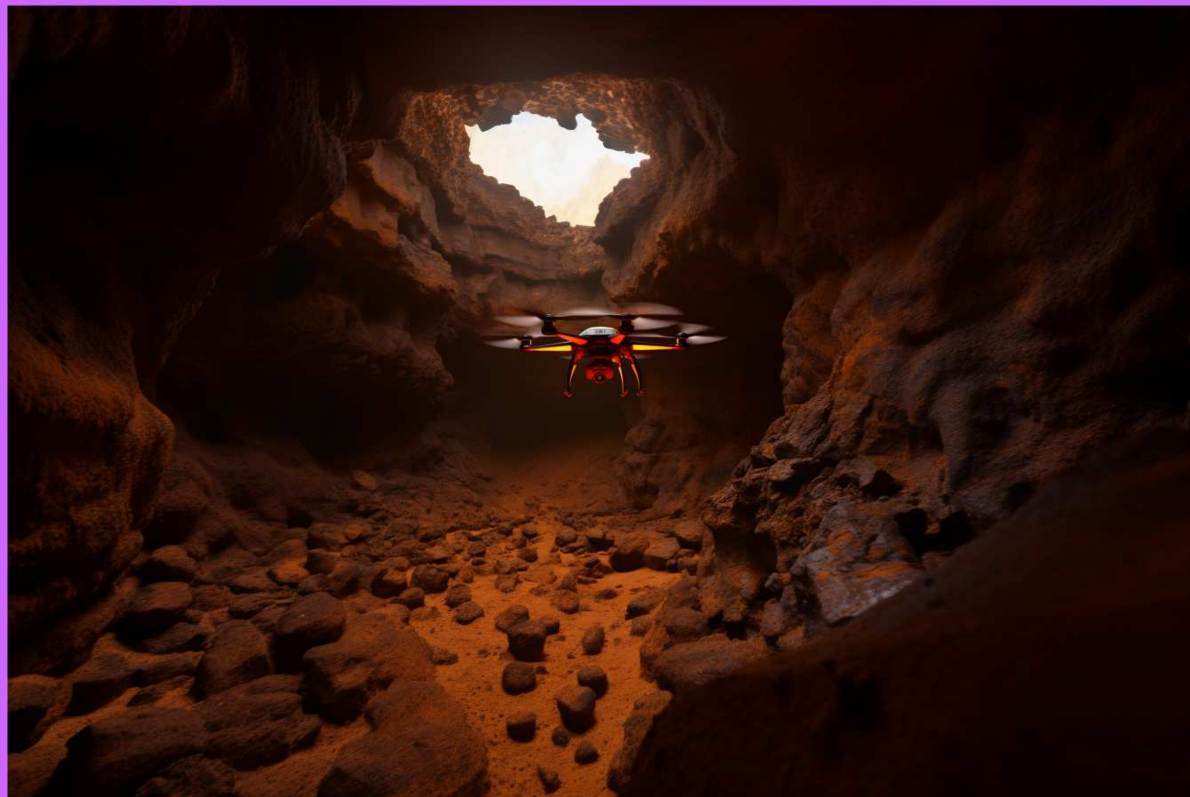
No. 82 February 2024



Union Internationale de Spéléologie (UIS)

Commission on Volcanic Caves

e-NEWSLETTER

http://www.vulcanospeleology.org/

No. 82 - February 2024

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The Commission on Volcanic Caves Newsletter has been published regularly since December 22, 1993. The Newsletter is available free of charge to all members of the commission, and to others who are interested in Volcanic caves.

UIS COMMISSION ON VOLCANIC CAVES

MISSION STATEMENT

The UIS Commission on Volcanic caves encourages exploration and scientific investigation on volcanic caves, and hosts the International Symposium on Vulcanospeleology about every two years

COVER PHOTOS

Top:
A flying NASA drone sent to Mars is exploring a huge lava tube cave and navigating through giant ice columns in huge passages underground

Bottom:
"Post Office" Cave on Isla Floreana, Galapagos. A. Addison photo

Members of the Commission on Volcanic Caves include:

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Warner, Michael	USA
Whitby, Jenny	Australia
Whitby, Gary	Australia
Woo, Kyung-Sik	Republic of Korea
Wools-Cobb, David	Australia

Editorial

It is a satisfaction to be able to give continuity to this publication, a few weeks before the Symposium in Galapagos. The Commission continues to show Speleology is a discipline and has an endurance of which we should be proud.

It is enough to review the works that are being published here to highlight the pluralism that implies knowing each other from distant points of the planet, with different methodologies, but with common objectives. Pluralism but also universality, so much so as to include, in this issue, images created by Artificial Intelligence on basaltic caves in formation, on another planet.

This is not to evade the challenges of our earthly, or "earthly" reality, but to confirm that we are in search of laws that transcend our immediate reality.

Galapagos once again occupies a central place in our activity, as it was 200 years ago for Charles Darwin when he elaborated his theory of the evolution of species.

For my part, I regret not being able to attend and I regret even more that I cannot nominate my country for the 2026 Symposium: the economic crisis, which we speleologists did not cause, continues to do damage, although we celebrate that we are connected to the rest of the world, where that crisis does not affect technical and scientific activities. We do so in the hope that, one day, we will have the final Word.

Carlos Benedetto
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President's column

Even though it is less than 18 months since the last International Symposium on Vulcanospeleology (ISV20) was convened in Dak Nong Province, Vietnam, ISV21 in the Galapagos Islands is now almost upon us. Despite the compressed timeframe for staging ISV21, the small organising team has been working hard to ensure the ISV presentations in Puerto Ayora and associated pre- and post- symposium field excursions to caves in the highlands of Santa Cruz Island, as well as caves on the islands of Floreana and Isabela are successful, and also memorable for all participants.

This issue includes a paper jointly authored by Stephan Kempe and two of the organisers of ISV21. It will serve as a good introduction to the geology and formation of volcanic caves that have so far been discovered in the Galapagos. ISV21 participants will have opportunities to visit the caves described in the paper, subject of course, to which field trip options they have selected.

Additional information on ISV21 is also included in this issue. If you have not yet registered to attend, I urge you to do so as soon as possible.

During the presentation sessions of the ISV in Puerto Ayora, there will be a meeting of the Commission. This will be its first meeting since ISV20 in Vietnam in November 2022. It will be an opportunity to review the Commission's recent activities, appoint a new Vice President, confirm other office-holders, raise issues and perhaps most importantly, consider where the next ISV could be convened. The next ISV is due in 2026 and at this stage, no offers to host the event have been received. All participants are invited to attend this meeting in person. Unfortunately, it is not feasible to provide for online participation in the ISV presentations and the Commission meeting. However, if you are not able to attend the meeting in Puerto Ayora, but have issues that you would like the meeting to consider, please contact me (warwillah@gmail.com).

Giuseppe Priolo has now posted out printed copies of the ISV19 Proceedings to all those who ordered a copy. I thank Giuseppe for his persistence in continuing to see this project through to a successful conclusion after surmounting Covid-19 constraints, health issues and the untimely passing of Roberto Conti.

Finally, I wish thank Carlos Benedetto for compiling and editing another solid issue of the newsletter. This would be a significant undertaking for anyone and especially so when it is in a language that is not their own.

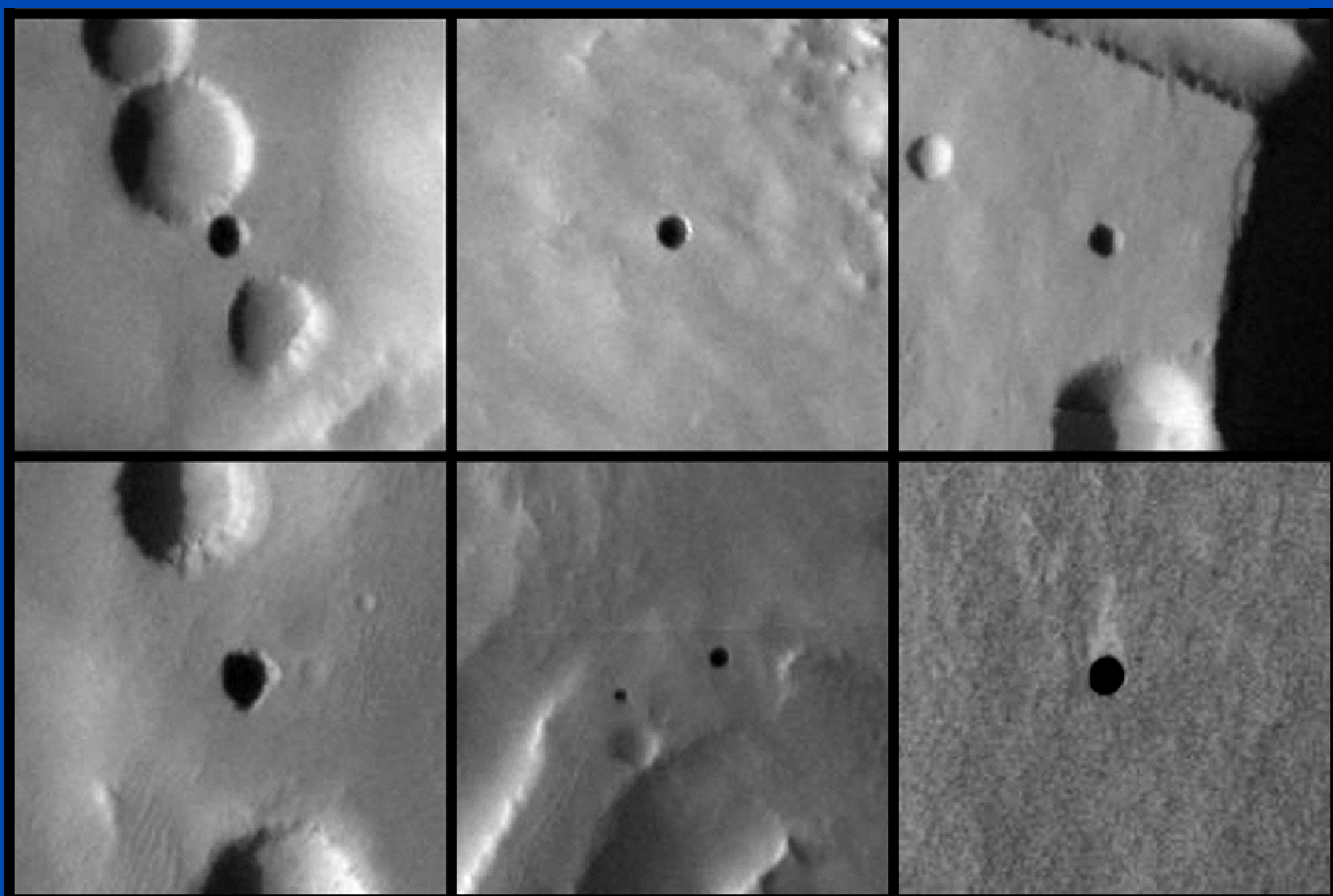
I trust you find this issue interesting and informative.

John Brush
President
UIS Commission on Volcanic Caves

Future Mars Helicopters Could Explore Lava Tubes

Originally posted on www.universetoday.com by Matt Williams, 19 January, 2024

The circular black features in this 2007 figure are caves formed by the collapse of lava tubes on Mars. Image credit: NASA/JPL-Caltech/ASU/USGS



The circular black features in this 2007 figure are caves formed by the collapse of lava tubes on Mars. Image credit: NASA/JPL-Caltech/ASU/USGS

The exploration of Mars continues, with many nations sending robotic missions to search for evidence of past life and learn more about the evolution of the planet's geology and climate. As of the penning of the article, there are ten missions exploring the Red Planet, a combination of orbiters, landers, rovers, and one helicopter (Ingenuity). Looking to the future, NASA and other space agencies are eyeing concepts that will allow them to explore farther into the Red Planet, including previously inaccessible places. In particular, there is considerable interest in exploring the stable lava tubes that run beneath the Martian surface.

These tubes may be a treasure trove of scientific discoveries, containing water ice, organic molecules, and maybe even life! Even crewed mission proposals recommend establishing habitats within these tubes, where astronauts would be sheltered from radiation, dust storms, and the extreme conditions on the surface. In a recent study from the University Politehnica Bucuresti (UPB), a team of engineers described how an autonomous Martian Inspection Drone (MID) inspired by the Ingenuity helicopter could locate, enter, and study these lava tubes in detail.

The study was conducted by Daniel Betco and Sabina Ciudin, two aerospace engineers at the University of Bucharest Polytechnic, with the support of Petrisor Valentin Parvu, an associate professor with UPB's Department of Aerospace Sciences. The paper that details their concept, "Autonomous Navigation for the Martian Inspection Drone," recently appeared in *Acta Astronautica*. In it, they describe how guidance, navigation, and control operations could be developed for their MID concept, which would rely on a convolutional neural network (CNN) to ensure autonomy.

Martian lava tubes were first noticed by the *Viking* orbiters, that studied Mars between 1976 and 1980. The images acquired by these missions revealed many features that showed how Mars was once a very different place. These included flow channels, basins, and alluvial deposits that indicated Mars once had flowing water on its surface. The presence of these lava tubes was confirmed by subsequent orbiters like the Mars Odyssey, Mars Global Surveyor (MGS), Mars Express, and Mars Reconnaissance Orbiter (MRO), which indicated that it was geologically active in the past as well.

As Betco and his colleagues told Universe Today via email, there are many things that make Martian lava tubes appealing to scientists. Much like lava tubes on the Moon, which are similarly large enough to accommodate entire planetary bases (or even whole cities), this includes natural radiation shielding and protection against the elements:

"In some instances, predicted surface values are reduced by as much as 98%. These lava tubes are of particular interest to astrobiology as they may preserve evidence of life on Mars by offering protection from UV radiation. Additionally, the caves could serve as a refuge for future human missions exploring Mars. Deeper locations within the caves could be utilized as a shield against micrometeoroids or as a heat insulator."

There is also considerable research that suggests that lava tubes may contain water ice and even be a haven for Martian life (most likely in the form of hardy bacteria). This makes lava tubes a viable location for astronaut habitats, astrobiology research, and possibly permanent settlements. Many mission concepts have been proposed for exploring these lava tubes, including networked rovers and robotic snakes. However, the *Ingenuity* helicopter – a technology demonstrator that accompanied the *Perseverance* rover to Mars – effectively demonstrated that aerial vehicles could be the best option for exploring Mars.

As Betco and his colleagues indicated, this includes the lava tubes that run beneath its surface, which would be tricky for rovers to navigate. "Aerial vehicles are well-suited for lava cave exploration as they can move in any direction in three-dimensional space, allowing them to enter the lava tube for inspection," they said. "In comparison, a rover is limited to two dimensions and would require a highly complex configuration to enter and navigate within a lava tube."

Using the *Ingenuity* helicopter as their touchstone, the team produced a design for their Martian Inspection Drone (MID). But whereas Ingenuity relies on two coaxial rotors, their vehicle has an octocopter configuration with eight. The vehicle will also have a suite of advanced scientific instruments for inspecting the cave and lava tube interiors. It will weigh a maximum of 15 kg, making it significantly heavier than *Ingenuity* – which weighs just 1.8 kg. As they describe it, the MID will also rely on an autonomous navigation system and AI to ensure it can make decisions without human controllers:

> *"A foldable mechanism is proposed to occupy a smaller volume during launch. Its autonomous navigation relies on acquiring data from sensors such as accelerometers, gyroscopes, altimeters, and cameras, processing them to determine the position and attitude of the drone during flight. Another layer of autonomy is implemented through MID's capability to make decisions regarding the next steps based on a trained Convolutional Neural Network (CNN) model. This model offers the possibility to detect and inspect lava-tube entrances (pits)."*

Looking to the future, it is clear that aerial vehicles will play a significant role in exploring extraterrestrial environments. This includes NASA's *Dragonfly* mission, the nuclear-powered quadcopter that will explore Saturn's largest moon, Titan (starting in 2034). Other concepts, like solar-powered aircraft and fleets of balloons, are being considered as a possible means of exploring the cloud tops of Venus and deploying sample-return drones to the surface. An autonomous helicopter, said Betco and his colleagues, could drastically expand future exploration efforts on Mars:

> "Our work's potential implications lie in the efficient exploration of the Martian planet, as the drone offers the possibility to survey and inspect areas of interest without requiring constant human intervention. The development of MID contributes to the integration of artificial intelligence in Martian missions. Even though the technology is not quite ready for this, the lessons learned and technologies developed now will drastically benefit future exploration of the Red Planet."

The team is currently working on implementing new capabilities that will allow their concept to inspect the insides of lava tubes using Simultaneous Localisation and Mapping (SLAM) techniques. If realized, similar concepts could be used to explore lava tubes and recesses on the Moon, Mercury, and anywhere else in the Solar System they are found.

Artist illustration of NASA's Ingenuity (upper right), a Sample Recovery Helicopter for the NASA-ESA Mars Sample Return mission (foreground), and a future Science Helicopter (upper centre). Credit: NASA/JPL-Caltech

Information for first-time Cavers to the Galapagos

Aaron Addison
Convenor, ISV21

General

The Galapagos islands are located 1000km off the coast of Ecuador and on the equator. The islands are considered part of Ecuador. Many visitors to the islands are under the impression that there are not many people living in Galapagos, this is not true. It takes a significant local population to support the non-stop tourism. The islands are under enormous pressure from visitation, this has only increased post COVID. The following information hopefully makes your visit more enjoyable, but we also hope you consider the impact that every person has on this global treasure. There is a Galapagos entrance fee of USD $100 payable in cash at the airport when landing in the islands.

Food

Although you can buy many things, prices for imported goods can be quite expensive (for example, batteries). There are snack items that work well for cave food. DO NOT bring nuts or fruits of any kind to the islands. All of your gear and carry-on luggage will be scanned at quarantine. It will also be examined when you move between islands.

