University of Pécs
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Formation, types and morphology of basaltlava caves

PhD thesises

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I. Introduction

The larger part of our globe, including the area of the World Ocean, is typically covered by basalt stones. A great percentage of this basalt is fluid and these pahoehoe type lava flows may come to the surface and cover up huge areas in a relatively short period of time. During and after its cooling, basalt lava produces caverns and caves not only differing in shape but also ranging from a few centimetres to several kilometres in terms of size. These pahoehoe type lava fields are very aptly referred to as 'helluhraun' in Icelandic, which translates into English as 'cave lava' (hellir = cave and hraun = lava).

Basalt lava caves develop very rapidly in comparison with caves found in karst areas and dissolution plays only a minor role in their evolution. Although they are genetically different structures, there are, interestingly, quite a few similarities in terms of their morphological and hydrological characteristics. As a consequence, lava caves can be regarded as structures with pseudokarstic features.

Vulcanospeleology is a field of science with research activities focusing on caves found in magmatic and volcanic rocks. Basalt lava caves have not yet been appropriately classified either in terms of their evolutionary processes or their resulting shapes, and the number of studies discussing their morphogenetic typology is also limited. Since studies on basalt lava caves have so far been focusing on the investigation of lava tubes, a detailed enquiry into smaller and scarcer morphology types with diverse evolutionary history and coming in various shapes are expected to open up new fields and bring new results.

Morphogenetic research conducted in the field of basalt lava caves has quite a large number of focal areas including Icelandic shield volcanoes, fissure eruption volcanoes, lava fields of both 'aa' and 'pahoehoe' type, as well as rocky ocean coasts.

I have been conducting field surveys in Iceland on a regular basis since 1997, most of which lasted several months. Besides Iceland, I have also made surveys on the flanks of the Fuji san in Japan, on the Jeju Island, South Korea, and on various basalt lavas in Hungary. With the work I am currently involved in, I would like to popularise my role model's Dénes Balázs's work achieved in the field, and wish to continue the research he had started.

II. Aims

The role of the doctoral paper is manifold: to discuss the genetics of basalt lava caves; illustrate the diversity of their morphology; provide a systematic analysis of the underlying factors; and give a detailed explanation of the individual morphogenetic cave types and their surface relations.

III. Research methods

For anyone to find and survey basalt lava caves, analyse the processes during which the various shapes and forms evolve, and make the relevant classifications, a comprehensive knowledge of all the relevant fields of physical geography is absolutely indispensible.

Prior to the field surveys I had examined syngenetic basalt lava caves, the various forming processes, the geological and hydrological features of the environment where their evolution occur, as well as the volcanologic processes shaping these caves.

When conducting a detailed field survey in the caves, I first had to identify the forming volcanic processes, the outflow of basalt lava to the surface, and the methods of segregation between fluid and solid zones. I went on to study the individual cave sections and estimated their cooling order and relative age to make inferences to the evolution process of each individual cave type. When attempting to establish cave sections' relative chronology I was assisted by a number of distinct signs in the caves: the contraction cracks formed during the cooling of the lava, the cave wall cross sections revealed after collapses, the large number of genetic types of various speleothems e.g. lava dripstones as well as their relative ages and forming place.

Out of the post-genetic basalt lava caves, I focused on the ones evolved by water erosion and investigated the following aspects: erosive processes of seas and rivers influencing host basalt lava stones and exerting an uneven but sporadically concentrated impact on differently structured basalt lavas; the appearance form of caves, the structural characteristics of caves predominantly made up of basalt lava (e.g. their resistance to erosion, directions of faults and fault density in the rocks), and the geological and volcanic origins of their development.

In Iceland alone I studied a total of 32 basalt lava rocks belonging to 11 different genetic types and single-handedly prepared detailed mapping surveys, ground plans and cross- and longitudinal sections for each type. For the survey I employed a Leica Disto D5 laser distance meter instrument to specify the horizontal and oblique distances with millimetre, and the dip angles with ± 50^o-ig $0,1^o$ accuracy. To measure higher dip angles, I used a Recta DS56 compass attached to the instrument and applied its dip-goniometre with 1 ^{o} accuracy.

