbonate caves worldwide. Yellow, pink and orange microbial mats are much more similar in composition to each other and differ substantially from white microbial mats, which are more diverse in their composition. Organic ooze deposits differ from each other and from microbial mats. Cultivation of microorganisms from these mats is shedding light on some of their properties, such as the ability to precipitate calcium carbonate and silica. This study sheds light on the nature of these diverse microbial mats and suggests there is much left to study.

Acknowledgements

The authors are extremely grateful for the financial support for sequencing received from the National Speleological Foundation. The Cave Conservancy of Hawai`i (CCH) has been very helpful in assisting with fieldwork, providing maps for sample locations, and photography assistance. Kenneth Ingham took many hundreds of wonderful photographs of the caves and our sample sites. We especially thank the many land owners/managers who provided access to their caves: CCH, Ric Elhard, the Bealls, Peter Epperson, Sheldon Lehman, and the Hawai`i Volcanoes National Park (collecting permit issued to Northup). Many CCH members and other cavers helped with the work in the caves, including Don and Barb Coons, Emily Davis, Mike Warner, Ric Elhard, Larry Flemming, John Wilson, Peter and Ann Bosted, Debbie Ward, Hazel and Doug Medville, Val Hildreth-Werker, Jim Werker, Nick and Sue White, Ron Carlson, Matt Garcia, Monica Moya, Wynelle Lau, Carl Snyder, Jenny Whitby, Steve Welch, and Leslie Melim.

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SURTSHELLIR IN HALLMUNDARHRAUN

Historical overview, exploration, memories, damage, an attempt to reconstruct its glorious past

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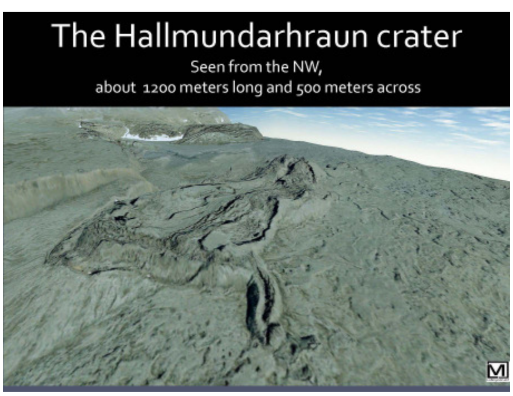
Historical overview

Surtshellir is first mentioned in the scaldic poem Hallmundarkviða, in Bergbúaþáttur, one of the shortest chronicles of the Icelandic Sagas (1). The chronicle deals with a farmer and a farmhand seeking a refuge in a cave in a snowstorm. The cave is inhabited by a troll. The troll does not object to the presence of humans. During the night it delivers a twelve stanza poem three times, with a bad omen to it: If the overnight visitors can't learn it, they will not enjoy a very long life !

The farmer memorized the poem and led a happy life. The farmhand however did not and perished shortly afterwards. The poem is ancient and stems from heathendom, from long before Christianity became the official religion in Iceland in the year 1000 AD.

Hallmundarkviða is hard to understand.

The scene is mountains, gorges, a volcanic outbreak, earthquakes, lava fields and lava tubes (2). The thundergod Thor and the firegod Surtur wrestle. The earth quakes, it's on fire and it burns. Kristján Sæmundsson 1966 (3) dates the Hallmundarhraun lava to 662-1016 AD and points out the fact it might have erupted around the time of the settlement of Iceland (in AD 874). Halldór Laxness 1969 (4) collected bone samples from Beinahellir / Vígishellir (Robbers Roost) in 1948 which were dated to 781-1237 AD. Haukur Jóhannesson 1989 (5) examined a soil section underneath the Hallmundarhraun lava and found the so-called Settlement layer, a very conspicuous solidly dated tephra layer, 871+/-2 years AD, just underneath it.



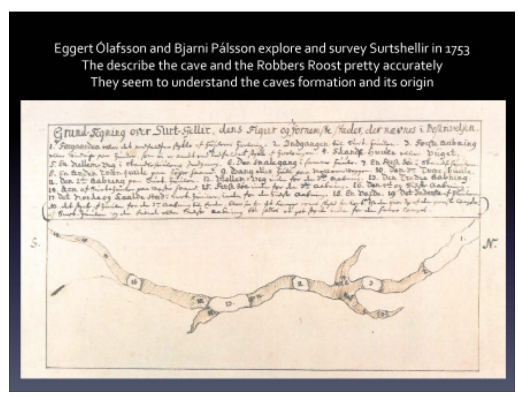
The Hallmundarhraun fires must therefore have been among the first volcanic outbreaks which the settlers experienced. The settlement of Iceland officially started when the Viking Ingólfur Arnarson settled in Reykjavík in 874. Hallmundarhraun is 27 miles long, it covers an area of 80 sq. miles and the volume is estimated to be 1.2 -1.4 cubic miles (6).

The Hellismanna saga, (a short 13th century adventurous tale) (7) relates how a band of outlaws took refuge in the cave in the 10th century and their subsequent killing. The monumental Sturlunga saga (also 13th century) (8) mentions the torture and maiming of Órækja Snorrason (son of renowned historian and chieftain Snorri Sturluson) taking place in Surtshellir around the year twelvehundred thirty.