Some vegetarian food is available, but it is not varied. In the local restaurants (which have good food for reasonable prices), you will not find lots of vegetables. The more costly tourist restaurants often have more varied vegetarian and regular menus. If you have special food needs, you may want to bring your own snacks. Fruits and vegetables can be bought in the local markets. Distances are not far to walk.

All drinking water should come from bottles or treated water sources. Do not drink or brush teeth with tap water, it is brackish and you will get sick. Being sick on trips is not fun, please do not risk it. There are numerous options for soft drinks, juices, beer, wine etc…

Trash

Consider what you bring with you. Disposable items that you intend to trash and leave there should probably be left at home. Consider how expensive it is to deal with waste on the islands. Do not plan to leave your used batteries behind. However, we have left excess decent (clean) clothing, and extra food with trusted locals for distribution. DO NOT wash caving clothes in your room sink or shower. We will designate a washing spot. There will be clothesline space for drying, but it is not unlimited. Please plan to share. Daily laundry service is available in town on a per kilo price of several dollars.

Money

Ecuador is standardized on the US dollar. There are ATM machines. Cirrus and MAC are commonly available. Daily maximum cash withdrawal for foreigners was $300 in the past. Expect some ATMs to be out of order at any given time. There are generally NO ATM machines on Floreana or Isabela islands, and credit cards are not widely accepted. Plan to take all cash for this portion of the trip. Smaller banks should be contacted prior to your trip so as to avoid any suspension of your account, Credit cards associated with large banks seem to be easier to use overall. Bring cash, but do not bring all large bills or damaged bills. Anything larger than a $20 may be refused, especially at non-tourist locations. Save your large bills for registration, and tourist spots where they are more common. Galapagos is primarily a cash economy.

Caving

The caves are very warm by North American standards. Most people cave in a T-shirt and lightweight pants. You will absolutely sweat through these clothes. It can be very beneficial to bring 2 sets of clothes and alternate days for comfort. Some people bring extra shorts and sandals to change into after harder trips. It is tempting to wear shorts in the caves, but please think about long pants of some kind. It helps prevent abrasion of your body. Caves can range from very clean (and sharp!) rock to very dirty and soiled filled passages. Do not bring coveralls, you will be reduced to a puddle of sweat.

Galápagos caving is hot work!

Lava is hard on boots, so bring sturdy ones. Some of the caves are glass and very young and/or un-weathered lava. Highly recommend that you bring leather boots and very good knee pads. Good, tough, but breathable gloves are a must. Leave rubber boots and gloves at home! Bring lightweight socks, at least 2 pairs.

There are many little laundromats where, for a quite reasonable price, your clothes will be washed, dried and folded. It is helpful to have a laundry bag. Drop off one day and pick up next. They didn't seem to mind cave clothes as long as they were not covered in mud. Pricing is by the kilo, so it is often cost effective to combine loads. Beware that many laundry locations use straight bleach and can damage fabrics. Be sure to let them know if you do not wish to have bleach used.

Power

All electrical power on the islands is by generation, and subject to occasional outages (usually during the day). The voltage is 120v so US plugs fit, but outlets are quite limited, and sometimes poorly grounded. A small power strip is recommended if you have many rechargeable things.

Additional essential items

- A good hat for the hot and direct sun. You are on the equator, there will be 12hrs of sun each day.
- Sun screen (50SPF or higher)
- A pack to carry your own water (we have had several people get heat exhaustion before even reaching the cave). You should be able to carry 2-3 liters in your pack when you head out into the jungle. I promise you will drink more water than you normally drink, even in the cave.

Optional gear

- Light\breathable clothing, include a long-sleeved shirt
- hiking pole(s)
- zip off pants
- thick socks
- water bottles (can also be purchased at local markets)
- GPS
- Camera
- Tripod

Discovery of a new cave type in Vietnam at the contact boundary of basalt and sedimentary rock in Krongno district, Dak Nong province

Authors: La The Phuc [1], Luong Thi Tuat [1];[*], Nguyen Thanh Tung [2]
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Fig.1. T22 cave has been discovered in Dak Nong UNESCO Global Geopark, Vietnam.

I. Introduction

On 22 April 2023, a team comprising La The Phuc, Luong Thi Tuat, and Nguyen Thanh Tung first discovered and explored a new cave type in Buon Choa'h commune, Krongno district, Dak Nong province, Vietnam. The cave was named "T22" to remember the date when it was first discovered and surveyed by our team (Fig.1). However, local people usually call it "Zebra Cave" because they said zebras had been seen living in it.

Fig.2. Location of T22 cave on Google Map.

T22 cave is located approximately 1,500m almost south (173^0) of Chu B'Luk crater, at an elevation of 490.3m (Fig.2). Coordinates: 12027'49" N; 107056'46" E. This is quite a small cave 18-20m long, 15-18m wide, and 3-5m depth, that was formed due to erosion of the weathered sedimentary rock at the boundary of two types of rock (Fig.1; Fig.3) in Buon Choa'h commune, Krongno district, Dak Nong province, in the area of Dak Nong UNESCO Global Geopark (DN UGGp). The entrance is a narrow space formed between two rock units: the upper is hard basalt, and the lower is soft siltstone, and claystone. In the cave, we realized that the roof is hard basalt, quite flattened, while the lower part is soft due to being weathered, creating a rugged, bumpy passage (Fig.1; Fig.3; Fig.4).

Fig.3. The narrow entrance of T22 cave

Fig.4. A rugged/bump passage in T22 cave

Fig.5. (l); Fig.6 (r). Banded and micro-folded structures of sedimentary rock are still preserved

Fig.7. Gravels of sedimentary rock stuck on the surface of basalt were found in T22 cave

Fig.8. Stratigraphical unconformity boundary between 2 geological formations in T22 cave

II. Some features of the cave

1. Geology

As mentioned above, the entrance is a narrow space formed at the contact boundary of two formations: Xuan Loc (βQ_1^2 *xl*), and La Nga (J_2 *ln*) (Fig.1).

Inside, the cave consists of two parts:

- The lower was formed by layers of siltstone, and claystone, terrigenous origin (Fig.1) of La Nga formation (J_2 *ln*). They were mostly weathered and turned quite soft. In some places, the banded and micro-folded structures are still preserved (Fig.5; Fig.6).
- The upper (roof of the cave) was formed by the hard basaltic rock of Chu B'Luk volcano (Fig.1; Fig.3; Fig.4), which belongs to Xuan Loc formation (βQ_1^2 *xl*). In the cave, we found a block of basalt with gravels of sedimentary rock of La Nga formation stuck on the surface (Fig.7). In the cave, the unconformity boundary between two geological formations shows clearly (Fig.8).

The cave was created by the erosion process of the sedimentary rock of the La Nga formation, leaving the space between two types of rocks.

2. Lava tree mold, charcoal, and crystal of pyrite in the cave

At the bottom of the roof, in basaltic rock, many lava tree molds of different sizes were found. The molds are some dozen cm to several meters long, with their diameters around 3-5cm to 10-30cm (Fig.9→ Fig.14). Observation of tree mold arrangement makes us feel that they were arranged into a pile by someone before lava flowed over the area (?). Another thought: could this be due to the lava flow overrunning an accumulation of plant tree material and pushing it together as the flow advanced (?). We quite surprisingly realized that some tree molds seemed even have been cut off one or two ends (Fig.10; Fig.11; Fig.12). Of course, this is only our first thought and it should be seriously considered and researched later. Above all, it is interesting that we can imagine and discuss to interpret the context that happened in the past here - right in front of "the pile of tree trunks" in the past, that have now become these tree molds.


Fig.9. Long lava tree molds on the roof...


Fig.10. Middle-size lava tree mold on the wall


Fig.11. One more lava tree mold on the wall...


Fig.12. Quite big lava tree mold


Fig.13. A lava tree mold right on the contact boundary of 2 types of rock


Fig.14. We found many lava tree molds here

On the surface of sedimentary rock, we found many small pieces of charcoal (Fig.15), and a big crystal of pyrite (Fig.16).

Fig.15. Charcoal on the surface of the cave.

Fig.16. A big crystal of pyrite.

3. Biodiversity

Despite the quite small size, some animal species have been found in the cave, including bats (Fig.17; Fig.18), frogs (Fig.19; Fig.20), spiders (Fig.21), and maybe ticks of some animals (Fig.22).

Fig.17. Big bat in T22 cave.

Fig.18. Small bat in T22 cave.

Fig.19. Frog with the color of the rock.

Fig.20. Frog hides in the fracture.

Fig.21. Cave spider.

Fig.22. Species of tick.

III. Scientific significance and remark

The mode of formation of T22 is different to all other lava caves in DN UGGp. The cave is the result of the process that happened post-eruption of Chu B'Luk volcano. So, it is a secondary/exogenic origin, not primary/endogenic like other caves in the area. We mean, T22 is not a lava tube, not a real volcanic/lava cave.

However, cave T22 itself contains a scientific value: it is a stratigraphical heritage, heritage type E of Dak Nong UNESCO Global Geopark (DN UGGp). It is a unique cave that shows clearly the unconformity boundary between two formations in the area: La Nga and Xuan Loc formations. It shows the transition between two periods in the geological history of DN UGGp: marine sediment deposition and continental eruption, while such a beautiful boundary is not seen anywhere else in the area.

Lava tree molds in basaltic rock in DN UGGP are not common: one in C3 cave, another in C2 cave, etc. Meanwhile, there are many lava tree molds in T22 cave. Besides, almost all lava tree molds in DN UGGP are found in the middle of the lava flow. But lava tree molds in T22 cave are distributed at the bottom/base of the lava flow. It demonstrates the trees were right on the sedimentary rock, then they were covered by the lava flow.

T22 is the contact of hot lava flow and the cold sedimentary rock. Now, we found quite many small lava tree molds and charcoal in the cave. Physically speaking, when the hot lava flow covers the cold rock in this place, its temperature cools down, so that the trees are not completely burned and not completely merged into the lava flow, providing good conditions and preserving the tree molds, even small ones.

To conclude: Cave T22 is a new cave type, just discovered in the area, a unique geological heritage, worthy of being added to the heritage treasure of DN UGGp.

AI generated images offer a unique view of lava tubes

by Dave Bunnell

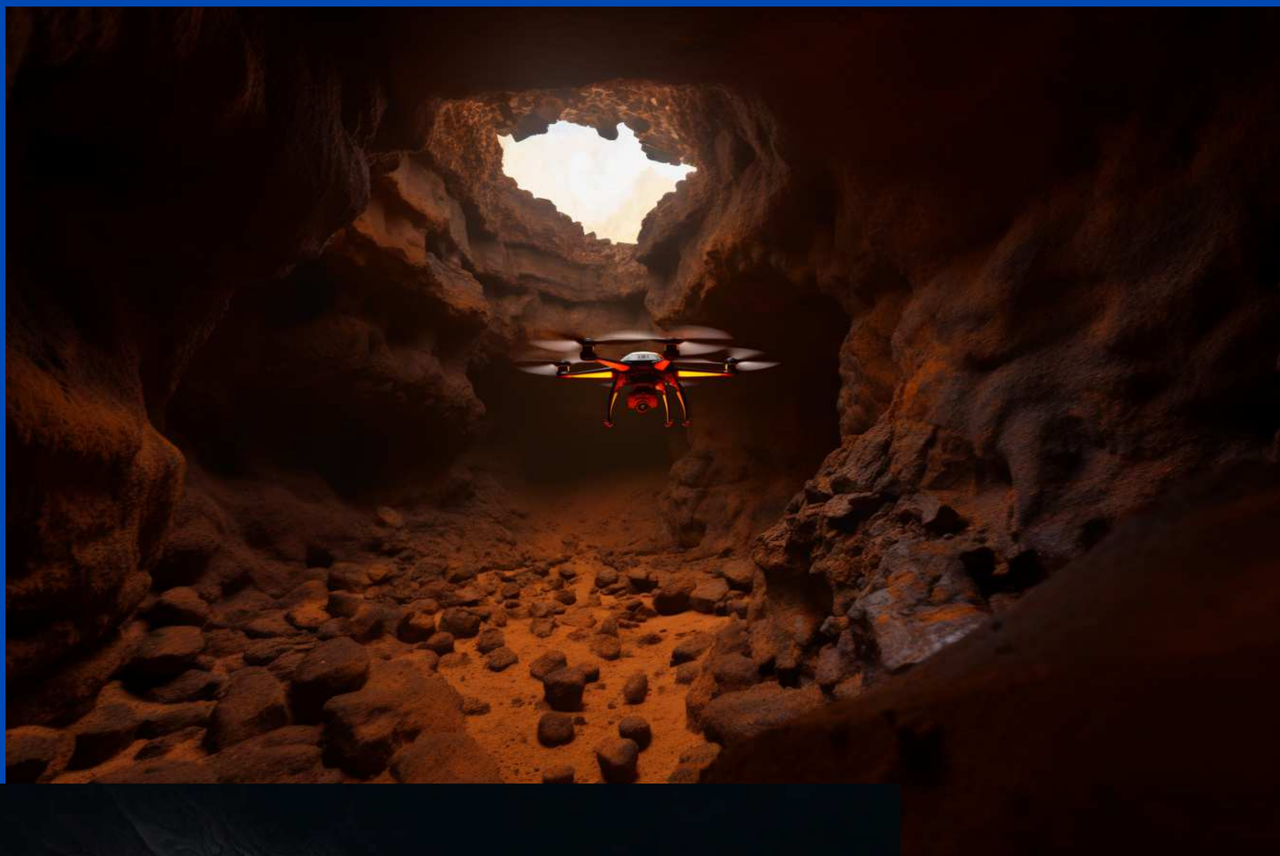
About a year ago I started making art with Midjourney, one of the leading AI art programs. To use it, you give it a text based description of the artwork you are imagining, and then it draws four small versions in one output. If you like any of the small versions, you can then upscale them into larger images. You can also use a photograph as a prompt to supplement your text based description.

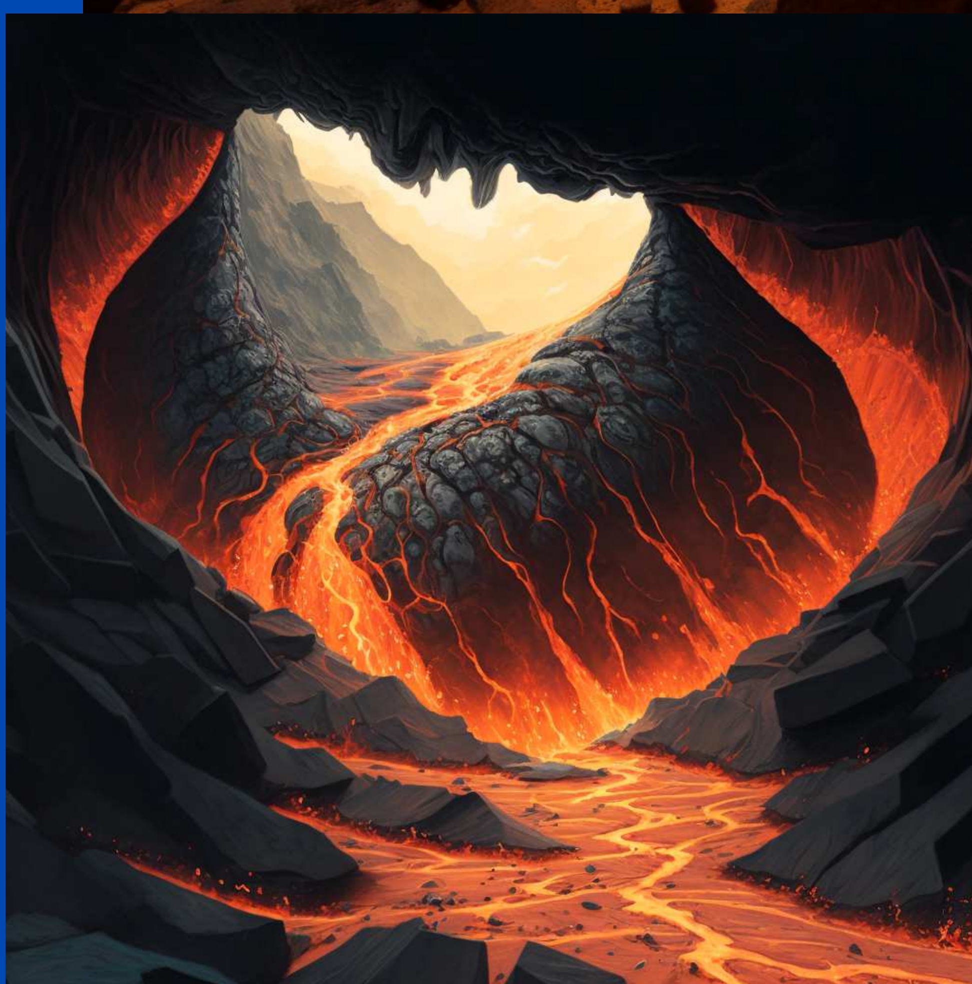
Most of what I made was naturally focused on caves, and what I mainly strove for was to produce images of a type I couldn't hope to make with my camera. Thus I hit on the idea of what it would be like to be in an actively forming lava tube, with an aerial or drone like perspective. I got some pretty decent results through text prompts alone. Here are some of the prompts I used:

1. a low aerial perspective of a river of lava coming out of a vent, flowing over old black ropey pahoehoe lava, then being swallowed by a large opening that drops into a vast cave, where the lava flows along the floor.
2. a low aerial perspective of a river of lava coming out of a cinder cone, flowing over black ropey pahoehoe lava, then being swallowed by a large opening that drops into a long cave passage, where the lava flows along the floor. Melting bits of ceiling ooze down forming stalactites. The full cave entrance is visible from deep inside the cave.
3. a flying NASA drone sent to Mars is exploring a huge lava tube cave and navigating through giant ice columns in huge passages underground
4. A view that a drone might capture if flying inside an active lava tube

Also, since I started producing the images, Midjourney has added more features. One of the more useful is the zoom feature, which basically generates more detail around the original image as you widen it. This is especially useful for getting a complete cave entrance as many images initially just show part of a cave entrance.