To counteract the deviation effects of the iron in the basalt, often causing a deviation between 10-15 degrees, for the measurement of dip angles I employed a 360 degree disc capable of 0.5 degree accuracy, which I attached to a home-made photo tripod. The directional angle between the 0 and 360 degrees was the straight line connecting the landmark near the entrance of the cave (and also shown on the map) and the equipment installed in front of the cave entrance.

To carry out a targeted investigation into the individual morphogenetic types of basalt lava caves, I also employed detailed topographical geology and photo maps as well as detailed orthophotos.

IV. Summary of results

During my research, I established morphogenetic categories for caves formed in basalt lava structures (see below). *Figure 1* shows a review of the various types and subtypes of basalt lava caves in relation to one another. On the list below, you will find the abbreviated form shown on *Figure 1* printed in arial font and put into brackets where necessary.

I. Syngenetic basaltlava-caves

1. Basaltlava-caves formed by draining (drained)

1.1. Lava tubes (lava tubes)
1.1.1. Roofing of an open lava channel (from open lava channel)
1.1.1.1. Growth of rooted crust from the edges of the lava channel (from the lava channel edges)
1.1.1.2. Aggregation of floating crustal rafts (aggregation of rafts)
1.1.1.3. Accretion to levees to built an arch (from levees)
1.1.2. In rifts and vulcano tectonic fissures (in rifts)
1.1.3. Partial draining of an inflated pahoehoe lava flow (inflated pahoehoe draining)
1.1.4. Surface lava tubes (surface tubes)

1.2. Vent-basaltlava-caves (vent)

1.3. Partial draining of a basaltic dyke (in dyke)

1.4. Subcrustal basaltlava-caves in inflated pahoehoe lava fields (subcrustal)
1.4.1. Pressure ridge cave (pressure ridge)
1.4.2. Tumulus caves (tumulus)
1.4.3. Lateral ridge cave and toe ridge cave (lateral ridge, toe ridge)

2. Lavacrust barrier ridge cave (lavacrust barrier)

3. Clastogenic basaltlava-caves (clastogenic)
3.1. Hornito (agglutinate cone) cave (hornito)
3.2. Agglutinate and spatter rampart cave (agglutinate rampart)
3.3. Spatter cone cave (spatter cone)

4. Gas blister caves (gas blister)
4.1. Gas blister cave in basaltic dyke (in dyke)
4.2. Gas blister cave in the depth of lava flow sor lava lakes (in depth of lava flow)
4.3. Secondary gas blister of tree mould caves (at tree moulds)
4.4. Subcrustal gas blister cave (subcrustal)

5. Basaltlava mould caves (mould)
5.1. Tree mould caves (tree mould)
5.1.1. Hollow lava column (hollow column)
5.1.2. Standing tree mould cave (standing)
5.1.3. Bended, broken tree mould cave (bended, broken)
5.1.4. Inclined tree mould cave (inclined)
5.1.5. Drifted tree mould cave (drifted)
5.1.6. Lying tree mould cave (lying)
5.1.7. Joined tree mould cave (joined)

II. Postgenetic basaltlava-caves

1. ………Basaltlava caves formed by erosive forces (erosion)

1. 1. ……Abrasive basaltlava caves – sea caves (abrasive)
1. 1. 1......In columnar jointed basaltlava (in columnar jointed)
1. 1. 2…..In irregular jointed basaltlava (in irregular jointed)
1. 1. 3. .By abrasive opening of a former cavern and its further formation (opening former caverns)
1. 1. 4…..In basaltlava delta (in lava delta)
1. 1. 5. By the quarrying of the basalt volcanic agglomerate, or looser structured (aa) lava from between the host compact basalt (in agglomerates)
1. 1. 6….In pillow lava (in pillow lava)
1. 1. 7….In basaltic dyke (in dyke)
1. 1. 8….Along the border of dyke and tephra (at dyke-tephra border)

1. 2……River erosion caves (river erosive)
1.2.1…... In columnar jointed basaltlava (in columnar jointed)
1. 2. 2…By washing out relatively fractured segments of sub-volcanic rocks (in subvulcanic rocks)
1. 2. 3… By washing out cemented basalt gravels and boulders as well as compound and less resistant fractured basalt agglomerate intercalated into solid basalt (in agglomerates)
1. 2. 4… By the opening of gas blisters and further development by erosion, and by the washing of the connecting pyroclastics (opening former caverns)