Exploration

In a letter to Olaus Borrichus 1675, Þorkell Arngrímsson, 1629-1677 (9), the son of Arngrímur Jónsson the Learned, 1568-1648, starts with writing about (10) having sent Olaus a few stalactites the year before. Þorkell mentions the stalactites and describes Surtshellir as a being a work of art. He estimates that its length exceeds 240 paces, with a width of thirty paces and the height being about the same as the width. He also describes the two main side passages, the Robbers Roost (Beinahellir / Vígishellir) and Vik.

The naturalist team Eggert Ólafsson and Bjarni Pálsson, 1772 (11) explore and survey Surtshellir in 1753. Judging from the direction of the flow of lava, they conclude that it must either have originated in the faraway Geitlandsjökull, or in the mountains behind it. They were immensely impressed by the cave, and proceeded to describe its size, the walls, horizontal benches, shelves and markings, the curious glazing of the walls, the stalagmites and stalactites, other formations and the Robbers Roost.

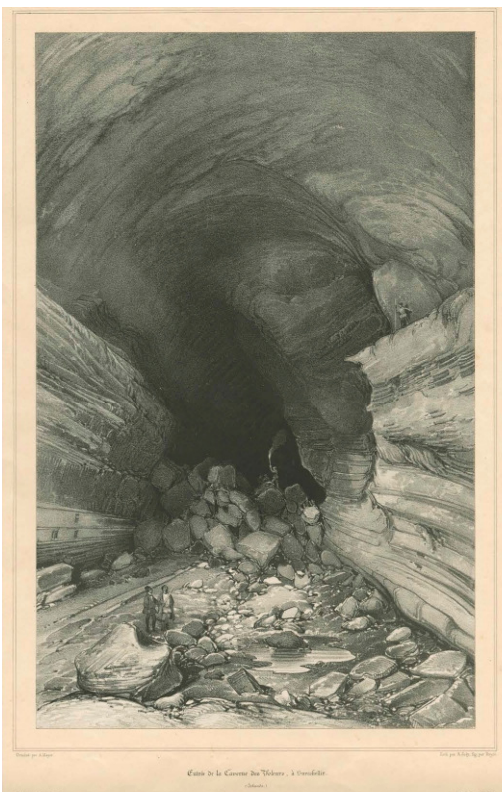


Both Eggert and Bjarni were highly educated naturalists and way ahead of their time. Bjarni later became the Royal Surgeon General of Iceland and Eggert the Vice Administrator of the North and West Iceland. They grasp how the cave came into existence and seem to generally understand how its structures were originally formed. They describe the Robbers Roost and discover a large heap of soft decaying bones which they find to be highly interesting. The heap was about six paces across and consisted mostly of cattle bones, all broken to the marrow.

They describe stalks of curious penta- and heptagonal crystals and other ice formations in the lower part of the cave (Íshellir), and find the icy surroundings to be stunningly beautiful. In the distal end of the ice-cave they came across an old cairn.

Eggert and Bjarni were the first to survey Surtshellir. They measure the total length of it as being 839 fathoms and take a few rock samples.

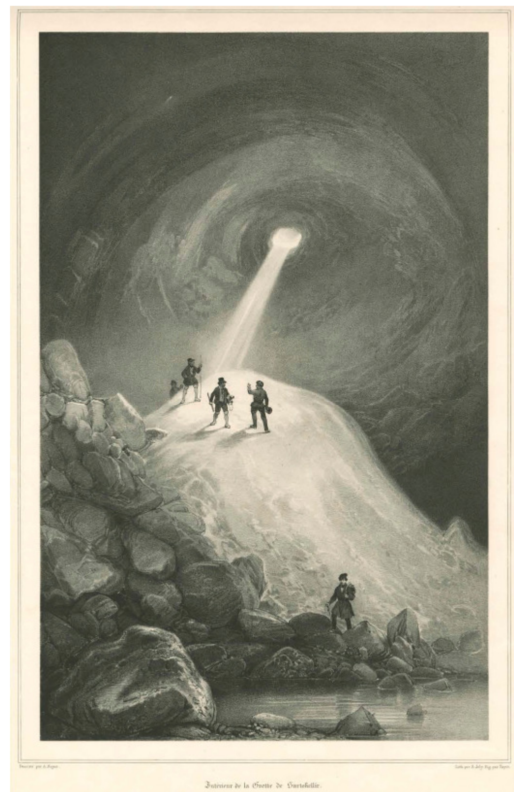
The next important description of Surtshellir stems from Ebeneser Henderson 1818 (12), a Scottish priest based in Copenhagen. Henderson was the founder of the Icelandic Bible Society. He brought a new translation of the Bible to Iceland in 1814 and distributed it around the country in years 1814-1815.



Henderson describes the main cave and the side passages with the Robbers Roost. He finds the ice formations in the ice cave, the distal part of the Surtshellir system, awe-inspiring, stunningly beautiful and describes this white glittering fairy world in a vivid poetic manner.

French royal explorer Paul Gaimard 1850 (13) visits Iceland and Greenland on the La Recherche vessel during summertime in both 1835 and 1836. The expedition's draftsman, Auguste Mayer draws four lithographs of Surtshellir. Mayer's pictures were the first to show the majesty of the cave.