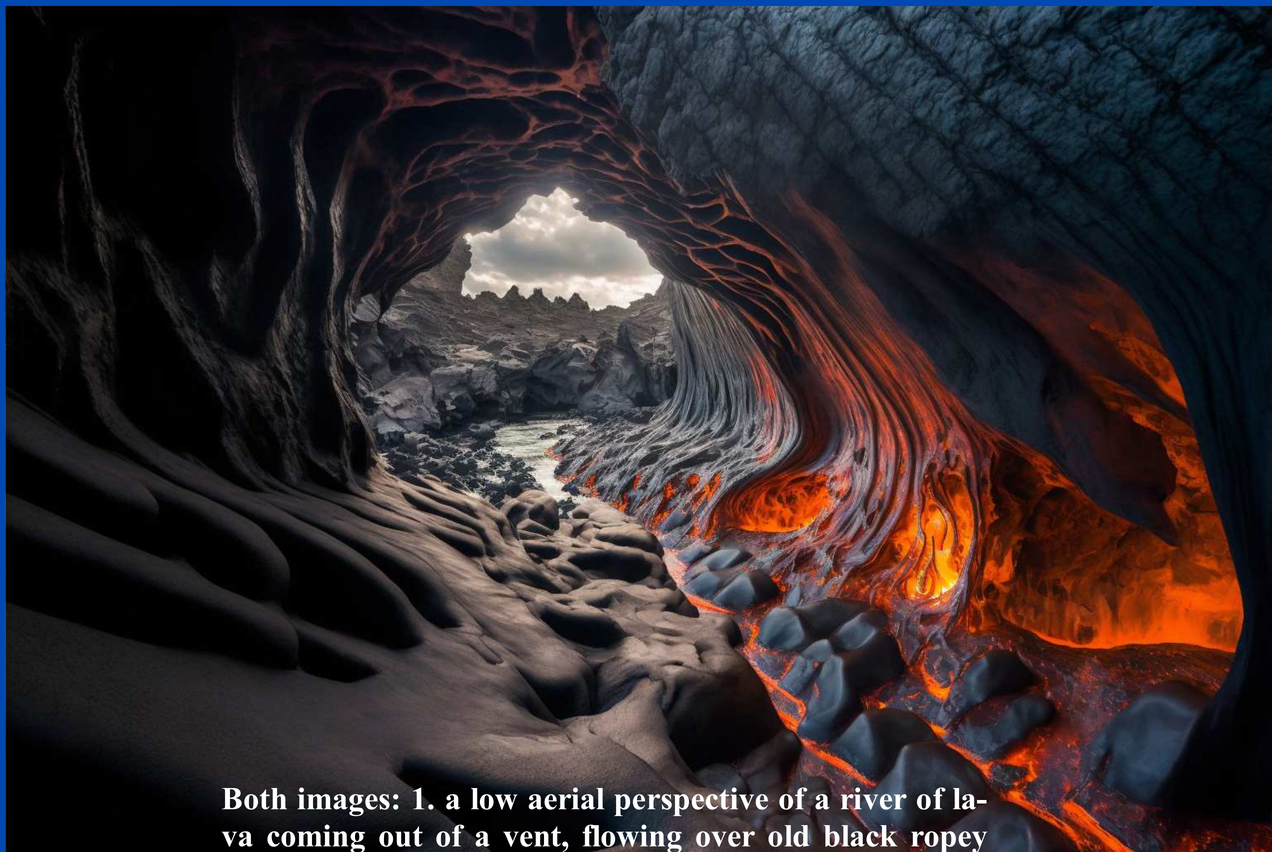
Adobe has recently added generative AI to the Photoshop subscription version. It allows you to start with your own photo and do generative fills of portions of it as well, or cut out and replace a background. Again, it users text prompts but also lets you select portions with a mask in which to do a generative fill. I've only tried it in their web beta and found it interesting enough that I plan to get the new photoshop to try it out. But since it can use your own image exactly as is, instead of just as a guide, it offers more chance to generate an image that is more your own than Midjourney would offer.



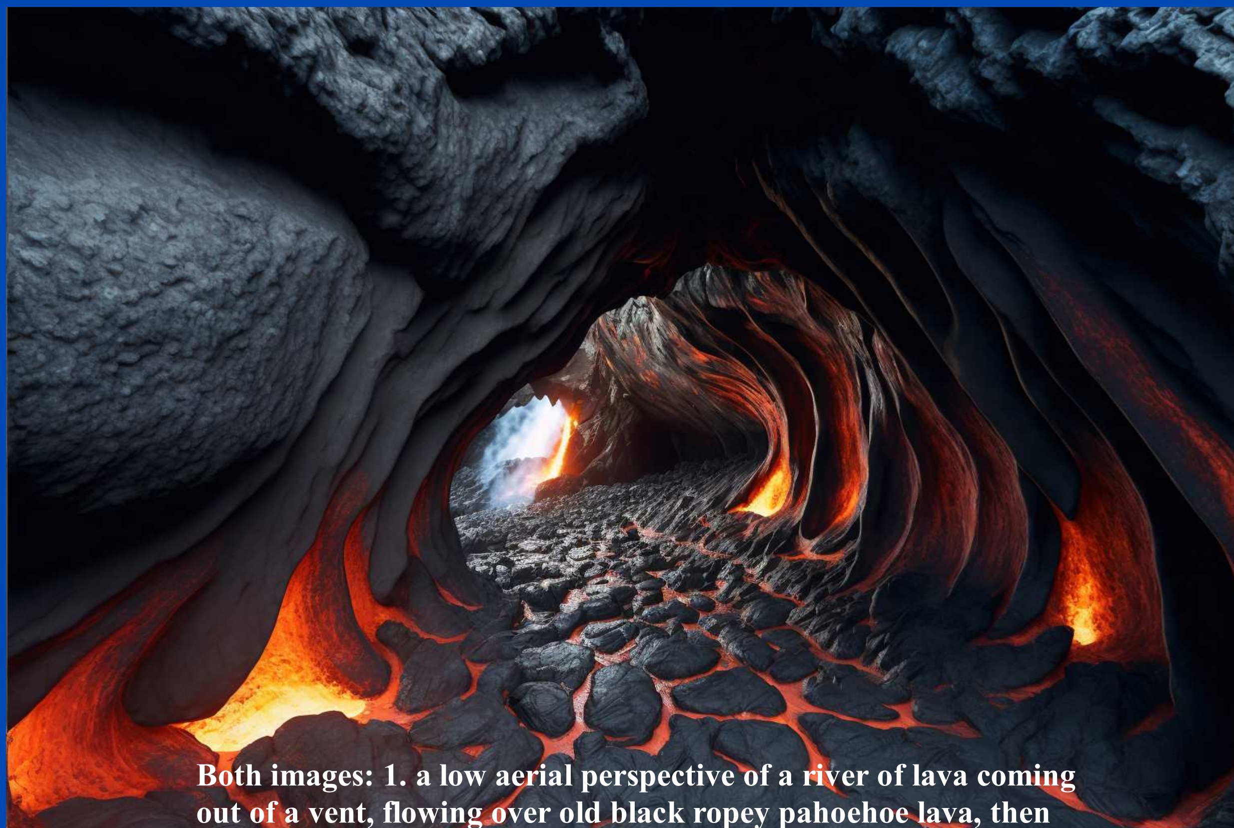


Top: 3. A flying NASA drone sent to Mars is exploring a huge lava tube cave and navigating through giant ice columns in huge passages underground

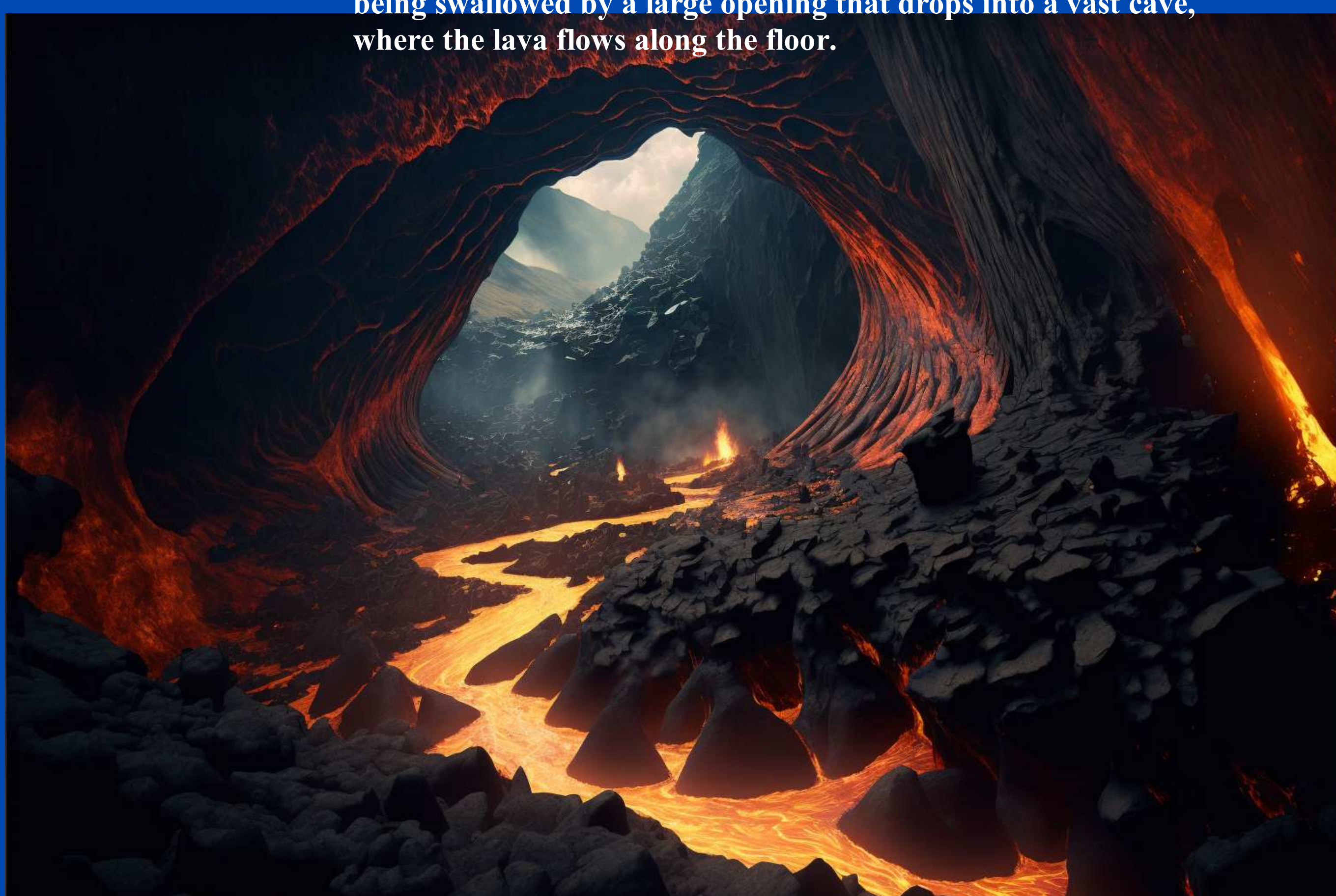
Bottom: 1. a low aerial perspective of a river of lava coming out of a vent, flowing over old black ropey pahoehoe lava, then being swallowed by a large opening that drops into a vast cave, where the lava flows along the floor.



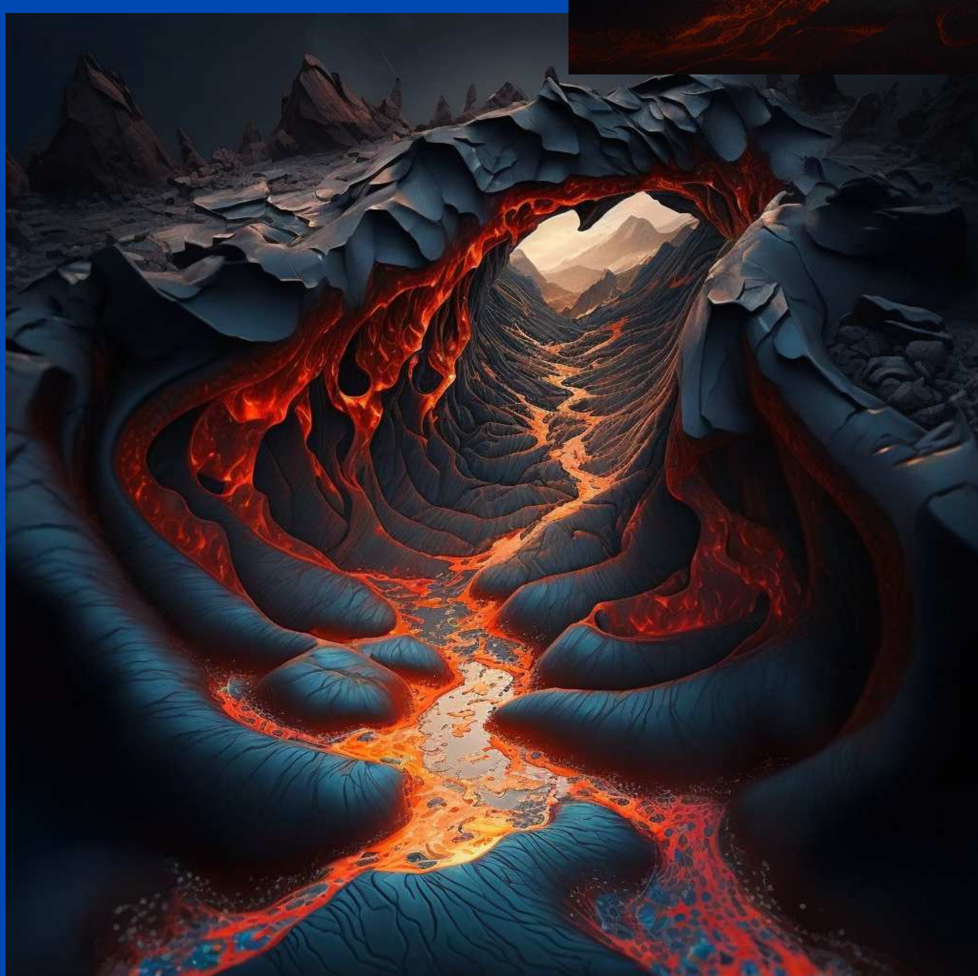
Both images: 1. a low aerial perspective of a river of lava coming out of a vent, flowing over old black ropey pahoehoe lava, then being swallowed by a large opening that drops into a vast cave, where the lava flows along the floor.



Both images: 1. a low aerial perspective of a river of lava coming out of a vent, flowing over old black ropey pahoehoe lava, then being swallowed by a large opening that drops into a vast cave, where the lava flows along the floor.



Both images: 2. a low aerial perspective of a river of lava coming out of a cinder cone, flowing over black ropey pahoehoe lava, then being swallowed by a large opening that drops into a long cave passage, where the lava flows along the floor. Melting bits of ceiling ooze down forming stalactites. The full cave entrance is visible from deep inside the cave.



Both images: 2. a low aerial perspective of a river of lava coming out of a cinder cone, flowing over black ropey pahoehoe lava, then being swallowed by a large opening that drops into a long cave passage, where the lava flows along the floor. Melting bits of ceiling ooze down forming stalactites. The full cave entrance is visible from deep inside the cave.

Basaltic rock shelters are potentially important for physico-chemical studies in North Patagonia caves

Carlos Benedetto

Fig. 1. The Tromen Volcano photographed in the early summer 2023-24

Buta Ranquil is a small city of 3,000 inhabitants in the north of Neuquén, at the foot of the imposing Tromen volcano and on the side of National Route 40. In the latter case as Malargüe, but further south: it is closer to the southernmost city of Mendoza (247 km) than to its own capital Neuquén (381 km).

Both have characteristics in common, one of them is that they are on the axis that crosses the Neuquén Basin from North to South where, in addition to oil and National Route 40, there are numerous caverns in microcrystalline gypsum from the Jurassic, some of them at the foot of the Tromen volcano, which dominates the landscape of Buta Ranquil.

In addition, the gigantic lava flows of pahoehoe (https://www.youtube.com/watch?v=aOxdO7UIFsQ&feature=youtu.be) reach this small town in the north of Neuquén. One of them is the Cueva de La Salamanca, surveyed in 1983; in this campaign we discovered that there is another cave on the other side of Route 40, which was covered with stones because there is a nearby spring of water that flooded it and that is dangerous for the animals that go to drink water. It is possible that both cavities are connected underground.

This "plugged hole" is considered a cavity to be explored, perhaps with caving-diving techniques. But that's for the future.

Two other shelters in basalts and conglomerates were also discovered. They are of little importance for caving, but of potential importance for the studies of cave minerals. As shown in photo 5, there is an abundance of bird guano, which could have the same importance as the one studied by Dr. Paolo Forti in 1997 in El Manzano, Malargüe.

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Int. J. Speleol., 27 B (1/4), (1998): 155-162.

CHEMICAL DEPOSITS IN VOLCANIC CAVES OF ARGENTINA

Carlos Benedetto *, Paolo Forti **, Ermanno Galli ***, Antonio Rossi ***

ABSTRACT

During the last Conference of the FEALC (Speleological Federation of Latin America and Caribbean Islands) which was held in the town of Malargue, Mendoza, in February 1997, two volcanic caves not far from that town were visited and sampled for cave mineral studies.

The first cave (Cueva del Tigre) opens close to the Llancanelo lake, some 40 kms far from Malargue and it is a classical lava tube. Part of the walls and of the fallen lava blocks are covered by white translucent fibres and grains.