2………Basaltlava caves formed by frost weathering (frost weathering)

3………..Crevice basaltlava caves (crevice)
3. 1……..Tectonic crevice caves (tectonic)
3. 2……..Rocksliding basaltlava caves (rocksliding)
3. 3……..Stope out basaltlava cave (stope out)
3. 3. 1…..Stope out by natural origin (natural stope out)
3. 3. 1. 1.. Stope out by human origin (consequent)

3. 4……Between collapsed basalt blocks – talus caves (in talus)

4………Basaltlava caves formed by dissolution (dissolution)

5………Postgenetic basaltlava tree mould caves (tree mould)

In the followings, I will discuss the new results obtained during my examination of the individual types.

1. The evolution of the forms and features of lava tubes

Ridges in reticular patterns on lava tube ceilings

During the cooling and contraction of cave walls, lower cave temperature is channelled towards the internal zones of the cave walls by the various contraction cracks. As a result, the basalt, found in the wall segments around the cooling cracks, cools down and hardens more rapidly. In the meantime, the majority of the wall segments located further away from the contraction cracks is still in a melted and liquid state and is likely to flow to advance. As a consequence of this, the walls segments located along the contraction cracks and crystallised to a larger extent (usually a 5-15 cm band) form ridges, typically positioned on the ceiling, and protrude from the cave walls.

This process is further enhanced by melted lava trickling down the partially melted wall segments located further away from the contraction cracks, where the lava welds and accretes onto the ridges, and thus further enlarges the relative discrepancy in height between the cracked ridges and the other wall segments.

Contraction cracks on the walls of lava tubes are often arranged into networks and, consequently, ceiling ridge structures also tend to make up a net-like character very similarly to the coffer-work of panelled ceilings in churches (*Picture 1*). These ridge layers collect the lava trickling down the cave walls and are the most likely layers to develop lava stalactites. My research activities were conducted in the lava tubes of Yongcheon, Waheul, Susan, and Socheon, Jeju Island, South Korea).

Picture 1. Along the cooling (contraction) cracks, the more rapidly crystallized ceiling segments protrude and create a coffered ceiling. The diameter of the coffer panels can range from 20-40 cm. The cooling wall segments, located further away from the cracks, spent a longer time in a melted state and allowing more lava to flow towards the ridges and thus further extending the coffers between them. Susan lava tube, Jeju Island, South Korea.

Forming site and distribution of lava stalagmites on cave floors relative to the activity of lava flow in the cave

In the vicinity of lava flow drift lines and as a result of larger and faster flows, the solidified outer crust develops much later in the middle zone of the lava tube cave floors. In this zone there is less time available for lava stalagmites to take shape and therefore they come in smaller sizes (5-10 cm).

Larger and thicker lava stalagmites (ranging from 20 or 40 cm to as much as 70) usually develop near the sidewalls where the lava flow may have stopped already at the beginning of the lava's retreat. Here lava stalagmites had more time available for development under unchanged circumstances. Lava stalagmites developing on the periphery of cave floors and reaching a larger size do not only collect lava dripping from the ceiling but also from the sidewalls which is welded and accreted into their structure. Lava stalagmites are formed from the lava accumulated on the ceiling ridges (see chapter 1) and dripping on the cave floor; and are typically located under longer ranges of 'lava collector ridges', neatly arranged in a line on the cave floor.

Lava stalagmites tend to be produced in the largest size and quantity right after the stoppage of the last lava flow moving through the cave. In the still hot cave, a large amount of fluid lava drips from the ceiling and the sidewalls, which is not carried away by an active lava flow. This claim is fully justified by the fact that tubular lava stalactites hang directly from the ceiling above lava stalagmites, and lava dripping from these stalactites build the standing stalagmites. Contraction cracks, developing with the cooling of internal segments and "inherited" into the surface lava crust, also serve as evidence for lava stalagmites to evolve during the cooling of cave walls, because these cracks often cut through the stalagmites on the cave floor.