Next, it is two Germans, William Preyer and Ferdinand Zirkel 1862 (14) who visit Surtshellir in the summer of 1860. They describe formations in the side passages of the cave far more accurately than their predecessors and mention a substantial amount of stalactites in the passage down flow from the Robbers Roost and in the opposite side passage Vik: "*Hier finden wir die längsten und schönsten Tropfsteine und in sehr gosser Menge*." They also mention taking samples from the bone heap.



Iceland became more and more popular among wealthy foreign visitors from the middle of the 19th-till the beginning of the 20th century. Most of the visitors seem to have taken "samples" from the bone heap and also seem to have taken samples of whatever formations they could find as souvenirs. It almost became a standard practice.

Two Austrian brothers, Zugmeyer 1903 (15) visit Iceland in the summer of 1902. The younger brother was an engineer. Together, they proceed to survey Surtshellir for a second time (after Eggert's and Bjarni's initial survey of 1753). They mention the decorated part in one of the side passages which Preyer and Zirkel had visited in 1862 and declare:

"*Ihre Decke ist mit zahllosen, aber nur 0,4 – 1.2 zoll langen Lavastalagtiten bekleidet*".
This can only mean that the stalactites were substantially shorter in 1902 than 40 years before. Visitors had to walk with their backs bent in these parts of the side passages, because of the low ceiling. Walking bent over like that, people are unable to look straight ahead and therefore unable to see what was hanging from the low ceiling immediately in front, just above their heads, and thus they tended to bulldoze the formations off the rock face.
Indeed, there is less and less mentioning of formations in visitors' reports, starting with that of Eggert and Bjarni in 1763 and thence onwards to Zugmeyers' 1902 (15) and Matthías Þórðarson's 1909 (17). Formations disappear from the reports as time goes by, the reason being, that you can't see what's gone already, it's not there any more!

In 1917, 15 years after the Zugmeier's visit, young Stefán Ólafsson from the farm of Kalmanstunga, only 16 years of age at the time (born in 1901), discovers an upwards flowing extension of Surtshellir, with two cairns showing the way in that cave, just like there had been a cairn in the Íshellir main cave, when Eggert and Bjarni explored it (11). The three cairns are irrefutable proof that both parts of the Surtshellir-Stefánshellir system had been visited by humans before 1753/1917.
Matthías Þórðarson 1920 (16), a friend of the people in Kalmanstunga, and at that time the Curator of Archaeological Remains and National Monuments in Iceland, learnt about the extension of Surtshellir two years later, in 1919. Matthías and a friend of his Helgi Hjörvar, accompanied by their wives, visit Stefánshellir in the company of young Stefán, the following year. Matthías (15) is fascinated by the intricate structure of the cave and the evenness of the floors; he talks about how remarkably uncollapsed the cave is and how easy it is to get around on the level smooth floors. There had been exceptionally cold winters during the previous years, especially in 1919, when ice covered the floor in places and ice formations decorated sections of the cave. In his four page description of the cave, Matthías (16) does not mention any rock-formations at all.
However, Matthías was already familiar with lava caves. He had explored the Surtshellir and Víðgelmir caves in the summer of 1909 (17), i.e. eleven years prior to his Stefánshellir visit. He also knew about the exploration of Raufarhóls-hellir in South-West Iceland in 1909 (18). In his 1910 description Matthías (17) mentions that the bone heap in the Robbers Roost has shrunk significantly, both since Eggert and Bjarni observed it in 1753 (11) and since P.E.K. Kålund described it in 1873 (19).
Matthías (17) had been absolutely fascinated in 1909 by the profuse lava decorations which could be found in Víðgelmir, a majestic lava cavern, situated a few kilometers downflow from Surtshellir. Somewhat by lack of adequate words, he reflects on the necessity of having Víðgelmir declared a national monument and mentions the possibility of gating it.
Martin Mills and Chris Wood survey Víðgelmir in 1972 (20). They are quite impressed by the cave and say at the end of their report: *A case for cave conservation; Víðgelmir lava tube cave is the outstanding example of Icelandic caverns which we have so far examined. It possesses many unique features and is particularly notable for its impressive size, its wealth of lava formations and its distinctive ice section.*

Memories, ÁBS.

My grand-aunt Valgerður, my grandmothers sister, born in 1901 (like her husband Stefán), , was the housewife at Kalmanstunga from 1930-1958. Kalmanstunga is the farm which is situated nearest to the huge caves of Hallmundarhraun and most of that lava-field's caves are property of the farm of Kalmanstunga with the exception of Víðgelmir-cave, which was awarded to the nearby farm of Fljótstunga around the turn of the 19th century. The leaseholders of Kalmanstunga were the first people to explore all the great caves in the area, with the exception, however, of Surtshellir.
I was first sent by my parents for a stay at Kalmanstunga at the tender age of five. It was customary in Iceland in those days to send children, even at a very young age, to relatives in the countryside to learn the ways of the land and lend a helping hand in whatever they could. I fetched the cows, ran errands, started riding horses at six and driving the tractor at ten for example. My first stay, in 1954, lasted four weeks. I instantly fell in love with Kalmanstunga and the majestic environment of the upper Borgarfjörður region. For the next nine years, I spent the four month of summer there, always as a helping hand. Of course, I was given added responsibilities as I grew older and at the first sign of springtime each year, I just could not wait to get over there.
Like every good housewife, Valgerður was in charge of everything. Her words were law. One of her laws was: One does not break rock-formations! Stefán and Valgerður were friends of the Iceland's renowned geologist Sigurður Þórarinsson who was a treasure trove of information about lava-caves. Sigurður pioneered several nature conservation

efforts in the fifties (21). In 1956, he took part in drafting the first nature conservation legislation in Iceland (22) and had a seat on the board of Náttúruverndarráð (Nature Conservation Council) est. 1956.