The second visited cave is a small tectonic cavity opened in a lava bed some 100 km southward of Malargue. The cave "El Abrigo de el Manzano" is long no more than 10-12 meters with an average width of 3 meters and it hosts several bird nests, the larger of which is characterized by the presence of a relatively thick pale yellow, pale pink flowstone.

Small broken or fallen samples of the secondary chemical deposits of both these caves have been collected in order to detect their mineralogical composition.

In the present paper the results of the detailed mineralogical analyses carried out on the sampled material are shortly reported.

In the Cueva del Tigre lava tube the main detected minerals are Sylvite, Thenardite, Bloedite and Kieserite, all related to the peculiar dry climate of that area.

The flowstone of "El Abrigo de el Manzano" consists of a rather complex admixture of several minerals, the large majority of which are phosphates but also sulfates and silicates, not all yet identified. The origin of all these minerals is related to the interaction between bird guano and volcanic rock.

Keywords: cave minerals, volcanic caves, Argentina

Fig. 2. Abstract of the article published in 1998 after Dr. Forti's discovery in El Manzano

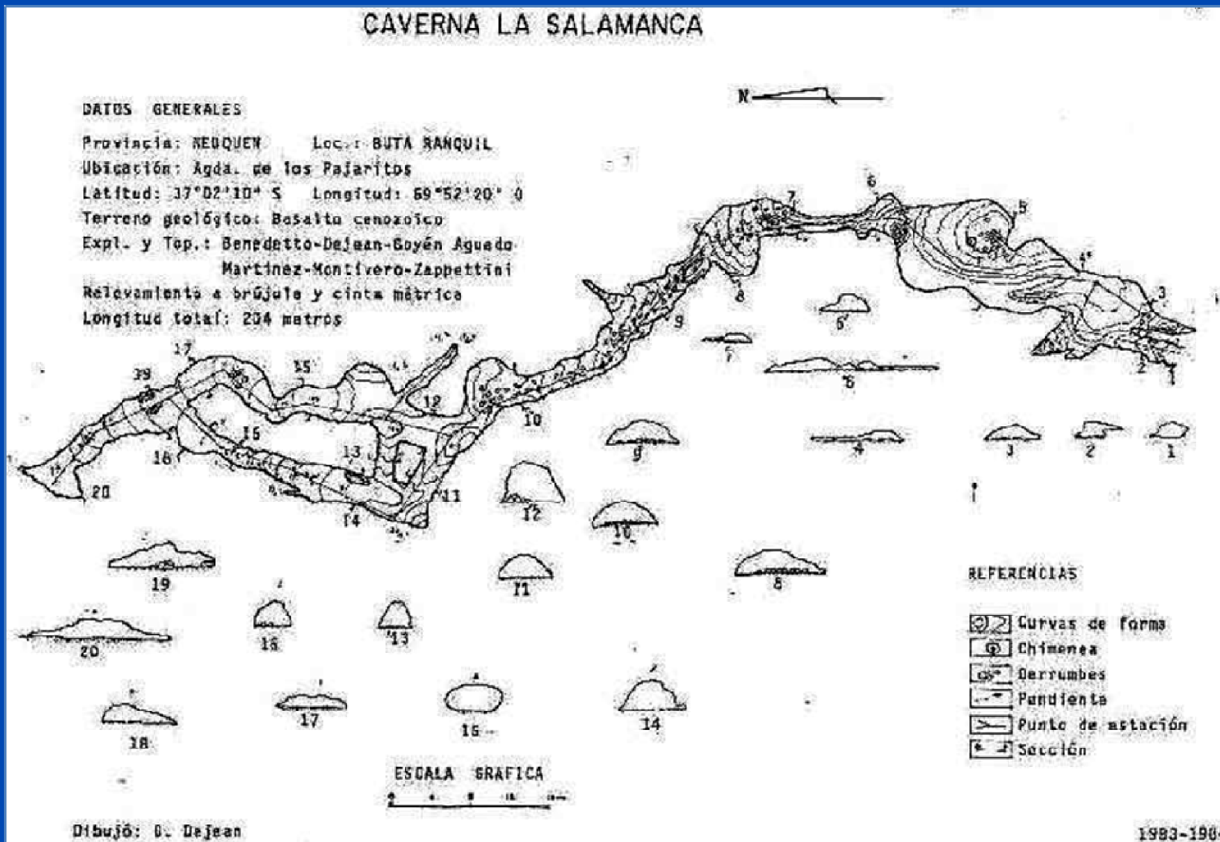


Fig 3: Map of La Salamanca Cave, dating from 1983

Fig. 4: The author at the entrance of La Salamanca. Photo December 2023

Fig. 5: Group of new cavers in one of the overhang caves found during classes

Fig 6: Spills of bird guano inside a basaltic cavity in Buta Ranquil, which may have the same physical-chemical importance as the eaves of El Manzano - Malargüe

Fig. 7. February 1997, Malargüe, at the inauguration of the III Latin American Congress of Speleology. Dr. Paolo Forti, University of Bologna, Italy, at that time president of the International Union of Speleology (UIS). At the end of the congress he explored Malargüe and discovered that the highest variety of phosphates endemic to caves in the world is concentrated in a small basaltic eaves. Photo Published in the HISTORY OF ARGENTINE SPELEOLOGY, page 74: http://fade.smartnec.com/images/prod/AdR8qVMQIFafDTmtqlzszPXY1gWh1y.pdf

Assessment of a high-humidity air-emanating cavity at the cinder cone volcano Atalaya de Femés, Lanzarote.

By Laurens Smets

The Atalaya de Femés is a volcano that erupted during the Early to Mid Pleistocene period. It is part of the Los Ajaches Massif in the southern region of Lanzarote, which constitutes the oldest volcanic structure on the island (until Miocene). Most of the Ajaches massif is composed of the deeply eroded remains of shield volcanoes that erupted 14 million years ago in the Miocene. Atalaya de Femés itself, however, is a much more recent cinder cone, less than one million years old (Figure 1 and 2).

Notably, Atalaya de Femés stands at an impressive altitude of 608 meters, making it the second-highest volcano on the island.

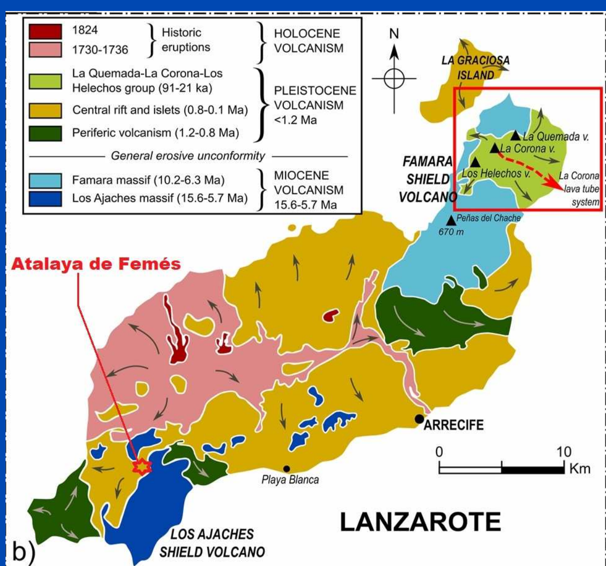


Fig 1 (left): Simplified geological map of Lanzarote;Carracedo et al., 1998; Coello et al., 1992;van de Bogaard, 2013; drafted by I. Tomasi.
Fig 2 (richt): Shade model of the old Los Ajaches massif and the El Rubicon lava platform, seen from the S.E.;Hansen and Moreno, 1999.

A cinder cone volcano, also known as a scoria cone, is a steep, conical mountain formed from loose pyroclastic fragments, such as volcanic clinkers, volcanic ash, or scoria, which have erupted from a volcanic vent (Figure 3).

In the specific case of Atalaya de Femés, it appears that subsequent eruptions led to the release of lava and layers of rough, welded pyroclasts, that buried unconsolidated cinder, ash and scoria on the flanks of the volcano.

In the one million years following the last eruptions of Atalaya de Femés, various geological processes, including significant erosion, occurred. On the western slope, both water and wind played a role in eroding the extensive pyroclastic deposits. In some areas, they even exposed volcanic clinkers and ash by removing the consolidated material (Figure 5a). The widening of cracks and crevices has also given rise to the formation of caves and ravines. Possibly, these erosional processes were aided by human activity as individuals may have excavated these crevices to seek shelter.

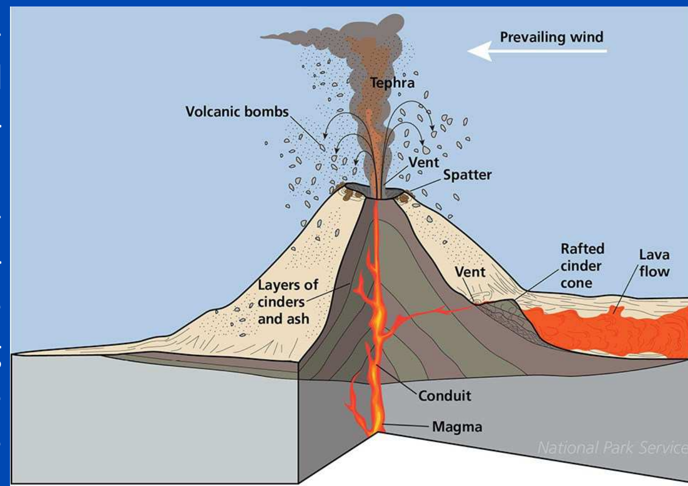


Fig 3 Theory on development of a Cinder Cone volcano; Ref.: National Park Service US,TTE, 2023; https://www.nps.gov/articles/000/cinder-cones.htm

In close proximity to Las Brenas, one can observe a lengthy and thick eroded lava flow, commonly referred to as the Malpais of the Atalaya de Femés volcano. This layer is also where you will find the labyrinthic Cueva de las Breñas, with a total explored passage length of nearly 2.3 km.

To the southeast, within the same layer, you also can find the Cueva del Diablo and Cueva de la Cura (Figure 4). These are both examples of wind erosion caves found within the welded pyroclastic rock.

The erosion of the unconsolidated layer below the welded pyroclastic rock has created small, relative low cavities. One of these is the 12 m long Cueva del Sendero 1 (entrance Fig. 5b; map and cross-section Fig. 5c). It is unique for Lanzarote because warm, moist air is emanating from a small orifice. On entering the cave, glasses and camera lenses tend to fog up.

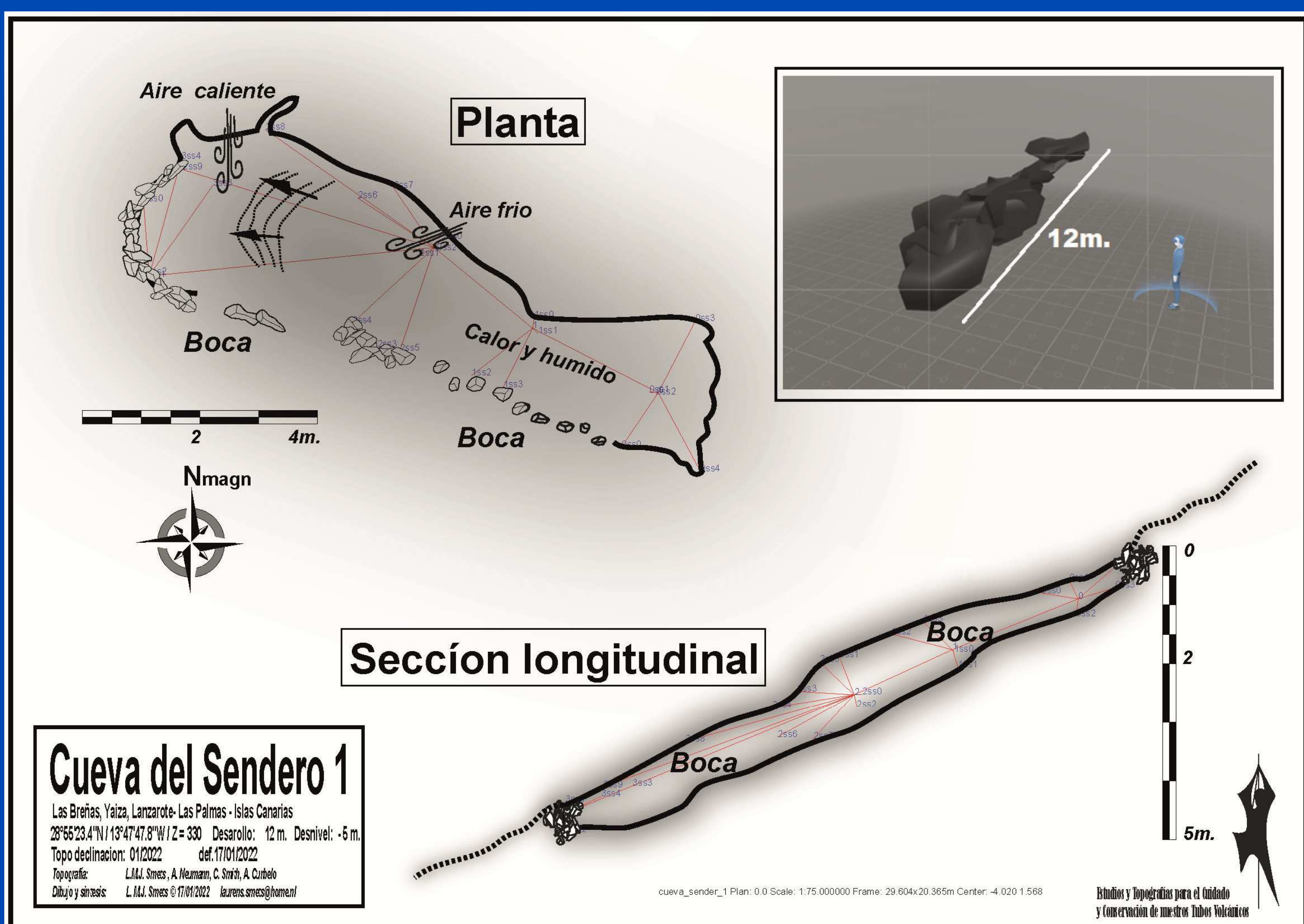
Fig. 4: Overview of Atalaya de Femés and its Malpaís. To the left: Cueva de la Cura + del Diablo; To the right: Cueva de las Breñas, Sendero 1 + 2.; Ref. Google Earth; Viewing North.

Fig.5a:View of a ravine on the western slope of the volcano towards the village of las Breñas.The person to the right is leaning on the welded pyroclastic layer.To the left the consolidated layer is disintegrated into large blocks by erosion of the underlying unconsolidated scoria.

Notably, Cueva del Sendero 1 is located at an altitude of 345m. asl. To the west on the same slope Cueva del Sendero 2 is located inside a Ravine on an altitude of 195m. asl.
The Malpaís de Atalaya de Femés is located on an average altitude of about 100m. asl.

Left. Fig 5b: entrance of Cueva del Sendero 1;

Bottom. Fig 5c: drawing of Cueva del Sendero 1.



How to Interpret this finding

Given the absence of known volcanic activity in the area and considering the age of the volcano, the possibility of finding a fumarole-like phenomenon is highly unlikely. Fumaroles are typically associated with active volcanoes and are characterized by the emission of volcanic gases and steam. In this case, a more plausible explanation should be sought to account for the unique features of the cavity.

Three distinct features requires explanation:

- Why is the cave warmer than the outside air at this altitude
- What causes the uphill movement of interstitial air in the cinder layers of the volcano.
- Where does the high humidity in the cave's air arises from.

Test case: Between March 2022 and March 2023, we installed two real time data loggers at the project. One was placed just above the air-blowing orifice, while the other was positioned outside**,** sheltered beneath a rock that remained in shade throughout the day.

The objective was to collect temperature and humidity data over a period of time, to compare the data of the local climate with those of the cave's microclimate, and to search for possible correlations between temperature and humidity changes.

Temperature variations and humidity levels may lead to condensation and the generation of warm, humid air within the cavity.

We used Voltcraft DL210th temperature and humidity loggers, configured to record measurements every 30 minutes during one year (Figures 6 and 7)

Left, Fig. 6: Position of the data logger near the cave outside;
Right, Fig. 7: Position of the data logger inside the cave.

Observations

The data volume for each logger amounted to 18,000 records.

As shown in Figure 8, the variability of data is higher in the outside than in the cave, as anticipated. Conversely, inside the cave, the variations are notably reduced, resulting in a more stable environment; again in line with our expectations.

Outside the cave, we recorded a maximum temperature of 40°C and a minimum of 10.2°C. The recorded relative humidity ranged from a maximum of 89.3% to a minimum of 14.3%.

Inside the cave, the temperature varied between a maximum of 39.4°C and a minimum of 17.1°C, while the relative humidity inside reached a maximum of 100% over extended periods and a minimum of 16.7% (Figure 8).

The average temperature inside the cave in this period was 22,3°C and outside the cave 20,2° C.

The average relative humidity inside the cave was 95,83% and outside the cave 66,63%.