A cause of sinking and collapsing in lava tube ceilings

Any new lava, flowing onto the roof of lava tubes even as much as a few thousand years later, might be expected to partially re-melt the cave roof due to its high temperature. The partially re-melt and consequently weakened ceiling sinks from the immense weight of the lava above it and eventually bends down. Later on during the cooling, some pieces of ceiling from between the cracks developing in the bent segments and moving downwards in diverging directions are likely to fall out revealing the upper-level already solidified lava flow that had caused the sinking of the roof earlier. The lower bedding plane of this new lava flow, revealed by the collapse of the roof, will become the lower cave's new roof. It has a reddish colour because its iron content made contact with the lower, already cooled, cave atmosphere rich in oxygen, so it undergoes oxidisation. These observations were carried out in the Majanggul cave on Jeju Island, South Korea.

2. One possible way for lava tubes to open

Lava tubes may open up simultaneously with the discharge of the lava, moving within the tubes, at particular points where the thick roof (1-5 metres) also acts as the surface of the tube.

Here, the overpressure produced by the huge quantity of internal lava may lift a part of the roof often, reaching as much as 40 or 50 metres, then, following lava discharge, this crust segment sinks lower than its former level. In the fractured zone, developing between the remaining sunk crust segments, the now empty lava tube may open up forming the entrance of the cave. This is how an entrance of a passage section in Surtshellir cave, a cave in the lava field of Hallmundarhraun, Iceland opened and developed. Here the lava crust—located the above the upstream (and formally lifted) lava surface—sank down, while the downstream crust section, unbroken from below, with the cave beneath, remained in situ position (*Picture 2*).

Picture 2. The entrance of the Surtshellir lava tube (B) which opened up with the sinking of the upper section of upstream lava crust (L). Hallmundarhraun lava field, Iceland.

3. The formation of vent caves during fissure eruption

The vent caves of the Leirhnjúkur fissure volcano, situated in Krafla Caldera in Iceland, were formed by basalt lava, upwelling and withdrawing directly from the magma chamber. When the volcano erupted in 1984, curtains of lava spurted up from the fissure (*Figure 2/a*) and split up to concentrate into separated lava fountains. On the upper edge of the fissure, the lava fountains created a vent row, detached by separation walls, while the rest of the fissure was covered by falling pyroclasts, and thus further expanding the height and breadth of the vent walls (*Figure 2/b*). In the last phase of the eruption, on spots where magma supply stopped abruptly, the lava retreated to the deeper parts of the feeding fissure; and the small vents supplying the former lava fountain emptied (*Figure 2/c*). The surface openings of these vent caves are rather small, (1-2 m wide) but widen out towards the bottom reaching a height of 4 to 5 metres.