„Valgerður´s law" became a national law (23) when, in 1958, lava formations were declared national monuments by the Nature Conservation Council and thus, as a rule, protected. Sad to say, however, this law or declaration has never been strictly adhered to and even less enforced.

One day Valgerður instructed her husband to show the kids, me and a year older niece of mine, the cave which he had discovered thirty-nine years earlier. This was in the summer of 1956, i.e. almost sixty years ago.

Stefán lamented. "*I don't want to go there any more*"…. "*Never*" …. "*I just can't do it*"…..

"*It breaks my heart to see the cave, everything in there has been damaged*" ….."*I am never going in there again*".

Protesting to his wife and trying to make a stand, Stefán showed more feelings and emotion than I had ever witnessed in a grown-up person before. The ill fate of the cave really hurt him. I was just seven at the time. The tone, the pain and the body language intrigued me and the memory of it has stayed with me ever since.

However, a few days later Stefán took us kids on a horseback riding trip to Fiskivatn, a trout fishing lake on the moor of Arnarvatnsheiði and on the way, he vaguely pointed the whereabouts of the caves out to us. Indeed, they are by no way not easy to pinpoint on the featureless lava field landscape. On the way back I noticed that we had already by-passed the caves. I made Stefán aware of this. He knew of course. He was just trying to keep his distance from the caves, hoping that we wouldn't notice. However, despite my young age, I was nevertheless wise to him! First I started pleading and begging, please, please Uncle, we want to see the caves, please, but to no avail, he just did not want to turn around. Then, in my utter frustration the almighty Valgerður sprang to my mind, her powers were without boundaries! I pulled myself together and said in as serious a grown-up tone as I could; "I'll tell Valgerður then"! Stefán, gave me a sharp look, then instantly changed his mind, swung his horse around and took us into the main entrance of the Stefánshellir cave. From there, it has five passages, going in all directions. Stefán had an old back injury and said he could not penetrate into the cave himself, nor did he want to. He just stood there in the entrance twilight and instructed us where to go. "*First, you go there and there and then you'll see this and that and then you turn back*." This, I found it absolutely amazing, he knew the cave by heart ! How could he *know* that?

The third thing about Stefán that made me wonder was how our innocent youthful enthusiasm elevated his own spirits. He relaxed and even started to smile. Straight away, the creation of the cave interested me immensely. How had it all come about, how had the rock formations been made? Stefán, however, was dead unwilling to tell us about the size of the stalagmites; neither did he want to tell us what the cave had looked like in former times. He didn't even acknowledge our questions about the stalagmites or stalactites, being this big, that wide, this long, or that high?

In spite of Stefáns reaction, or perhaps even *because* of his reaction, or I don't know exactly why, I somehow got the impression Stefánshellir had perhaps never been very decorated with "dripstone" formations. At least I always thought Stefánshellir had been nowhere near as magnificent as Víðgelmir, which I visited three years later, in the company of Kalman, Stefáns son. Matthías Þórðarson's (16) description, which I first saw in the nineties, also led me astray for some time, since Matthías does not mention any "dripstone" formations at all.

As kids we used candles and two, even three 3 volt battery torches to explore Stefánshellir. Batteries were expensive in those days and we were expected to use them sparingly. We had Sunday afternoons off and often went riding, however, on rainy days, we usually went to visit the caves.

The reason why we preferred Stefánshellir was its intricate structure, its narrow passages and how easy it was to pass through. It was our playground and we even liked to get purposely "lost" in the cave! However, we always somehow managed to find our way out and were quick to get our bearings on the surface, even in foggy weather. It never occurred to me in these times to search for the breakage spots where stalagmites had once stood. In the nineteen-fifties, there were no stalagmites over 3 cm in length present in Stefánshellir and we did not find a single fragment lying on the floor. Stefánshellir was not like the innermost part of Víðgelmir, where the "dripstone"- formations were still scattered around and broken stalagmite fragments littered the floor in places.

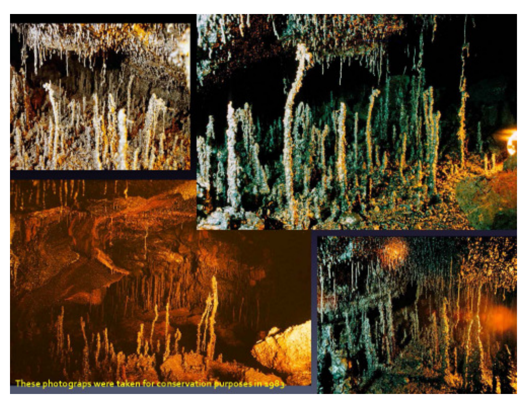
In the main passage of Stefánshellir, some dozens of meters down flow from the main entrance, there were several "fat" cave hornitos still standing proud on the floor in the fifties-early sixties, when we kids were playing there. These formations were rather flat lava slabs of different sizes, some quite large, up to 25 inches in diameter. In my memory they were perhaps up to 15- 19- 24 inches high. They did not particularly interest me at that time, they just stood

there eerily, as an inherent part of the cave. It was not until later, long after they had been removed, that I finally understood their formation: They had been formed by frothy lava oozing up under gas pressure from underneath the floor.
The lava formations in Víðgelmir had a profound effect on Matthías Þórðarson (17) in his 1910 report. He found Stefánshellir (16) quite impressive, but in his four page description of the cave, as previously stated, there is no description of "dripstone"-formations at all.