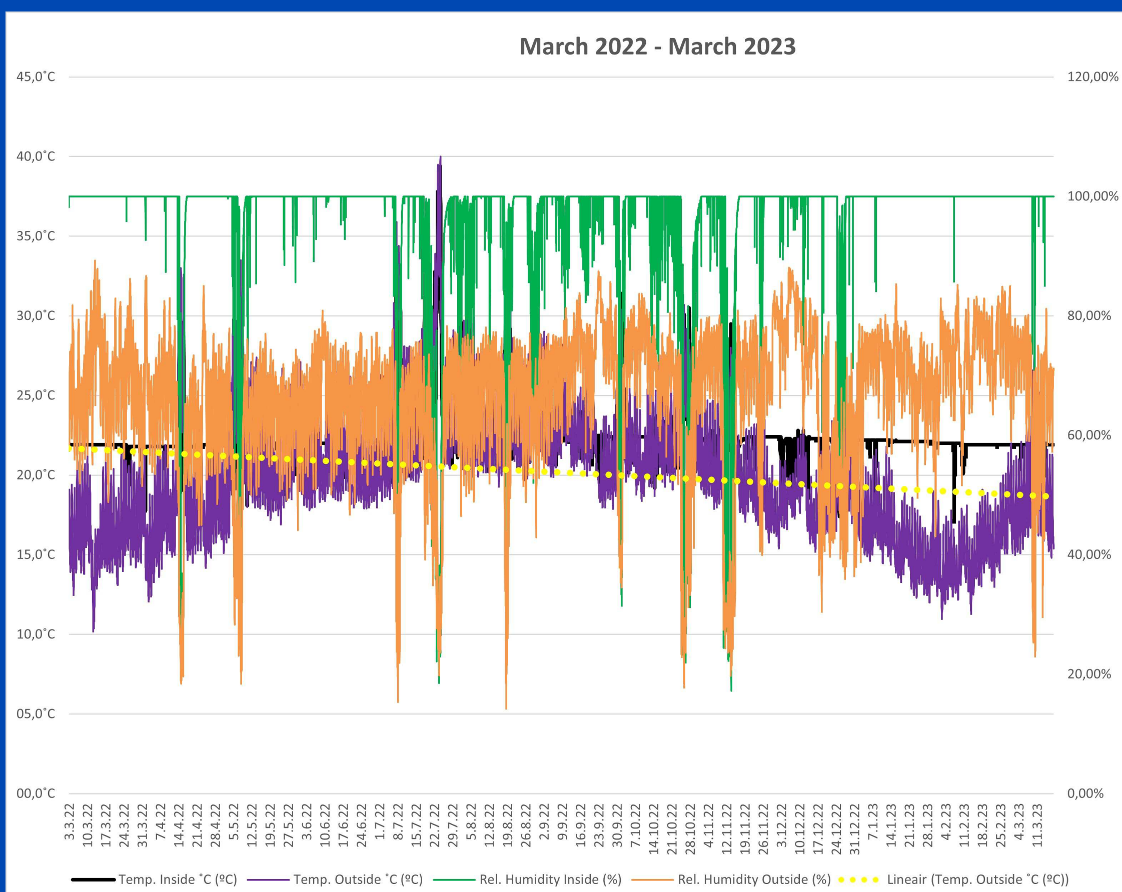


Fig. 8 : Overview of the temperature and relative humidity between March 2022 and March 2023;The yellow dotted line represents the linear regression of the temperature outside.

To rule out volcanic activities, it is essential to delve deeper into the records. As anticipated, volcanic activity would manifest as relatively stable data over a long period, with temperature and humidity showing no significant correlation, and emanation records unrelated to the local climate data.

Figure 8 illustrates that the average outdoor temperature (indicated by the yellow line) is lower than the average temperature within the cave (depicted by the black line). This temperature variance can be attributed to the daytime solar heating of the pyroclastic layer.

Especially on scorching summer days when the pyroclastic layer can exceed 50°C in heat, this effect of highly elevated temperatures within the cave can be observed.

In Figure 9, a clear relationship is evident between the cave's micro-climate and the local climate from March to May 2022. There is a correlation between temperature peaks both outside and inside, although the overall temperature inside remains consistently stable at 22 degree. Relative humidity inside the cave demonstrates a more pronounced connection with the external environment. Peaks of low humidity outside correspond to a delayed decrease in humidity within the cave. When observing the average regression lines, it becomes apparent that when the external temperature rises, humidity both outside and inside decreases. On days when the external temperature climbs to nearly 34°C, the relative humidity rapidly drops both inside and outside of the cave, sometimes even to below 25%.

It’s also apparent that the airflow, which emanates from the cave, maintains a constant source of humidity. Inside the cave, relative humidity remains close to 100% for most of the time, while the local climate registers an average of 62% humidity during the period from March to May 2022.

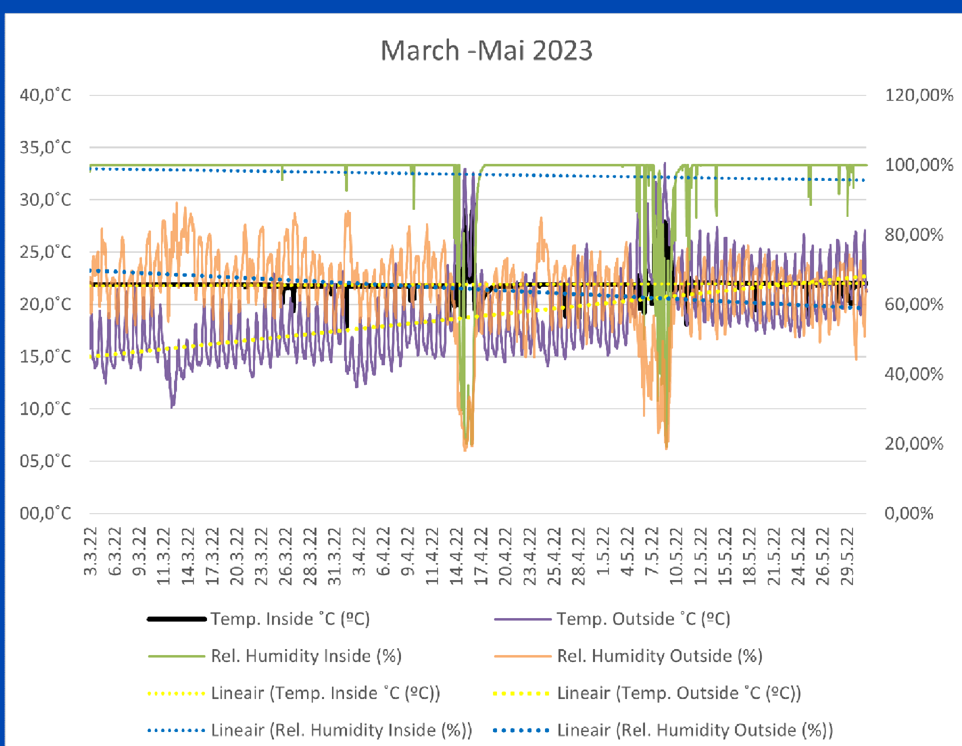
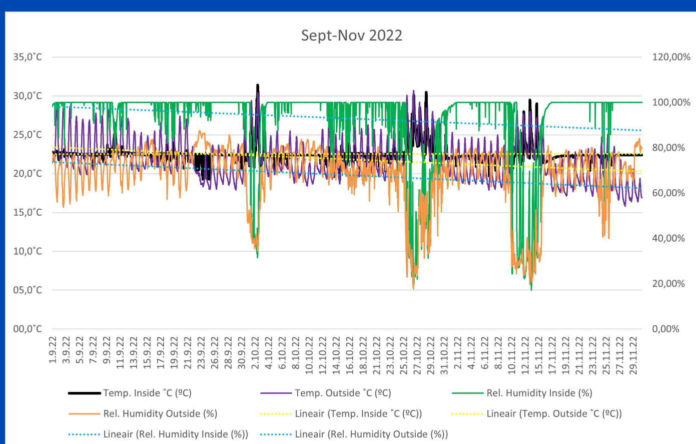
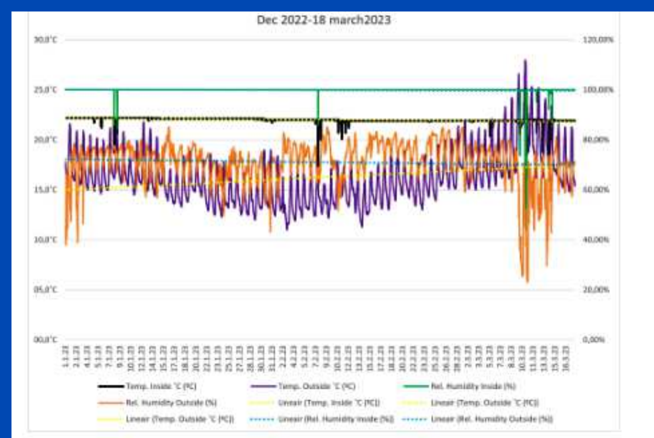


Fig. 9 : Overview of the temperature and relative humidity between March 2022 and May 2022; The yellow and blue dotted lines represent the linear regression of the temperature and relative humidity

In Figure 10, you can observe a similar pattern of fluctuations and correlations as what was evident during the period between March and May 2022.
Between September and November 2022, the regression lines of relative humidity inside and outside the cave run almost perfectly parallel, with an average difference of approximately 16%. Additionally, the reaction time to a sudden temperature increase in the local climate, aligns with the temperature rise inside the cave. This may be influenced by the absence of an airflow and the warming of the cave from the external environment.
In Figure 11, covering the period from December 2022 to the 18th of March 2023, we observe a repetition of the same pattern of fluctuations. Inside the cave, relative humidity remains consistently close to 100%. The average relative humidity inside and outside the cave again





To the left Fig.10: Records between September and November 2022; To the right Fig 11: Records between December 2022 and March 2023.

exhibits a nearly parallel regression, with an difference of approximately 27%.
Hypothesis . Hypothesizing regarding the mechanism enabling air to flow through a cinder cone volcano and subsequent emanation from a cavity: The surface of the cinder cone volcano is primarily composed of densely consolidated welded pyroclasts, which form an upper layer above volcanic clinkers and ash (Figure 12 and 13). Over time, the mixture of clinkers, ash, and scoria may have experienced slight compaction. In specific regions, voids or hollow spaces may have developed between the layer of clinkers and the layer of welded pyroclasts. These hollow spaces provide a conduit for air to flow through the volcano, and the air subsequently carries moisture that emanates from these cavities.

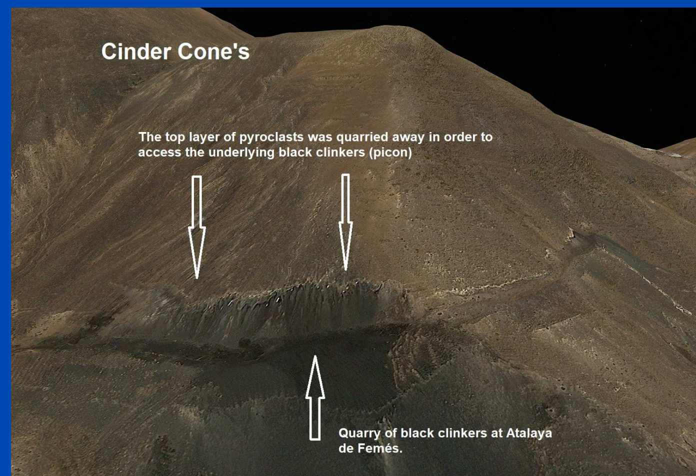


Fig. 12 (left): shows the dipping layer of welded pyroclasts, with the layer of clinkers and scoria below. Fig 13 (right): showing a "picon" quarry at Atalaya de Femés. Source Google Earth.

Given that the eroded barrancos extend along the volcano's flank, containing crevices, cracks, and fissures all the way down, it becomes evident that the wind, which emanates from our cave, must travel a considerable distance underground before resurfacing higher up on the mountain. The temperature of the wind emanating from the underground remains stable, as is typical in cave systems. Not in line with common observations is the fact that the yearly average temperature inside the cave is 2,1 degrees higher than the average yearly temperature outside the cave (average 22,3°C inside and 20,2°C outside the cave).
According to the data this variation is expected to be caused by the daytime solar heating of the pyroclastic layer which acts as a stable heat reservoir and effects the temperature of the emanating air during the whole year.

Because of the relatively high humidity levels of the air in Lanzarote and the cool nights, condensation occurs throughout the island during the nighttime hours. The welded pyroclasts constitute a soft and porous deposit, readily absorbing this condensed water. This moisture then gradually permeates downward, being absorbed by the clinkers and ash, much like the process observed in the vineyards of La Geria. The wind enters through cracks and fissures lower down on the volcano's flank, soaking up the damp air through voids and porous scoria below the layer welded pyroclasts. Higher up, it releases this air, now due to changes in temperature fully saturated, creating a chimney effect.

The humidity within the cave remains consistently close to 100% due to continuous condensation. There are occasional deviations in the data, which are presumed to occur when there is no airflow or wind outside the cave, and the temperature within the small cave increases as it warms up from external heat sources.

Fig 14: humid air emanating from a void, leading to the growth of various types of moss and algae.

In conclusion, the Cueva del Sendero 1 appears to be a unique place for Lanzarote. It intercepts warm air, that rises through the porous scoria below a compact layer of welded pyroclasts. As the airgains altitude within the scoria, it cools and the relative humidity reaches 100% surpassing the dewpoint and condensing inside the cave at a small orifice. There the water allows mosses and algae to thrive.

Acknowledgement

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A special thanks goes to Stephan Kempe for his diligent efforts in editing this work and for his role in structuring the results of our observations.

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NEW INSIGHTS INTO THE GENESIS OF PYRODUCTS OF THE GALÁPAGOS ISLANDS, ECUADOR

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Abstract

Stephan Kempe, Greg Middleton, Aaron Addison, Theofilos Toulkeridis & Geoffrey Hoese: New insights into the genesis of pyroducts of The Galápagos islands, Ecuador

There has been little research on the genesis and development of pyroducts (or lava tubes) originating from Galápagos volcanoes. Pyroducts are responsible for the lateral, post-eruptive transport of lava because they are highly effective as thermal insulators. After eruptions terminate, these conduits often be- come accessible as caves. In March 2014 the 16th International Symposium on Vulcanospeleology brought a large group of vulcanospeleological specialists to the Islands. During the meeting a number of pyroducts were visited and studied in context on the island of Santa Cruz and around Isabella's Sierra Negra volcano in the western, most active, part of the Galápagos. The longest of the caves, Cueva del Cascajo, about 3 km in length, was partly surveyed and nine presence of oxbows, secondary ceilings, lavafalls, collapses and pukas were particularly studied for evidence they reveal about developmental stages of pyroducts. The resulting data show that the pyroducts were formed by "inflation" with the primary roof consisting of uninterrupted pahoehoe sheets. No pyroducts were identified that developed by the crusting-over of channels. The studies strongly confirm inferences drawn from other hot-spot related islands, such as Hawai'i.

Key words: Ecuador, Galapagos Islands, volcanic rock caves, pyroducts, lava caves, speleogenesis.

INTRODUCTION

Although a large number of researchers has studied the origin and development of volcanoes, their geological processes and landforms (e.g., Lockwood & Hazlett 2010), speleology in the volcanic environment and the understanding of the formation of lava caves is still a debated topic (e.g., Sigurdsson *et al*. 2000; Heliker *et al*. 2003). For those researchers seeking to understand what happens during the formation of volcanic caves and the processes that are responsible for their formation and enlargement, much appears still to be learned (e.g., Kempe 2002, 2012, 2019; Bunnell 2013; Sauro *et al*. 2019). In order to further work on some of the most fundamental questions in this research area, the 16th International Symposium on Vulcanospeleology (ISV) was held in Puerto Ayora on Santa Cruz Island, Galápagos. Excursions acquainted the international participants not only with the lava caves on this island, but also with the volcanoscape on the neighboring island of Isabella (where three caves were visited). The meeting was organized by Theofilos Toulkeridis (Ecuador) and Aaron Addison (USA) and attended by ca. 80 cavers, many of whom were exposed to the problems of vulcanospeleology for the first time. This high number of attendees in this remote region indicates that support for this specific speleological topic is increasing. Since then, further symposia were held in 2016 on Hawaiʻi and in 2018 at Lava Beds, California. The proceedings of these symposia are a prime source of the most recent research results in the field, accessible through the ISV site: http://www.vulca-nospeleology.org/symposia.html. In 1991 Dr. W.R. Halliday organized the 6th ISV on Hawaiʻi (Rea 1992). Since then, the number of caves and the kilometers surveyed by members of the Hawaiian Speleological Survey (HSS) and other organizations has been multiplied by a factor probably close to 100, illustrating the outstanding role of the Hawaiian volcanism in the understand of the underlying processes responsible for lava cave genesis. The Bulletin of the HSS ("Hawaiʻi Underground") informs about the most recent research results. However, we still are far from understanding cave development associated with flowing lava in all its facets.

Here we briefly discuss the insights into the genesis of the volcanic caves, or *pyroducts*, obtained during the Galápagos meeting with regard to the caves visited in Hawaiʻi and elsewhere. These "insights" are mostly a number of in situ-observations leading to questions, many of which will need much more research in this expanding field of volcanology and associated landforms. The "insights" also owe much to the continuing discussion between the participants of the Galápagos symposium and with the authors during the fieldwork. It is not the intent of this paper to review the extensive international vulcanological and local speleological publications: for this the reader is for example referred to, for example Kempe (2002, 2019) or Sauro *et al*. (2020).

GEOLOGICAL SETTING

The presently active Galápagos hotspot has produced several voluminous shield-volcanoes, most of which are inactive due to the ESE-movement of the overlying Nazca oceanic plate (Holden & Dietz 1972; Hey 1977). The main Galápagos Islands are located east of the N-S trending East Pacific Rise and south of the E-W-trending Galápagos Spreading Center and some 1,000 km west of the Ecuadorian mainland (Fig. 1). With an area of less than 45,000 km^2 the Galápagos Islands represent one of the most volcanically active regions of the world (Simkin *et al*. 1981).

In the case of the Galápagos hot spot, this process of magma supply has existed for more than 90 million years (Ma) while the lithospheric plate has moved many thousands of kilometers in the same time interval, carrying the hot spot-generated volcanoes away (Hoernle *et al*. 2002; Werner *et al*. 2003). Two aseismic volcanic ridges were created, the NE-moving Cocos Ridge and the E-moving Carnegie Ridge and associated seamounts on the Cocos and Nazca Plates, respectively (Harpp *et al*. 2003). These submarine extinct volcanic ridges are the result of cooling/contraction reactions of magma, as they slowly sank below the sea surface due to the lack of magma supply, lithospheric movement and strong erosional processes.