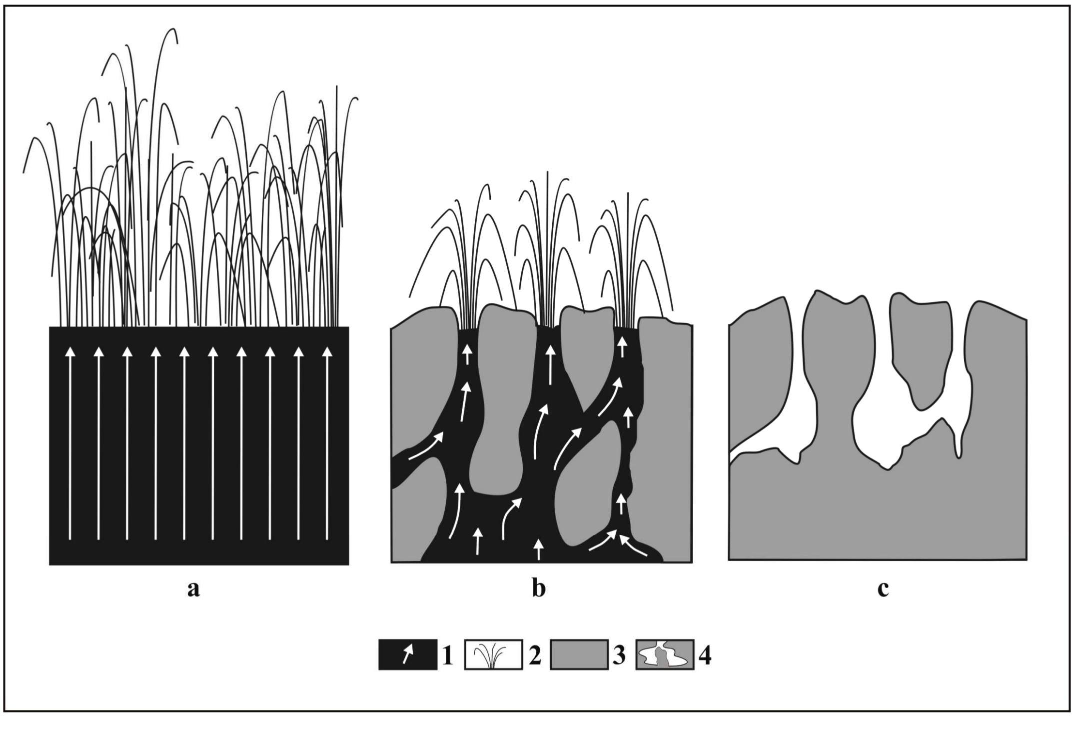

Figure 2. The formation of vent caves during fissure eruption.
Key to symbols: 1. Movement direction of the upwelling basalt lava 2. Lava fountain
3. Pyroclastic material partially occluding or covering the fissure
4. Vent caves formed with the withdrawal of lava

4. Clastogenic basalt lava caves

Pahoehoe lava flows may surge into swampy areas saturated with water, as a result of which lava eruptions or—due to the interaction of lava and water—steam explosions may occur, as much as 10 or even 100 km from the lava source, during which the lava brakes into fragments. From the ejected and still semisolid lava fragments (agglutinates), in the event of a central eruption, there might be cone-shaped structures (edifices) or hornitos built, which may form a cave by enclosing a particular volume of their environment.

Agglutinate rampart caves and spatter cone caves may be formed above the fissure eruptions supplied directly from the magma chamber, or during the falling back of semisolid or hot scoria fragments ejected from lava fountains.

Because these caves are formed in the interior of lava edifices built of pyroclastites, my suggested terminology for their distinction is “clastogenic”.

The morphology of hollow hornito caves and the reasons of the strong stability of their edifices

During my surveys carried out in the Aðaldalshraun lava filed in Iceland, I investigated hornitos, which are rather typical of that lava field and may reach a height of 2 to 5 metres. I took a closer look at hornitos with a diameter similar in size to their height, and studied the morphology of hornito caves while I also attempted to uncover the reasons for the strong stability of hollow hornito edifices.

The floor level of hornito caves is usually 0.5 or 1 metre lower than the cave’s surroundings and therefore the cave’s height is larger than the relative height of the cave in relation to its surroundings. The diameter of these caves ranges from 1 to 5 metres and they become gradually narrower from the floor towards the roof forming a dome-like shape. One hornito has one cavern at a time, but in some rare cases we may encounter 2 or 3 hornito caverns joined together.

The diameter of an average hornito skylight may range from 0.5-1.5 metre, which may further widen due to external forces or collapses stoping up from within the cave. Entirely closed hornitos are only very scarce: in this case the interior of their top cupola becomes lined by the ejected and accreted lava materials of the inner lava fountains and spatters coming from below.

The thickness of the walls of the hollow hornitos in Aðaldalshraun is usually 1.5 – 2 metres, and becomes gradually narrower until they reach the top of the dome at 5 – 15 cm.

The stability of hollow hornitos is only partly subject to the thickness of their walls built of agglutinates. The stability of hornito cupola walls also increases as a result of the piling up of lava agglutinate pieces on top of one another, which are also welded and accreted together. This process is further intensified as, following the agglutinates’ impact on the building-up hornito walls, they flow on the pieces below them to a smaller or larger extent.

5. Subsurface basaltlava caves

Fluid lava injected under the gradually solidified surface crust in pahoehoe type basalt lava flows, and accumulating in such places, uplifts or arches up plastic, semisolid and solid state basalt lava crust. From below this crust—due to the causes described in the literature of the subject—the fluid lava zone partially or entirely discharges leaving caves behind.

Caves formed in this manner usually are usually located in a depth of 10-50 cm, right under the solid surface crust, so to distinguish them the suggested terminology is „subsurface.

Because the inflation lava of the pahoehoe type may have various types, fluid lava may also accumulate in diverse ways. With the draining of the fluid lava having a large variety of forms and shapes, several different morphological types of subsurface caves are formed.

An essential prerequisite for the evolution of the subsurface caves: the plastic zone of the lava field's surface crust.