As time went by, I started to get more and more curious and wanting to know, just exactly how decorated Stefánshellir had previously been ? No photographs had been made to my knowledge and nobody who knew was around anymore. Except perhaps myself. The talk at the kitchen table in Kalmanstunga in the fifties had never left me. The voices of Stefán and Valgerður and Stefáns feelings, their stories about people removing and damaging the "dripstone" formations and looting the bone-remains. Their statement when similar decorated caves were discovered in the Gullborgarhraun lava-field in 1957: "*It won't take them long to destroy them*." By the first "them", they meant whoever visited the caves; with the other "them", they meant the formations. Only eight years of age I wondered: How *can* they know? They must know!!! It's inevitable!! The caves will get damaged. Sad! Why? For this reason I became more aware of, and read over half a dozen newspaper articles about damage to the Gullborg caves from the late fifties until the mid seventies and became "all" ears when news about damage came on the radio. I visited the Gullborg caves in 1966 and photographed what was left (about half) in the very decorated end of Borgarhellir in 1984. When I checked the same place in 2007 most of the formations were gone so I photo-documented the damage.
The feeling slowly grew in my mind: Stefánshellir must also have been quite decorated. The old couple at Kalmanstunga, Stefán especially, must have had something painful to regret. Even though he did not want to talk about it. Or perhaps that was the reason. Stefán knew what the cave had looked like. It hurt him even to think about it. They both knew what had happened.
Their prophecy of Borgarhellir, the most decorated of the Gullborg still rings a bell: "*It won't take "them" long do destroy them*"; (meaning the formations) they retorted to the radio. They knew, the prophecy came true.
As time went by this (sadly) became an accepted fact in Kalmanstunga. Almost like a law of nature. Sensitive formations in caves with unrestricted access, known to the general public and tourists alike, inevitably get to be destroyed. There are no exceptions, as most of us know. Even conscientious experienced cavers cause damage. The old people at Kalmanstunga knew that the whereabouts of sensitive caves should be kept secret. Gating was unthinkable in 1957. It was almost just as unthinkable in 1972 when Mills and Wood wrote their report (20).
Víðgelmir repeatedly "gated itself" with an iceplug. The first known formed in 1917 (16). The last plug to close the cave formed in the early seventies and the ice remained until 1990.

Solid evidence

Tourism has increased exponentially in Iceland. In 1980 there were 50 thousand visitors. Doubling every 10 years from 1980-2000 and tripling every 10 years since then. Last year the number of tourists exceeded 1.3 million. Due to mis- and over-interpretated laws, dating right back to the Settlement of Iceland about public rights of passage, there is free access to land practically everywhere. For the public and tourists alike. Caves included. The tourist-industry takes an indiscriminate advantage of this.
The gps location of over 500 cave entrances was published in 2006. The location of several hundred cave entrances is available on the internet and the webpage has even been translated into Russian ! Several tourist firms use the caves for their customers and advertise trips on the internet to unprotected sensitive caves. The sensitive inventory of lava caves has been protected since 1958 (23). Even though decorated caves are *de facto* protected, this is not respected much and visits to such caves are advertised on the internet.



The author of a foreign webpage with excellent photographs from two of the (three) protected caves, and a few very sensitive ones, is currently trying to promote geo-tourism in Iceland. In his ignorance the author is not only sending a totally wrong message, he is also endangering the very caves and the environment which he is trying to promote. The rare protected gated caves have even been broken into. Unprotected caves with protected dripstone formations (since 1957 (23)) are in grave danger.

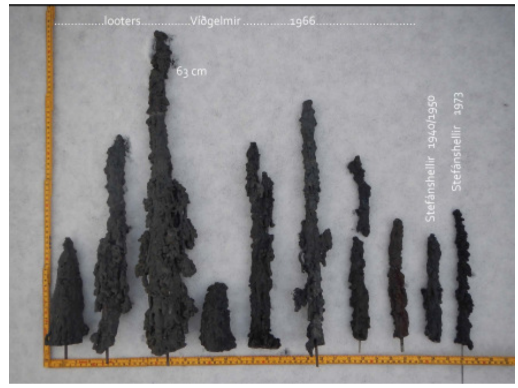
The environmental situation is serious. The final words of the authors of the chapter about Iceland in; Geoheritage in Europe and its conservation, (24) 2012, are painfully true, they say: *Total reformation of the environmental assessment practice by planning authorities is inevitable. It is necessary to strengthen the legal framework in order to ensure elaborate and professional practice. The lack of knowledge of the geo-heritage is extensive at administrative levels, and education is desperately needed to raise public awareness of geoconservation.*

Presently, a sort of gold digging fever is prevailing in the reckless and ubiquitous travel industry. The local environmental authorities, especially the Environmental Institute are woefully inadequate and lack the necessary means of enforcement when it comes to the first aspect (i.e. protection) of its duties and the second as well, i.e. a rational utilization of the highly sensitive environment which Iceland boasts of.