With time, these submarine volcanic ridges as well as various microplates, have accreted on the South American continent (Reynaud *et al*. 1999; Harpp & White 2001). Western islands just above the Galápagos hot spot have the morphology of large shield volcanoes with deep calderas, while the eastern island volcanoes are small shield volcanoes with gentle slopes and almost without calderas (McBirney & Williams 1969). Exceptions to the general picture of the main Galápagos Islands are the northern islands of Wolf and Darwin, which are considered to be a result of the interaction of the Galápagos hot spot and the Galápagos Spreading Center (Harpp & Geist 2002). Holocene and historic eruptions have occurred on the main 16 active volcanoes of the Galápagos. Frequently associated with the shield volcanoes are hundreds of short-lived relatively small, cinder-, ash- and spatter cones. Some extinct volcanoes are represented by the islands Española, Santa Fe, Pinzon and Rabida. The island of Española is, at some 4 Ma, the oldest extinct volcano of the Galápagos while parts of the volcanic activities at San Cristobal island are almost 2.5 Ma old (Hall 1983; White *et al*. 1993). Many volcanic features such as lava caves, 'a'ā, pahoehoe and pillow lava, olivine beaches and many more are encountered in almost all islands and reflect the interesting volcanic evolution of the Galápagos, which combined with its geodynamic relation, gave rise to the unique endemic life on these islands (Darwin 1859). Santa Cruz is the most central island of the Galápagos. It is a large shield volcano with a high abundance of parasitic cones, large lava caves and enormous pit craters (e.g., Los Gemelos) and is subdivided into two main units (Bow 1979). The older unit is the Platform Unit with an age of 1.3-1.1 Ma, while the younger unit is rep- resented by lavas of the Shield Series with ages as young as 30-20 ka (Bow 1979; White *et al*. 1993) (Fig. 1).

The plagioclase and olivine phenocryst-bearing tholeiitic lavas of the platform series include faulted and uplifted parts which appear today as independent islands such as Baltra, Seymour and Las Plazas. The latter was evidently formed below the sea surface due to the almost exclusive occurrence of pillow basalt. These old and therefore lower units show intercalations with marine carbonates with a precipitation depth of <100 m. Based on their morphology and the lack of vegetation, the younger overlying lavas of the Shield series appear to be only a few thousand years old (White *et al*. 1993). These lavas, which mainly flowed from the summit but also from the flank of the volcano, are composed of a range of different volcanics, mainly exhibiting olivine tholeiites and transitional alkali-basalts besides some hawaiites (Bow 1979; White *et al*. 1993).

The Sierra Negra shield volcano on the western is- land, Isabela, is volcanically young and one of the most active volcanoes in the Galápagos. This volcano is 40 to 60 km wide and has, with its 9-10 km diameter caldera, the largest but simultaneously the shallowest elliptical caldera of all volcanoes of the Galápagos. Eruptive centers and different lava fields have been divided into five distinctive age groups, all being younger than 6000 years (Reynolds *et al*. 1995). These are alkaline to tholeiitic lava flows that erupted from E- to NE-trending circumferential and radial fissures situated on both sides of the summit caldera on the upper flanks and on the western and eastern lower flanks (Chadwick & Howard 1991). The caldera itself has undergone several episodes of collapse, upheaval and deformation (Amelung *et al*. 2000; Vigouroux *et al*. 2008). These are alkaline to tholeiitic basaltic lava flows erupted from east to northeast, with circumferential and radial fissures situated on both sides of the summit caldera on the upper flanks and on the western and eastern lower flanks (Kurz & Geist 1999). Ten historic eruptions occurred in the last 200 years. The last eruptive activity took place at the end of October 2005 and lasted a week, after 26 years of quiescence (Geist *et al*. 2008).

PYRODUCTS

Within the family of lava caves or, perhaps more accurately, volcanic rock caves, (for an overview see Kempe 2002, 2019), we find both primary and secondary caves. The second group contains sea-caves, caves formed by the erosion of water and tectonic caves. Of these, we visited “La Grieta” an impressive, seawater-filled graben with associated fissure- and talus-cavities in the proximity of Puerto Ayora, the main port of the island of Santa Cruz.

All other caves visited are primary caves, i.e., vents (Triple Volcán on Isabela) or “pyroducts”. “Pyroduct” (Lockwood & Hazlett 2010, pp. 138ff), colloquially also called “lava tube”, “lava tunnel”, or “lava pipe”, is “*a term coined by an eye-witness* [i.e., the missionary Titus Coan (1844)] *describing active subterranean ‘rivers of fire’ during the 1843 eruption of Mauna Loa. Pyroducts come in many shapes and sizes (few of them “tubular”) and form in many different ways….”.* They can be defined as *“…. any internal lava conduit in a flow, irrespective of shape and size, regardless of whether it contains molten lava during eruptive activity or is preserved as an elongate cave after eruptive activity ends and molten rock drains away. Etymologically, the word pyroduct (“fire conduit”) could also describe surface lava channels, but we shall restrict the term only to describe subsurface features…*“.

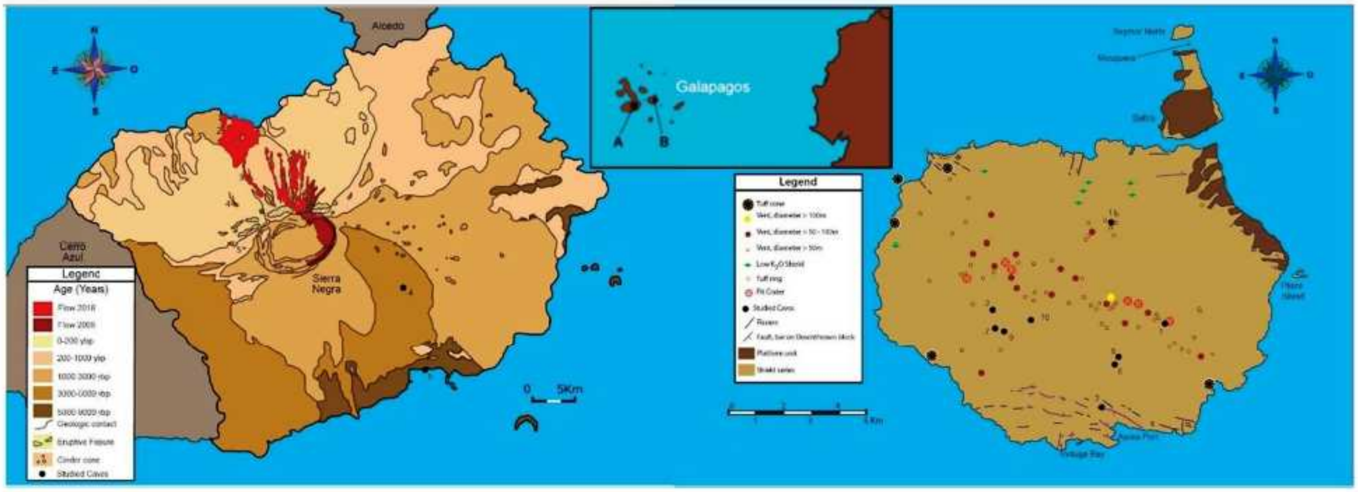

Fig. 1: General situation of the Galápagos Islands (center) and the geological maps of (left) southern Isabela Island and (right) Santa Cruz. Pins locate the caves visited during this study; numbers refer to Tab. 1. (maps based on Toulkeridis 2013).

Therefore, pyroducts are of prime importance in understanding the architecture of basaltic island shield volcanoes, basaltic intracontinental lava fields and hot- spot volcanics (e.g., Calvari & Pinkerton 1998). Without pyroducts, extremely long lava flows could not come into existence. The recent eruption of the E-Rift of the Hawaiian shield volcano Kīlauea 1983-2018 (known as the Puʻu ʻŌʻō-Kūpaianaha eruption) (Wolfe 1988; Heliker *et al.* 2003) allowed the study of some aspects of pyroduct genesis and function. Episodes 48 and 50 to 53 (Helz *et al.* 2003) formed 12 to 14 km long pyroducts issuing lava to the ocean. A few of the conduits are still accessible. MgO-content of quenched glasses measured on samples from the Kūpaianaha lava pond and on pyroduct samples taken at skylights or at the ocean front indicated that the temperature of the lava dropped only about 0.6°C per km. Similarly, temperature measurements through skylights showed a temperature loss of about 1°C per km (reviewed by Kauahikaua *et al.* 2003). Thus, closure of a primary roof across flowing lava is probably one of the most important processes in providing thermal insulation of the flowing lava resulting in the extended flow and further development of any pyroduct. The recent experiences from Hawaiʻi and elsewhere imply that pyroducts are able to be formed by at least four different processes (Kempe 2012). Two of them, involving "inflation" (Hon *et al.* 1994) and "confluence" (Bauer 2011; Bauer *et al.* 2013) arise from pahoehoe flows containing proto-ducts, while the other two process- es are associated with the freezing-over of lava-channels. This can be achieved by the inward growth of benches of by the welding of floating clasts. Both of these roof-closing mechanisms were documented for pyroducts associated with the Etna eruption of 1991-93 (Calvari & Pinkerton 1998). Due to the unusual steep slope of Mount Etna of up to 30° pyroducts also form there within the core of ʼaʼā flows, so far a phenomenon not documented in Hawaiʼi. Hawaiian experience however shows that the first type, the formation of a pyroduct by inflation, is most probably the main process involved in the initiation of a long-lived pyroduct (Fig. 2). The 16^{th} International Symposium on Vulcanospeleology gave an opportunity to test how these Hawaiian models as well as experiences and field observations gathered in different volcanic areas worldwide would apply to another important basaltic island volcano group (McBirney & Williams 1969; White *et al*. 1993; Toulkeridis 2013 and references therein).

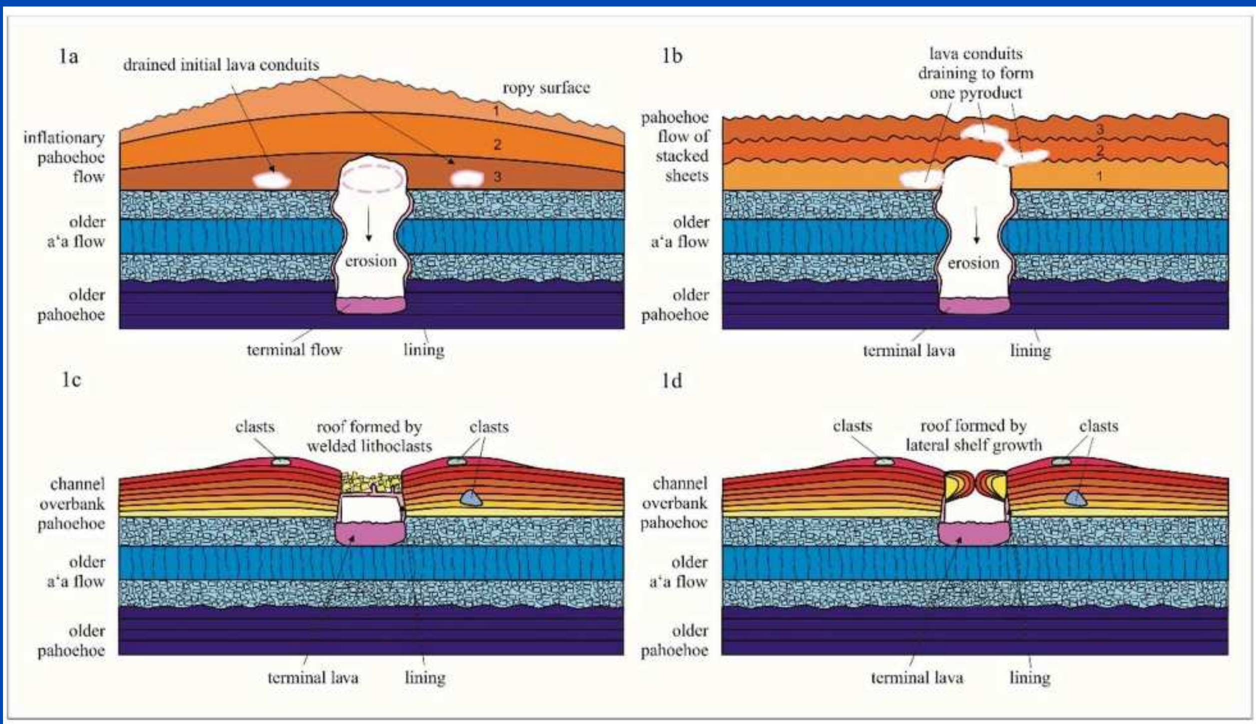

Fig. 2: Schematic cross-sections of the four models of pyroduct formation known so far. The amount of erosion shown can be quite variable, even within the same pyroduct. Also, the underlying strata does not necessarily need to be an 'a'ā flow. Cross-section 1a shows the "inflationary mode" where the roof sheets are oldest at the top and youngest at the bottom. There several ducts can develop in parallel that are drained once one of them cuts down, collecting all of the flowing lava into one bed. Cross-section 1b illustrates pyroduct formation by "confluence" of lava from several small conduits within lava sheets deposited on top of each other. Here the oldest lava sheet is at the bottom and the youngest on top. All the flow in these ducts converge and erode an underlying lava flow, preferentially an easily erodible layer of 'a'ā rubble. Cases 1c and 1d illustrate the "crusting over of a channel". This can either happen by the jamming and welding of floating clasts (1c) or by the slow accretion of shelves and roof-closure across a channel along a central suture (after Kempe 2012).

INVESTIGATING GALÁPAGOS CAVES; MATERIALS AND METHODS

Constantin *et al*. (2018) briefly refer to the research history of Galápagos and the number of caves known, totaling 57 (29 on Santa Cruz, 4 on Isabella and 14 on five other islands). Of these we discuss f nine pyroducts that were investigated prior to and during the symposium (Fig. 1): Cueva del Cascajo, Cueva de Gilda and Gallardo, Mirador de los Túneles (Cueva de Kübler), Cueva de Chato 1, Cueva de Royal Palm, Tortoise Junction tourist cave, Cueva La Llegada and Cueva de Premisias on Santa Cruz Island and Triple Volcán, Cueva de Sucre and Túnel del Estero on Isabela Island. In addition, detailed surveys were conducted in Mirador de los Túneles/Cueva de Kübler and in the upper 150 m of the Cueva del Cascajo. There a Leica Disto was used to determine length and inclination and a Silva compass to measure azimuth.

The grid was calculated with a self-written Excel routine. Otherwise photographs and notes were taken, and the morphology and outcrops discussed by a number of participants. Addison (2011) published maps of the Triple Volcán vent, of the Cueva de Sucre and of the Túnel del Estero.

The pyroducts visited can be subdivided into two groups; those that have a roof composed only of their thin primary roof and those that have a very thick roof composed of the original primary roof and later thin ’a’ā surface flows (Tab. 1).

Table 1 General observations concerning the lava caves visited (“puka” is Hawaiian for “hole”).

No	Group 1	Thin Roof	Downcutting	2ndary Ceilings	Lavafalls	Pukas	Oxbows	Stage
1	Cueva del Cascajo (3,010 m)	Thin, one sheet 0.8 to 1.5 m thick with shear- induced vesicle layers	Substantial (>10 m), canyon-like	Mostly one, but sometimes up to 5	At least four major	Variety of pukas	Two small	3
2	Mirador de los Túneles (929 m)	Thin, one thick sheet	Substantial	None	None in western part	Five (two in side branch)	One substantia l	3
3	Cueva de Premisias (431 m)	One thick or several thin sheets	>11 m	One at current exit	None	Two	None	2
4	Cueva de Sucre (339 m) 5	One thick or several thin sheets	Small (less <1 m)	None	None	One	Multiple - trunked	3
5	Túnel del Estero (90 m)	One sheet	None	None	None	None	None	1
	Group 2	**Thick Roof**	**Downcutting**	**2ndary Ceilings**	**Lavafalls**	**Pukas**	**Oxbows**	**Stage**
6	C. de Gilda (410 m)	Not clearly visible	Several meters, cave slot-like	Only at lava fall	One	One	None	2
7	Tortoise Junction tourist cave (203 m)	Multiple small ‘a‘ā flows, primary roof removed	Several meters	Two	None	One	None	2
8	Cueva de Gallardo (2,316 m)	Very thick, primary roof one sheet, 0.8m thick with several m of thin ‘a‘ā flows above	Several meters	None	Several “cascades”	Four, lining collaps e	Two	3
9	Cueva de Chato 1 (515 m)	Very thick, primary roof 0.5-1 m thick, with several m of ‘a‘ā flows above it. Primary roof largely eroded	1 to 2 m	None	None	Three	Many	3
10	Cueva de Royal Palm (1,040 m)	Very thick, primary roof possibly removed, with several thick ‘a‘ā flows above	>5 m	Several	One	Two	One	3
11	C. La Llegada (2,066 m)	Very thick, 0.8-1.25 m	Substantial, >8 m.	Variable ,up to 3	Multiple	Many	None	3

THE PRIMARY ROOF – OBSERVATIONS

The first group of caves has a thin roof structure. The primary roof of Cascajo Cave, for example, is composed of only one sheet (Fig. 3) between 0.6 m and over 1 m thick. This sheet is textured by several horizontal zones of high vesicle concentration. Along these planes there is structural evidence of slippage on the lower face. Furthermore, the vesicles in these planes are not vertically oriented, but demonstrate horizontal elongation. The second group of caves have thicker roofs with more complex structure. These have a thick primary roof with multiple additional thin ’a’ā layers. Thick, massive layers with low vesicularity are observed. These can be bounded with rubble above and below. A notable example of this is in Cueva de Gallardo, beyond the lowest puka. A cold collapse (i.e., a collapse long after the activity in the duct has subsided) has opened the roof for closer inspection (Fig. 4). There we are able to note the primary roof as it stretches across the cave. The roof is parted by vertical contraction cracks and by horizontal separations along vesicle concentrations. Above this layer, an ’a’ā flow is observed with its typical tripartite structure: a central, thick and massive core of low vesicularity, accompanied by rubble layers below and above. Above this, and forming the cave roof up to the present day, is the inferior side of another ’a’ā flow.