The lower, plastic zone of the upper crust of pahoehoe lava fields—located beneath the outer, solid surface and above the fluid zone—has a vital role because it can inflate the lava to a greater extent. This plastic zone with considerable tensile and yield tense does not break, but keeps its form against the pressure of the accumulating fluid lava underneath. With the continuous increase of the hydrostatic pressure of the fluid lava injected under the surface, the plastic zone tends to bend, stretch or slightly flow; while no disruption or fracture occurs in its interior. Owing to the above features, this plastic zone prevents the enclosed and accumulating fluid lava from coming to the surface, and thus the fluid lava squeezes through the fractures of the outer solid crust only to a small extent, if at all, and keeps accumulating and consequently further lifting the surface crust from beneath.

Morphogenetic differences between sub-crustal caves and lava tubes and their reasons

The volume of subsurface caves formed beneath uplifted or arched basalt lava crusts—unlike in the case of lava tubes—roughly coincides with the volume of lava discharged from beneath the surface. Following the discharge and due to the lack of support it may slightly sink further, bend inwards or break in; whereas lava tubes are capable of rendering the diversion of horizontally flowing fluid lava with a much larger volume then theirs.

As opposed to lava tubes, sub-crustal basalt lava caves do not divert a significant amount of fluid lava coming from other parts of the lava flow, and therefore there only very few signs indicating a current of lava on the sides of their cave walls, e.g. lava striates printed parallel with the direction of lava current.

If the draining process is periodical during the forming of sub-crustal basalt lava caves, then the sinking and primarily vertically moving melted lava will engrave vertical striates—with its solidified and broken pieces of the inner lava crust—into the still plastic sidewalls.

The formation of lava rise caves

The almost flat parts of solidified surface crusts of basaltlava flows can uplift as a result of the inflation caused by the accumulating fluid lava under it. These uplifted broad areas over the up-ponded parts of lava flows are the so called lava rises.

In some cases the accumulated lava below the lava rises subsides and separates from the surface crust because of its draining into the deeper parts of the lava flow. If the uplifted part of the lava surface crust can support itself, a flat cave remains under it with a ground plan slightly elongated towards the direction of the lava draining but they can branch because of the bifurcation of the drained lava.

The disjunction surface between the surface crust and the sunken viscous lava forms the floor and the ceiling of the cave, which have a rough surface with pointed, shark-tooth projections with size generally less than 3 cm. Rough surfaces can also develop because of the mass of still-plastic lava layers which are pulled away from one another. If the viscoelastic disjunction layer beneath the surface crust is vesicular, pitted and filamented cave ceilings and floor surfaces can evolve.

Lava rise caves are more likely to develop over flat depressions of the original surface onto which the lava has flowed.

The formation of lava tumulus caves

Tumuli evolve when fluid lava injects underneath the surface crust of the basaltlava-flow and the increased pressure of fluid lava below the surface crust is concentrated at a certain weak spot of the surface crust contemporaneously with the solidifying of this area.

The pahoehoe lava flow accumulates in the form of several layers above the surface depression. The thicker lava, accumulating in such a depression and capable of transmitting a larger amount of heat, has a thinner surface crust in comparison with other surrounding crust segments (*Figure 3/a*). Due to the continual accumulation (inflation) of fluid lava under the crust and owing to its smaller strength, the crust above the depression will lift more rapidly in relation to the surrounding crust area. Due to the ignescent hot lava located below, the outer solid crust layer—cooling more slowly and therefore having smaller crust strength—arches up into a dome-like shape (*Figure 3/b*).

(*Figure 3/a,b,c*). It results that the solidifying lava surface crust arches up by the pushing up from below forming a bulging form without horizontal shortening. The upper hardened parts of the swelling surface crust are usually cracked open by the excessive upward bending (*Figure 3/b*). The fluid lava is injected into the fractures which are several centimetres or decimetres wide cutting through the surface crust, and in many cases the molten lava extrudes through the crack openings of the crust and spreads out onto the surface of the arching tumulus and covers it (*Figure 3/c*). These outflows - also called squeeze-ups – can greatly stabilize the arched surface crust, and prevent it from collapsing when the fluid lava-support drains away from below (*Figure 3/d,e*).

If the molten lava which once filled the tumulus drains away from below it, there is a cave remaining with a rounded or elliptical ground-plan and with a lenticular form in section. The width of lava tumulus caves usually ranges from 1-2 m up to 10-20 m, while their average height is from 0.5 m to a few meters.