Documenting damage is interesting. However, it is not exactly fun; in fact it's quite sad, really. Solid evidence, research and education are the only way to build the foundations of a badly needed political and legislative interaction.

Damage

In 2009, we counted the bases of 76 stalagmites in an almost 200 ft long passage, we thought had been the most decorated part of Stefánshellir.

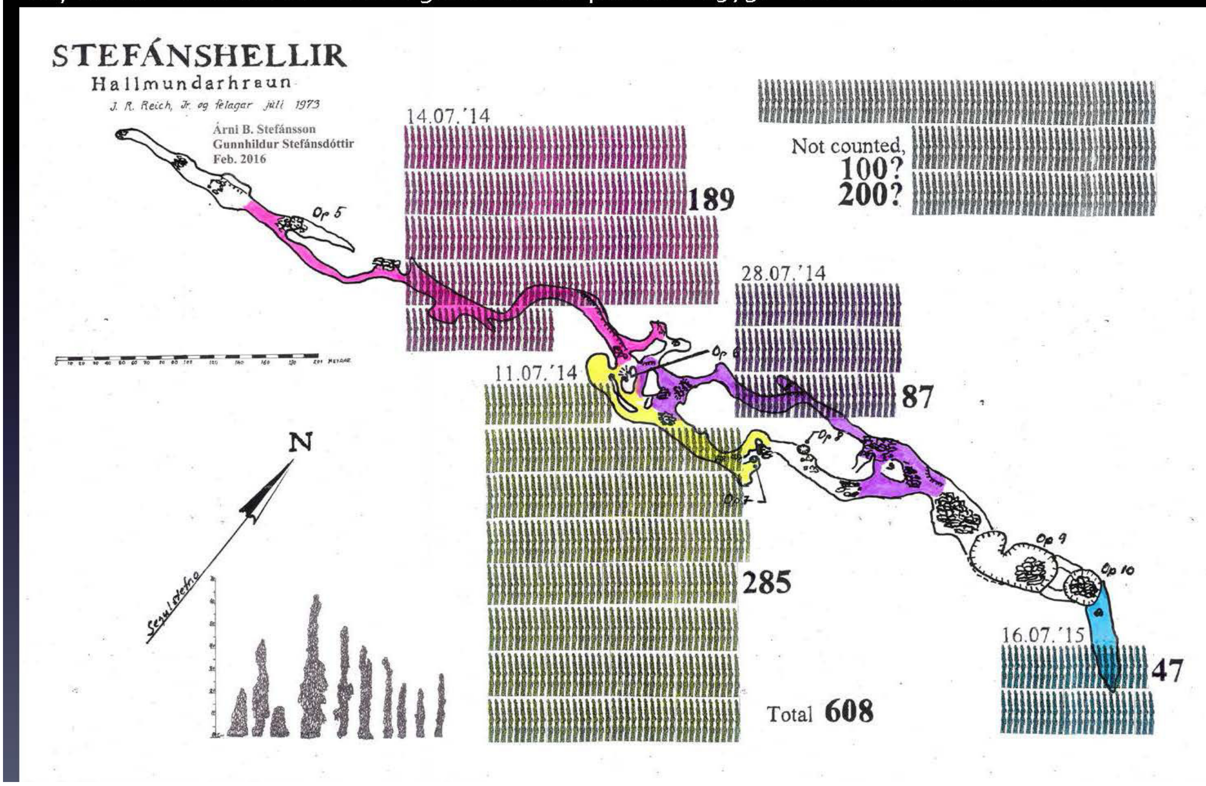


Subsequently our team decided to try to document the damage in Víðgelmir-cave. One of us knew Víðgelmir quite well, after having visited it in 1959 and 1961. It was still quite decorated at that time and still remained vividly in his memory. But even then, there were rumors and reports about serious damage. There was talk in Kalmanstunga in the mid and late fifties, that Víðgelmir should be gated. Víðgelmir had belonged Kalmanstunga until about the end of the 19^{th} century. Stefáns father and his older brother Kristófer were the first to explore Víðgelmir in the company of Matthías Þórðarson (16). The people at Kalmanstunga had always had warm and tender feelings towards the caves. However, after around the turn of the 19^{th} century, they no longer had a saying over what happened at Víðgelmir.

On two separate trips in January and July 2010, with the help of a lot of people, we counted the bases of 1093 broken stalagmites in Víðgelmir. Judging for the fragments littering the floor in places, over nine tenths of these broken stalagmites and stalagmite fragments had been removed. We counted 525 stalagmites over 2 in long in the innermost part of the cave. Of 20 stalagmites which one of us repaired with the help of a fellow caver back in 1995, seven were now broken. The fragments of one had been removed. Víðgelmir was gated in October 1990 (25). The broken repaired stalagmites were a proof of damage after the gating in 1990. That damage took place after the cave was "only" visited by "responsible cavers" and guided groups.