Fig. 3: Cross-section of pāhoehoe sheet forming the primary roof of the Cueva del Cascajo. Note the presence of horizontal vesicle concentrations along which the layer may have slipped when hot (Photo: S. Kempe).

Information about the structure of the primary roof is of importance if building across or near to a lava cave is planned. For example, driving a bulldozer across the roof of Cascajo Cave may turn out to be fatal. Jordá-Bordehore & Toulkeridis (2016) and Jordá-Bordehore *et al.* (2016) discuss engineering considerations and roof stability of lava caves.

THE PRIMARY ROOF – DISCUSSION

These characteristics suggest that the first group of caves has a simple development. They form when a pahoehoe sheet quickly covers the ground, solidifies and degases, forming vesicles inside. The layer then becomes less dense and the hot, fluid lava of the next pulse can creep below it, “inflating” the first sheet. Interestingly we could not find examples of multiple inflation sheets such as de- scribed from Whitney’s Cave (Kempe *et al.* 2010) or the Huehue Cave (as described in Model 1, Fig. 2a).

Fig. 4: Panorama of a roof collapse of Cueva del Gallardo below its last puka downhill. Here the meter-thick primary roof is still intact (right lower layer) overridden by an irregular ‘a‘ā flow that also collapsed and a second ‘a‘ā flow that forms the roof (Photo: S. Kempe).

The evidence of slippage suggests that flowing lava underneath was in direct contact dragging on the lower side of the roof. The elongated vesicles are further indicators that the sheet has been exposed to differential drag. It appears that the surface structure of the pahoehoe sheet has been lost due to bioturbation (i.e., rocks turned over by uprooted trees) and a cover of ash-derived reddish soil. Therefore, it remains uncertain whether the roof-sheet displayed a ropy structure. Explaining the roof structure of the second group of caves is more difficult. In order to unravel the development of the roof structure of the second group of caves one needs to assume that the primary roof has been, after its establishment and following the initiation of the underlying pyroduct, modified by surface lava flows (Fig. 5). Given time, this most likely would be the fate of any primary roof as later eruptions would bury it over the eons. However, in these cases, these later flows are in part forming the cave’s roof with the primary roof missing. Thus, these flows must have been emplaced by the same eruption that fed the pyroduct. In that situation the roof might grow many meters thick, finally overloading the primary roof. The eventual roof collapse would be assimilated by the flowing lava in the pyroduct and possibly carried away. This process is capable of explaining why we observe large irregular halls with roofs formed by welded ’a’ā or the massive layers of ’a’ā core layers such as observed in Chato I. In the case of Cueva de Gallardo, the primary roof survived the loading by additional surface flows, but further uphill, where the entrance puka separates the lower and the upper part of the Cueva del Gallardo (and separating them into actually two caves, albeit of the same pyroduct), the primary sheet must have collapsed and been carried out during activity. Thus, today we enter the cave (both downhill and uphill) through large halls. These halls are taller and also much wider than the original pyroduct, convincing evidence of collapse and upward enlargement during the pyroduct’s activity.

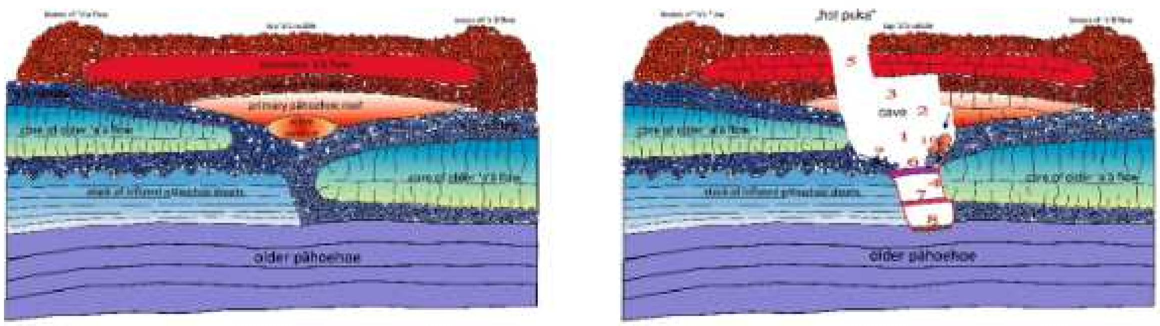

Fig. 5. Left: A pyroduct (red oval) is established in the depression between two older ʻaʻā flows (in blue). In turn, these are underlain by a stack of inflationary pāhoehoe sheets (with a ropy surface) and a massive older pāhoehoe stack (all blue as an indication that they are cold). The pyroduct was established with only one pāhoehoe sheet (reddish). Later, but during the same eruption and while the pyroduct is still active, a massive ʻaʻā flow covers the area (red). Right: Now the pyroduct is well isolated thermally and starts to cut down. First the underlying ʻaʻā rubble from the older flows is removed and a wide cave is created (1). This destabilizes the roof and the pāhoehoe sheet collapses and is carried out (2). Next the bottom rubble of the transgressing ʻaʻā flow collapsed and is carried out as well (3). Only a thin layer a rubble, welded to the ʻaʻā core remains so that it looks as if the roof of the cave is formed by ʻaʻā rubble. Further downcutting into the core of one of the underlying ʻaʻā flows narrows the cave to a canyon. Along its sides, a glassy lining covers the walls (thick red line; 4). The deepening canyon, in which the lava flows at its bottom, allows the ʻaʻā core, still forming the cave's roof, to cool quicker. Shrinkage cracks form. This eventually leads to the collapse of a skylight, called a "hot puka" because it occurred during activity and its collapse material is removed by the flowing lava (5). The opening allows colder air to enter and a secondary ceiling to solidify on top of the active flow at the bottom of the canyon (6). Further downcutting into the bottom ʻaʻā rubble of the older underlying flows creates again a gas space above the actively flowing lava and a lower secondary ceiling solidifies (7). Finally, the eruption ceases and the lower passage is evacuated. Only a thin layer of welded terminal ʻaʻā remains in the cave (8). Further collapse of ʻaʻā rubble from the walls (9) and further collapse of the primary roof (10) collect on top of the upper secondary ceiling. In the end, the cave (in this schematic evolution) has three levels, separated by two internal secondary ceilings (septa). The upper passage, with a welded ʻaʻā rubble ceiling and loose ʻaʻā rubble and other breakdown blocks at its bottom now does not resemble its original pyroduct anymore. The graphic combines observations made mainly in Cueva del Cascajo and Cueva del Gallardo.

INTERNAL FEATURES OF PYRODUCTS

Tab. 1 shows that many other internal features that are found in Hawaiian caves, are also present in Galápagos, namely evidence of downcutting, lavafalls, secondary ceilings (septa) and braiding (i.e., the presence of ox- bows).

It is not self-evident that these features would be present. For example, in the Jordanian lava caves in the Harrat Al-Shaam, no lavafalls have yet been found, evidence of downcutting is inconclusive, secondary ceilings are absent and even braiding is seen only once (Kempe *et al*. 2012).

Similarly, the lava caves at Undara, Australia, do not show any of the above-mentioned features (Middleton & Kempe in press). As it happens, these two sites are intracontinental lava fields and not island shield volcanoes like the ones in Hawai'i and the Galápagos. However, this difference is not a sufficient explanation for such behavior and will need future consideration.

Braiding is a feature established earliest in the development of a lava conduit (embryonic braiding; Allred & Allred 1997). It apparently comes about when several flow paths are established beneath the primary roof. The conduits with the lower flow-rate and those that are high- er in elevation are drained first while the later trunk pas- sage cuts down. Thus, these passages, if they are not filled by lava surges, generally form low mazes near the ceiling of the final cave. Fig. 6 shows a short oxbow in the upper passage of Cueva del Cascajo.

Fig. 6: View of a short, braided passage (or "oxbow") in Cueva del Cascajo, upper passage, near Station Z19, viewing downhill. The right-hand side was drained as the main passage on the left cut down. Note Puka 2 of the cave in the background. The floor of the main passage is a secondary ceiling with an over 5 m deep passage below it (Photo: G. Middleton).

Evidence of these higher passages being filled is occasionally seen where cross-sections are exposed through erosive or melting processes, or where outflows of molten lava from the filled passage dripped down into the trunk passage resulting in various forms of secondary lava formations, such as sheet flow on walls, stalactites and stalagmites. This described process provides a fundamental role in the formation of a variety of lava rock speleothems (e.g., Kempe 2013).

Downcutting is one of the most basic processes in pyroducts. The first, undebatable evidence has been observed in Earthquake Cave, Hilina Pali, Kīlauea, Hawaii (Kempe & Ketz-Kempe 1992a, b). There the lining of the conduit fell off, revealing an ash layer (stratigraphically identified as Pahala Ash).

Since ash clearly is not forming an integral part of a lava flow, its outcropping in the wall of a pyroduct is a clear proof of "thermal downcutting" and the cave has been used in a model of this process by Greeley *et al*. (1998). Since then many other sites have been discovered and most of the pyroducts (beyond the simple braiding stage) have evidence of downcutting as, for example, demonstrated for Kazumura Cave, Hawai'i (Allred & Allred 1997). Downcutting becomes recognizable where the lining falls away revealing 'a'ā rubble behind. Such sites were discovered in all of the caves listed in Tab. 1 apart from Cueva de Sucre and Túnel del Estero (see also Fig. 7).

The mechanisms causing the rapid downcutting in a pyroduct still remain a matter of debate. Mechanical and thermal processes may act either alone or in unison. Mechanical erosion, for example, can relatively rapidly erode through ash lavers, paleosols or loose 'a'ā rubble. When it comes to cut through the core of an 'a'ā flow, melting seems to be the option. Melting would consume a large amount of energy, cooling the flow. Melting, how- ever, only needs to be partial, since only the glassy parts of the basalt need to be fluidized, while phenocrysts can be plucked from the partial melt by the drag of the flowing lava. Meter-sized scallops, caused by the turbulent remelting of 'a'ā blue-rock have been observed occasionally, sustaining such a model. Remelting seems to be achievable since pyroducts appear to be active for weeks and months as documented for the last Kīlauea eruption (Kauahikaua *et al.* 2003) or the historic Mount Etna eruptions (Calvari & Pinkerton 1998, 1999). With flow rates of several cubic meters per second, enough thermal energy may be available to explain the observed down-cutting through massive 'a'ā cores.

Fig. 7: Cueva del Premisias: The lining (behind and above person) has fallen away, revealing an 'a'ā rubble layer that transgressed a paleosol, oxidized by the trangressing 'a'ā flow. Above the 'a'ā rubble part of the 'a'ā core is visible (Photo: H. Marinakis).

One of the means by which erosion seems to work is the lavafall (Allred & Allred 1997; Kempe 1997). Erosion is present in several of the visited caves. Fig. 8 demonstrates a lavafall in Cueva del Gilda. There the fall did not develop a specific morphology, such as some of the large falls in Kazumura Cave that have generated huge plunge pool rooms. In many cases one can observe semi-vertical shelves that mark former positions of the lavafall, illustrating that the lavafall has migrated substantially uphill. Again, the question arises, how exactly a lavafall is developed.

It might be mechanical, with the falling lava ham- mering at the floor and thereby undermining the foot of the lavafall. The cascading lava would be able to abrade the face of the fall. On the other hand, the falling lava would also be capable of melting the fall's face more readily due to the large lava velocity thinning the boundary layer between the flowing lava and the underlying rock.

Fig. 8: A 1 m-high lava fall in Cueva del Gilda (Photo: G. Middleton).

As the downcutting proceeds, the initially oval- or half-oval-shaped conduit becomes rectangular in cross- section with lava flowing at its base. It then appears to function as an underground canyon with a gas space above the flowing lava river. Any change in the energy balance of the pyroduct can consequently cause the renewed formation of a roof on top of the lava river, i.e., splitting the canyon into a lower, active pyroduct and an upper inactive, gas-filled passage. In the literature (e.g., Calvari & Pinkerton 1999) the existence of secondary ceilings (septa) is sometimes misinterpreted as evidence for two independent conduits on top of each other. This does not make sense because a younger pyroduct would never be emplaced exactly on top of an existing conduit. The younger flow would always stay to the side of the previous conduit and its morphological ridge.

Fig. 9: View uphill from Puka 4 into the Cueva del Cascajo showing several secondary ceilings at various levels (Photo: G. Middleton).

Further downward erosion may repeat the process, leaving several secondary ceilings above each other (Fig. 9).

In most cases the energy balance is disturbed by the local collapse of the primary roof, forming an opening (in Hawai'i called a *puka*). Then hot gas may escape from the cave and cold air might enter. This causes to solidify a septum below and downhill of the puka due to the fact that hot gas rises. If two pukas open, then relatively long secondary septa may form between them. They would start at the lower puka and continue uphill as long as there is a temperature difference. The heated air/gas mixture would then rise from the upper puka like fumes from a chimney. Alternatively, it is conceivable that in deeper canyons the energy balance may be disturbed enough to cause to solidify the surface of the lava river without any pukas in operation. The secondary ceiling is sometimes re-enforced by spills from uphill up to the point that the entire space of the passage above is filled. Tab. 1 indicates that several of the caves visited on Galápagos have secondary ceilings (e.g., Fig. 9).

The most enigmatic case of a secondary ceiling has been encountered in Cueva de Premisias. There, the up to 12 m high canyon ends abruptly uphill in front of a vertical wall (Fig. 10) with only an opening of about 3 m wide and 1 m high at its base. This has been the cross-section of the lava river in the final stage of the cave development. The wall above appears to be solid, just textured by two cupola-like half-spheres that may have formed by melting due to hot gases convecting upward from the lava issuing from the constriction. Behind the constriction, the secondary ceiling rises slowly towards the exit, a relatively small puka. This rise may have caused a ponding of the lava causing an overflow onto the secondary ceiling. Looking back from the puka downhill there is indeed no open space above the secondary ceiling. The former upper passage appears to be entirely filled with lava. This seems to be a plausible explanation of the situation, applying the rules deduced so far. However, it may not be the only explanation.

Fig. 10: The uphill termination of the canyon of Cueva de Premisias (Photo: S. Kempe).

CUEVA DEL CASCAJO, A CASE STUDY

In 1990/1991 Spanish speleologists explored and surveyed Cueva del Cascajo, at that time the longest cave in the Galápagos and in all of South America (Hernández *et al*. 1992). Unfortunately, the published map is lacking internal details. Due to the extensive presence of secondary ceilings, the exact length is not known yet, but the cave is reported to be about 3 km long. Fig. 11 shows the upper 150 m of Cueva del Cascajo (Z-series linked to Y-series at Y14) which was surveyed during this study. It appears to be one of the most interesting and complex sections of this cave. Small inaccuracies in the measurement of the inclination lead to the fact that the bottom of the upper passage (see longitudinal section) is nearly overlapping with the ceiling of the lower passage.

Throughout the entire length of the cave shown on the map, the passage is divided by a secondary ceiling. The lower passage is divided by further ceilings.

The upper passage with three pukas, marks the original level at which the cave has been formed. Puka 1 is a trench that gives access to the upper passage down a small breakdown slope. There the primary roof is composed of only one sheet, being 0.6 m thick. The uppermost secondary ceiling forms the floor of the passage that opens up to walking size. On the left (coming from the entrance), the lining of the pyroduct has fallen away, revealing ʻaʻā rubble The passage

makes two relatively sharp bends, first to the right, then to the left, resuming its overall ESE course. Across from station Z20, the ʻaʻā is poorly welded and after moving some of it, a hole, communicating to the lower passage, was opened. At station Z19 a pillar is encountered (Fig. 6). The southern passage is well above the floor of the main passage, marking the original level at which the cave formed. Beyond, ca. 50 m from Puka 1, Puka 2 opens up. It sits off-center above the apron and collapsed because there the passage is up to 8 m wide. From the amount of rock collapsed it remains unclear whether Puka 2 had already a small opening during activity (i.e., if it was a “hot puka”) or if it collapsed after the termination of the activity (a “cold puka”). This discussion is essential, because the source of the cold air causing the solidification of the secondary ceiling needs to be determined. Beyond, the passage continues until breakdown is encountered. To the left another apron is covered with blocks from the ceiling. Here the primary roof did not entirely collapse because it seems to consist of several pāhoehoe layers, just as in normal inflationary roofs. Between the breakdown blocks, 40 m below Puka 2, at station Z13, a small hole leads into the lower passage. From here another 30 m of passage with only a few blocks leads to station Z15 at the brink of Puka 3. The puka, actually a double skylight, is again off-center, on this particular occasion to the left of the passage. The collapse of the puka has also punctured the floor, i.e., the upper secondary ceiling, so that one is able to look down into the lower passage. The collapse of the primary roof and that of the secondary ceiling has produced a sizable pile of blocks (at station Y12); thus, both collapses seem to be “cold”. Beyond the puka the upper passage is lower and blocked by breakdown. At this place the secondary ceiling appears to be at least a meter thick.

Back at station Z13 and to the hole in the floor, one is able to climb easily down to the lower passage (see pas- sage cross-section st. Z13, Fig. 11). There the secondary ceiling appears to be less thick. In fact this hole most probably has not been caused by breakdown but is a spill hole or a gas-escape hole. This would explain why a set of secondary ceilings extends downslope from there. It seems that they solidified because colder air leaked down from the upper passage. These secondary ceilings are of variable lengths and allow one to climb down to the lowermost septum as on a flight of steps (see longitudinal section, Fig. 11). The lower-most secondary ceiling (level 6 if counted from above) ends downhill 6 m upslope of station Y12. It has a total length of 54 m to be added to the cave's length. The intermediate levels are of various lengths, the longest one measures 35 m, extending from station Z5a to Z12 (level 2 from above). The remaining three levels are only about 5 m long and leave only small openings in between them (see longitudinal section, Fig. 11). At station Z10 there is a col-lapse hole in the lowest secondary ceiling and above it the next higher septum ends zipper-like (Fig. 12).