On five separate trips in 2014 and 2015 we counted the bases of 608 broken stalagmites in Stefánshellir. If we extrapolate that number to the parts of the cave we did not survey, roughly 750 to over 800

The first eight stalagmites on the lower left were taken from looters in Víðgelmir in 1966
The ninth was taken in Stefánshellir in the forties and returned 2012
Jay Reich found the tenth stalagmite in four pieces in 1973. The same as used in the



stalagmites must have been removed from Stefánshellir. Most of the stalagmites were obviously removed early (cf. "*it won't take them long to damage Borgarhellir!"*) i.e. in the nineteen twenties and thirties. But remarkable, beautiful cave hornitos were removed as late as the nineteen sixties. The stalactites, the lava straws have suffered an incredible amount of damage. There are just level breakage spots or very short stubs left in most parts of the cave. A few tubular stalactite straws, faint remnants of former glory, perhaps 2-4 in long, can still be seen where the ceiling is at its highest.

According the the old people in Kalmanstunga, visitors repeatedly broke the lava straws, even from the highest parts of the ceiling with their sticks and torches. (Just like some of us found innocent joy in breaking icicles from roof edges and ledges, when we were kids). The breakage took place in spite of guidance and in spite of the guides, often children asking, even begging them, i.e. the perpetrators to spare the formations. Nevertheless, the extent of the damage to Stefánshellir and how decorated the cave had been, came as quite a surprise to us. Strange since one of us had practically grown up in the cave and had experienced Stefán's pain. He should have known, but it was not that simple.

Discussion about damage often came up at the kitchen table in Kalmanstunga in 1954-1958, when the old people were still doing the farming. Stefán once said: "*That's the way it is*." Somebody added: "*Everybody knows it*." Silence,… and then someone added: "*Nobody sees it*."

That got to be a saying or a catch phrase in Kalmanstunga for a summer or two. Mostly about things that went wrong, or about things that did not go as well as wished.

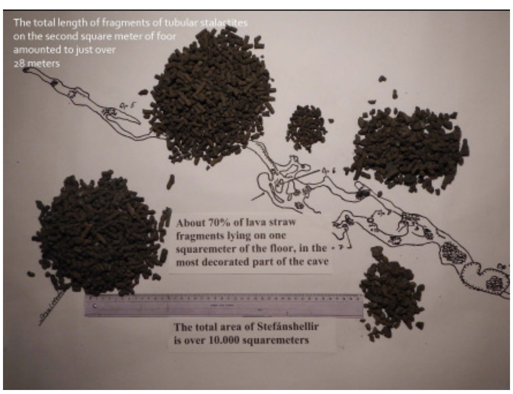
“*That’s the way it is,*
everybody knows it,
nobody sees it”
There is a lot of meaning in those words. They became a kind of a singsong:

“That’s the way it is,
everybody knows it,
nobody sees it… “

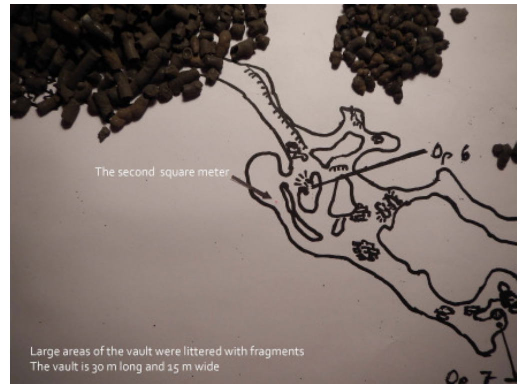
That’s the way it is, everybody knows it, nobody seeeeees it…. etc.”

The thing is, it’s not funny. It’s quite serious, and sad, very sad.

Stefánshellir has been immensely damaged. The damage was by far more extensive and by far more serious than the authors expected.



We were able to recover about 70% of the fragments of the tubular lava stalactites from two square meters which we had selected in two different places. The rest, (about 30%), lay in tight cracks and fissures and was unrecoverable. From one sq. meter (10.76 sq.ft) of floor below the ceiling, in the most decorated part of the cave, we managed to recover 1.516 fragments, whose average length was 0.75 in. The total length of fragments underneath this one sq. meter of ceiling was 93 ft 2 inches and the total weight was 65.25 oz.



In all we documented the removal of 608 stalagmites from Stefánshellir, thereof around twenty driblet spires (27) (driblet cone, lava boil). In our estimate, a total of 750-800 stalagmites decorated Stefánshellir in its prime. Today however, each and every single one of them has been removed.

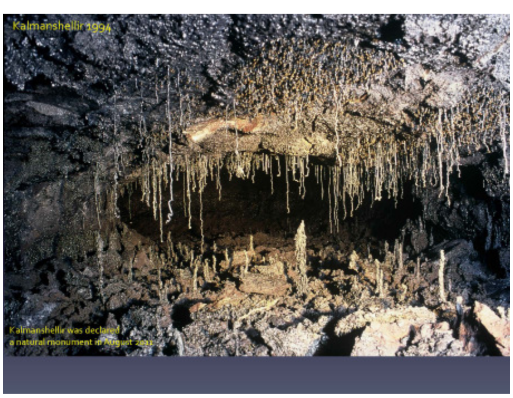
The fragments of lava straws (tubular lava stalactites) litter large areas in various places to a different extent. A conservative estimate of the total length of fragments littering the cave’s floor is well above over 10 kilometers.

Most of the damage probably took place in the early twenties. Some even earlier, starting shortly after Stefan discovered the cave in 1917.
The driblet spires were intact in the early nineteen sixties. They were probably removed in the mid or late sixties.

It is astonishing how thoroughly the job has been done. Every single formation has been removed, broken or otherwise damaged.

Of all lava caves in the world known to the authors, after Víðgelmir, Stefánshellir contained the greatest number of lava stalagmites. Judging from number of broken stalagmite bases, driblet spire bases and the amount of fragments of tubular lava stalactites, helictites and globular stalactites littering the floor, Stefánshellir was profusely decorated in earlier times. With its intricate labyrinthine structure and the amount of stalagmites and stalactites it boasted of, Stefánshellir was probably the most aesthetic large lava cave ever found. Beauty of course is in the eye of the beholder, an inner feeling. Felt or experienced in relation with the observers background, knowledge, well-being and state of mind.

Once the main entrance to Stefánshellir became public knowledge, the cave itself also became accessible to all and simple to enter. With its level floors, Stefánshellir is easy and fun to pass through. Here it stands like a medieval dungeon, proud of a past which no presently living person ever witnessed or will be able see again. You'll see!



Stefán's pain and his reluctance to visit Stefánshellir in 1956 are more understandable to us now. His unwillingness to talk about the cave; to talk about the love he lost as a young man, his helplessness, it can now easily be comprehended.

That's the way it is.....
Everybody knows it....
nobody sees it,

The last verse/line brought a faint smile on Stefán's face at the kitchen table. Recollections rushed through his head. Nobody sees it. Them good old times. His teenage love. Her youthful beauty is just a distant memory now. Vividly painful, her fragile smile vanished within a blink of an eye. No-one else ever admired the splendor which Stefán once did. He took his memory with him to the grave, when he passed away in 1977. Life goes on.

That's the way it is.....
Everybody knows it....
Nobody sees it

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P.S. Speculation / back thoughts: The reason Matthías Þórðarson (16) does not mention the formations in Stefánshellir in his 1920 report may be because he was aware of the attention his 1910 report about Víðgelmir (17) had caused. Looting of Víðgelmir probably started right after the article appeared in Eimreiðin magazine. Matthías's description of the formations in Víðgelmir in the 1910 report is just as, or even more inviting, than the description of the formations in Vegamannahellir in the Tíminn newspaper in July 1963 (28). Vegamannahellir was practically cleaned out within seven weeks (29).

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MINERALOGY OF CENTRAL AMERICAN CAVES: PRELIMINARY RESULTS

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Abstract

In the NW section of Irazú volcano, the highest volcano in Costa Rica, (3400 m.a.s.l.), three volcanic caves have been located: *Minerales, Mucolitos* and *Pizote Espantado* caves. The origin of these caves is complex, associated to many different process, i.e. collapse, erosion, tectonic activity, high temperature degasification and possible dissolution of volcanic rocks by very acidic waters. The exceptional environmental conditions of the sorroundings of the caves, such as an active volcano with a recently dried crater lake and the presence of fumaroles and active faults, allowed the precipitation of unique worldwide minerals in their inside. The hosting rocks are pyroclastic with high degree of hydrothermal alteration, silicification and tectonically affected by the central trace of the active Central Rio Sucio Fault. The area were caves are located was totally covered by volcanic material (30 to 160 m thickness) before the debris avalanche of December 8th, 1994. For this reason, it is suggested that minerals and the access to the cave are relatively recent (<22 years). The caves show important environmental conditions variations, e.g. temperature ranges from 9 to 30 °C, relative humidity from 74.2 to 96.8 % and pH of infiltration waters from 1 to 2. Herein we present preliminary results of the mineralogy of speleothems of Irazú caves, based on diverse analytical methods such as Raman spectrometry, LIBS, XRD/XRF and scanning electronic microscopy (SEM) coupled to a microprobe EDX. Preliminary results suggest the presence of more than 54 diverse minerals, mostly hydrated sulfates, 20 of those has never been reported in cave environments before. Presence of hydrated sulfates has also been detected on Mars (i.e. jarosite and gypsum), which makes these caves a natural laboratory for astrobiologic studies and a potential Mars analogue.

VOLCANIC CAVES OF COSTA RICA

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Abstract

Costa Rica is a volcanic arc located in a complex geotectonical triple junction, where the Middle American Trench separates Cocos and Caribbean plates, and the Panama Fracture Zone separates the Cocos and Nazca plate. The arrival of the Galapagos tracks and Cocos Ridge to the subduction has produced ceased of volcanism in a 195 km gap within the Talamanca Range and changes in the composition of volcanic rocks from basaltic to andesitic trend. With more than 400 volcanic focus (from relict to active volcanoes) is to be expected cthat volcanic caves should be abundant in Costa Rica. However, the predominant andesitic composition of the magmas makes difficult the development of traditional lava tubes. In addition, the tropical climate and weathering are factors that influence negatively the conservation of volcanic caves. This work shows for the first time a review of the volcanic caves in Costa Rica, as well as some of their speleogenetic features. There are four lava tubes (pyroducts), two possible volcanic pit caves, four volcanic complex caves (genesis associated to tectonics, erosion, dissolution, collapse and high temperature degasification), four mould caves, three caves developed on pyroclastic rocks and several caves in associated to talus and stream-cut (lateral and wave). Most of the Costa Rican volcanic caves have non-traditional origin. Therefore, the study of these caves will give us clues for understanding the speleogenesis of "non-traditional" volcanic caves.