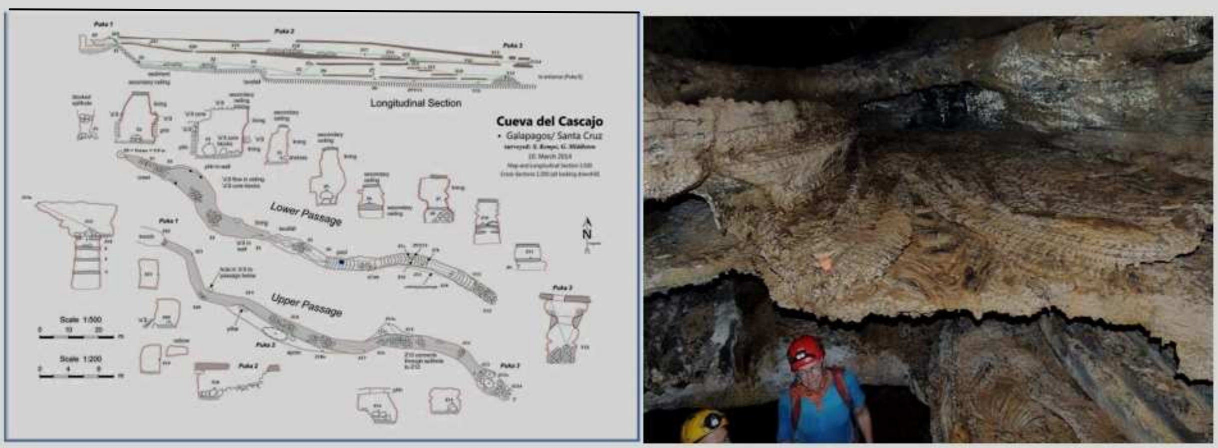

Fig. 11 Longitudinal section. Fig. 12: "The Zipper", illustrating the closure of a secondary ceiling by inward and downslope growth of small shelves (Photo: S. Kempe).

Below the lowest secondary ceiling the cave passage has a width of 4 m and a height of 1.2 m. The final lava flow in the cave therefore had a cross-sectional area of 5 m^2. This passage gives access to the upper part of the lower cave at station Z6. There the secondary ceiling ends but continues in the form of shelves for 20 m. At Z6 a low levee at the beginning of the secondary ceiling is evident (Fig. 13). It is remarkable since it shows that no lava balls strand-ed on top of the secondary ceiling. Furthermore, no spattering is evident, suggesting that the lava was essentially degassed. These observations reveal much regarding the properties of the lava in the cave.

Upward of station Z5 the shelves swing around in a regular oval, preserving the pattern of the turbulence of the terminal flow in the cave. Then the shelves almost join and curve up-ward, forming convex shells hovering above a lavafall (Fig. 14). Above, the shelves can be fol-lowed for some distance on the walls, marking the level of the terminal flow (station Z4 is on this shelf).

The cave widens upslope of station Z4 to the largest and probably most complex room in this section. In contrast to the passages visited before, here most of the lining has collapsed during activity and has been carried away. This allows a view of the country rock behind the lining (Figs. 15, 16). On the walls on both sides a series of

Fig. 13 (left): Levee at station Z6 on top of the lowest secondary ceiling looking downhill (Photo: G. Middleton). Fig. 14 (right): Lavafall and shelf-oval between stations Z4 and Z5, looking downhill (Photo: G. Middleton)

Fig. 15: View of the south wall be- low station Z2. To the right remains of the lining can be seen while to the left the eroded-into rocks are ex- posed, a series of pāhoehoe sheets covered by ʻaʻā rubble (Photo: S. Kempe).

pāhoehoe sheets are exposed (Fig. 15) followed by a thick irregular layer of ʻaʻā rubble and a thick ʻaʻā core near the ceiling (Fig. 16 upper left). The unusually large blocks on the floor of the passage derive from this ʻaʻā core. Above the ʻaʻā core, the ceiling is formed by the top-rubble of this ʻaʻā flow. It is the identical rubble that is exposed in the wall of the upper passage at station Z20 where the hole connects down to the lower passage.

Beyond this hall-like widening, the passage resumes the form of a narrow canyon with intact lining. The passage is filled with a breakdown pile, the origin of which is uncertain, because at the top of the pile, the uppermost secondary ceiling is reached that has only a relatively small hole filled with blocks. Daylight is not visible, even though this point is beyond the opening of Puka 1 in the upper passage. To the left of the blocks, we opened a low crawlway. This leads into a small room behind the breakdown that ends in a miniature lavafall, sealing the backside. On the floor another secondary ceiling is evident and after a few blocks of breakdown were removed, a second crawl was entered that lead to a narrow, about 5 m-high shaft. It was not possible to climb to its top due to the presence of fragile rock. The survey suggests that it is to the south of the trench at Puka 1. Its genesis is difficult to understand and will unfortunately remain an enigma for the time being. The floor of the shaft, as well as the crawl and the entire area at the foot of the breakdown in the big hall down to station Z4 is covered with reddish sediment as in a delta, interspersed with large quantities of shells

Fig. 15: View of the south wall be- low station Z2. To the right remains of the lining can be seen while to the left the eroded-into rocks are ex- posed, a series of pāhoehoe sheets covered by ʻaʻā rubble (Photo: S. Kempe).

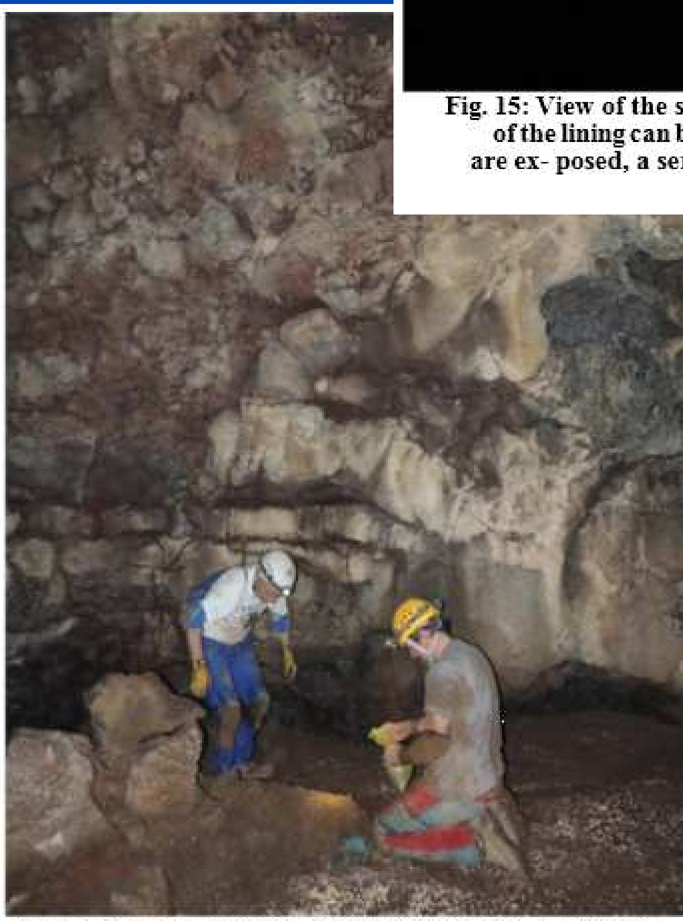

Fig. 16: View downhill towards station Z3 (on the big block in center). At the ceiling the core of an ʻaʻā flow is exposed that also is responsible for the big breakdown blocks on the floor. The ceiling to the left isformed by ʻaʻā rubble while to the right the uppermost secondary ceiling is seen, forming the floor of the upper passage (Photo: S. Kempe).

from land snails (compare Fig. 15). Small stream beds indicate that the sediment is washed in from the trench at Puka 1 during flash floods.

Notwithstanding small errors in the survey, it is possible to calculate the slope of the pyroduct. This is best done for the upper passage since the slope of the lower passage is modified by erosion. Between stations Z22 and Z15 the sum of horizontal survey lines amounts to 136.5 m and the vertical distance is 8.2 m. This yields a slope of 3.44°. Better yet is the slope of the ceiling. As Z22 is 0.5 m and Z15 1.3 m below the ceiling, the vertical distance is reduced to 7.5 m, yielding a slope of 3.1°. In contrast to this the floor, i.e. the upper secondary ceiling, has a vertical distance of 7.2 m (Z22 2.2 m above floor; Z15 1.2 m above floor) yielding a slope of 3.0°. Such a slope is quite typical for pyroducts (compare Kempe 2019). When looking at the longitudinal section, it is evident that the slope is less in the downslope and higher towards the upslope end of the surveyed section.
The total depth of the cave is quite variable. At station Z3 the lower passage is 5.8 m and the upper passage 3.6 m high (Z20). With an estimated thickness of 0.5 m of the upper secondary ceiling, the total depth of the pyroduct thus amounts to 10.1 m. At Z13 the depth is 11 m and at Y12, 8 m (measured always below the primary roof). At the commonly used entrance (Puka 5 in our count) the depth is only 5.2 m. These data indicate that the depth of erosion is quite variable (differences of a factor of two). The depth of the few small side-passages is a meter (at st. Z19 but also at the ceiling below Puka 5), suggesting that the lava eroded up to 10 m down.

CASE STUDY CUEVA DEL GALLARDO

The lava forming Cueva del Gallardo flowed from the upper exit in the tourist section (TS) south-south-west. The flow was mostly confined to just one conduit. Only two (one short, one longer) oxbows (cut-arounds) are encountered in the non-tourist section (NTS). There the original lava flow split, possibly flowing around an obstacle. The conduit that had the larger flow-rate cut down and drained the other, higher conduit. The level of these higher conduits marks the level of the initial lava level when the flow crept across the surface.
This initial sheet of lava, the primary roof, is best observed just below the lowest skylight in the NTS (Fig. 5). The primary roof is composed of a more than 1 m thick lava sheet that stretches without much change in thickness across the passage. It is only structured by vertical contraction cracks and horizontal vesicle accumulations, some of which led to a split in the rock causing a sort of layering within the lava sheet. Whether this sheet has a ropy surface structure is not clear because we were able to observe it only in cross-section, but it certainly is a sheet of pāhoehoe. On top of this sheet lies an irregular, welded ʻaʻā rubble layer. Above that lies the thick core (“blue rock”) of the interior of the ʻaʻā flow. The ʻaʻā core partly also collapsed forming the unusually large and angular blocks along and below which, , one has to crawl. This ʻaʻā-unit was emplaced on the roof of the cave after it formed. It could have derived from the same eruption that fed the pyroduct or from a later eruption. In any case, it loaded the roof with much additional weight, causing its post-activity collapse, exposing the primary roof and the two layers of the ʻaʻā flow.

The existence of one primary roof sheet excludes the possibility that the cave formed by the crusting over of an open lava channel. Thus, the cave belongs to the "inflationary" pyroducts, i.e., the cave roof formed first and the lava kept flowing underneath invisible to any surface observer (had there been one).

The entrance to both the upper TS and the lower NTS section is through another collapse (entrance puka). The structure of the roof exposed above both of the cave entrances has a more complex interpretation as it is composed of several, irregularly thick and bent sheets of lava. These lava sheets are well above the primary pāhoehoe sheet that should be much lower than what now forms the cave roof. These layers therefore were emplaced later onto the roof, just as the ʻaʻā flow discussed above. However, these flows must have been emplaced while the pyroduct was still active because, when observed from underneath, they are seen to have been thermally eroded, forming small cupolas. Apparently, the initial primary sheet of the roof was removed partially (by breakdown) and then an inundation event (initiated by a constriction or collapse further down the pyroduct) caused the lava to rise to the ceiling, leaving a prominent accreted layer seen on the ceiling. Shortly after, melting of the interior of the blocks between the contraction cracks commenced.

The material adjacent to the contraction cracks was already cooled and is preserved as ridges along both sides of the contraction crack. Thus the ceiling has the appearance of large, irregular honeycombs (Fig. 17). This ceiling texture is observed in the hall uphill of the puka collapse and some way into the continuing passage as well as in the preserved ceiling below the collapse and also into the downward continuing passage (Fig. 18). Because of the hot breakdown, that formed a hall-like widening, more lava and greater heat was available in this section of the cave causing these unusual cupolas.

Fig. 17: View towards the ceiling in Cueva del Gallardo upslope of entrance puka (tourist section). Its pattern reminds one of a honeycomb. The interior of the blocks seem to be thermally eroded, while the material adjacent to the contraction cracks remains as pronounced ridges (Photo: S. Kempe).

Once the constriction was removed and the lava began flowing again, the adjacent to the contraction cracks was already cooled and is preserved as ridges along both sides of the contraction crack. Thus the ceiling has the appearance of large, irregular honeycombs (Fig. 17). This ceiling texture is observed in the hall uphill of the puka collapse and level of the lava receded to the height of the tunnel leading off, causing a shelf to freeze out within the former hall. Much later the entire roof collapsed, forming the present entrances. During the activity of the pyroduct it apparently did not have any collapses open to the surface, because otherwise the hot gases would have escaped and internal, secondary ceilings (septa) would have formed, such as seen in Cueva del Cascajo. The total flow through the cave is difficult to judge, but it might have been substantial. Nevertheless, this substantial flow (judging from the relative stable area of the cross-section in the NTS) may have been short-lived, because the downward erosion below the level of the small oxbow was in the order of 1.5 m. Shelves are also not prominent (because of the lack of gas-escape) but do exist in a few places also giving witness to a moderate downward erosion.

The lining of the cave is well preserved and only in a few places is one able to observe that older layers, such as ʻaʻā rubble, were eroded into. Not many lavafalls occur in the cave. The highest, albeit not vertical, is found right at the upper entrance (exit) of the TS. Several smaller falls, all less than a meter in height, are found in the NTS. This again implies that downward erosion was not a prominent process within this pyroduct. Most remarkable is the terminus of the cave: it is a lava sump, i.e. lava ponded above a constriction. Thus the passage becomes low, but at the same time the heat in the ponded lava was preserved for a long time. This enabled residual melt to be extruded from the ceiling and walls, forming a rich population of drip-generated

Fig. 18: View into Cueva del Gallardo below the entrance puka (non- tourist section). Here also the roof shows a honeycomb pattern with the interior of the blocks thermally eroded and the contraction cracks forming ridges (Photo: S. Kempe).

stalagmites, up to one meter long and final extrusion of stalactites up to one meter long (Kempe 2013). That the ponding lava had a considerable depth is demonstrated by the deep contraction cracks in the floor that are not seen elsewhere in the cave (Fig. 19).

Fig. 19: At the terminus of the Cueva del Gallardo the lava seems to have ponded, providing heat for an extended time period. Thus, deep contraction cracks in the floor developed and residual melt was extruded from the ceiling, forming lava stalactites and stalagmites (Photo: S. Kempe).

CONCLUSIONS

The genesis of the visited caves on Galápagos can be explained by the pyroduct models developed by studying lava caves on Hawai'i. Of the four models suggested so far, the caves on Galápagos seem to fit the "inflation model" (Fig. 2), i.e., the caves developed below a primary roof of pāhoehoe. However, in Galápagos the primary roof seems to consist of only one sheet, while in Hawai'i most inflationary cave roofs seem to consist of several sheets. This single sheet may nevertheless be quite thick and may be separated by internal shear zones, marked by horizontal layers of vesicles.

In a subgroup of the visited caves, the primary roof consists of additional flows of the same eruption on top of the primary pāhoehoe sheet. These roofs are several meters thick. In the course of activity both the primary pāhoehoe sheet and part of the overlaying lava can collapse and be consumed in the flow. In this way relatively irregular internal ceiling structures may arise (Chato I, Gallardo, Royal Palm).

The most prominent process enlarging the Galápagos pyroducts is downward erosion. Evidence of this process has been observed in all but two of the caves in the form of exposed older 'a'ā flows and even an older paleosol (Premisias, compare Fig. 7). This downward erosion can amount to as much as (in Cascajo) 10 m.

In order to characterize the various pyroducts, we are able to review common features and correlate them to the developmental stage of a given pyroduct. These features include oxbows, relative amounts of downcutting, lavafalls or other erosive features, pukas and secondary ceilings, as well as evidence of any process resulting in further structural modification.

More advanced development of a pyroduct is correlated with a greater presence and total number of these features. By a correlation of these features we are able to define three stages of development:

Stage 1, juvenile pyroducts exhibiting embryonic braided or single conduits with no evidence of secondary ceilings, erosion or lavafalls,

Stage 2, a well-developed adult stage having some consolidation of channels and channel erosion and possibly including oxbows, one or few secondary ceilings, or other features but lacking significant morphological modifications from them; and, finally,

Stage 3, fully mature with well-developed channels rep- resenting significant downward erosion, with a partial loss of the primary roof, often multiple secondary ceilings and other evidence of significant structural evolution.

We consider that the correlation of features in this way between pyroducts in various contexts may assist in furthering the understanding of the processes that form them. Using these criteria we have assigned relative maturity levels (Tab. 1) to the individual caves with the Túnel del Estero being the least developed (exhibiting no downcutting with no specific internal differentiation) and the Cueva del Cascajo as the most developed (exhibiting the largest amount of downcutting, multiple internal roofs, extensive structural modification.) Undoubtedly, further work is needed to establish uniform principles to help us understand and describe the formation of pyroducts in the Galápagos and elsewhere. Certainly, only further detailed observation and mapping of pyroducts will be able to advance our understanding of the genesis and development of lava flows and thus better explain basalt-based volcano behavior during eruptive activity.

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