The absence of “tide marks” on the sidewalls and ceilings of tumulus caves indicates that the draining out of fluid lava from below the upheaved and arched surface crust was accomplished in a single uninterrupted act.

The withdrawal of the liquid lava which was the support for the surface crust generally causes a collapse and a skylight forms on the flank of the tumulus, which reveals the cave in it.

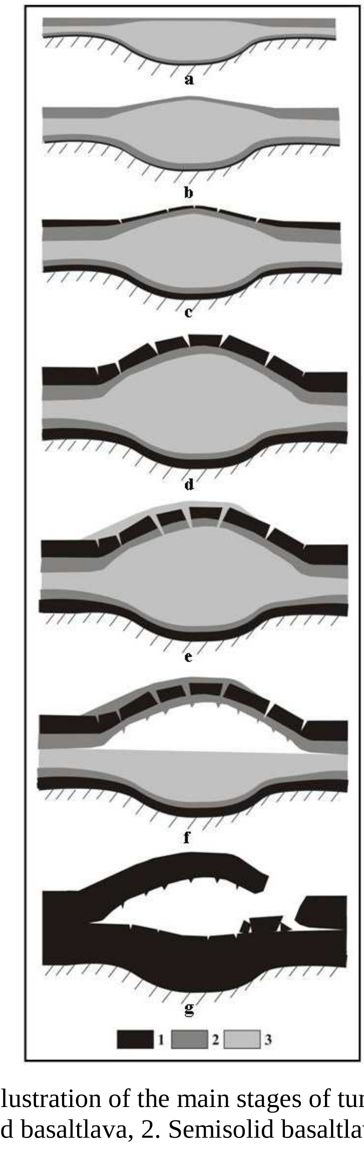

Figure 3. Schematic illustration of the main stages of tumulus cave development
Legend: 1. Solidified basaltlava, 2. Semisolid basaltlava, 3. Fluid basaltlava

Lateral ridge caves, toe ridge caves

Lateral ridges form when the inner part of basaltlava flows with a convex uplifted and solidified surface crust sags because the supporting ponded lava underneath sinks. As a result, at the edges and the toe of the lava flow, ridges of surface crust form, which are aligned parallel with the flow direction. Toe ridges form as a result of the same process but at the toe regions of the lava flows.

On the sides of these ridges the broken slabs of surface crust dip inwards and outwards forming the sidewalls and the roof of the cave, which is situated under them. The surface of the sunken lava forms the floor. These types of caves have an elongated shape parallel with the lava flow edge, with a triangular cross section.

6. Lavacrust barrier ridge cave

The lateral compression resulting from different speed between the hardened surface crust of basaltlava flows and the fluid underlying lava lifts up and buckles the solidified surface crust causing a shortening of it. It is generally caused by the pressure of the flowing fluid lava, so the pressure ridges generally align perpendicular to the direction of the lava flow. While the surface crusts arch up, a rather long and narrow cave forms under them.

Pressure ridge caves generally have a triangular cross section because of the upheaved flat slabs of the broken surface crust which form the roof and sidewalls of the cave.

7. Contributions to the forming and typical shapes of gas blister caves

Gas blister cave in basaltic dyke

If the feeder dyke of a fissure eruption is filled with stagnant or slowly moving pyromagma the gas bubbles have sufficient time to join together. In case the upper part of the pyromagma in the dyke solidifies, the expanding gas blisters are prevented from escaping to the surface, therefore they can reach a considerable size, which might be a few metres in diameter. The shape of the gas blister caves can depend on the width of the dyke, and can be flattened by the accumulating gases expanding in a horizontal way in the fluid magma, because the vertical expansion is blocked by the upper solidified parts of the pyromagma.

The opening of gas blister caves and one possible account for the original and apparent differences their size

Gas blister caves, sited deep below lava surfaces and formed earlier in the magma, only very rarely open up. If this should happen, it will trigger the destruction of their syngenetically ns evolved shape, too. Gas blister caves may be revealed by glacier rivers in the canyons of Iceland made up of lava flows, or possibly by sea abrasion on seacoasts; but just as simply as they are revealed by these natural forces, they may also undergo profound transformation or may even be completely destroyed.

In the immediate vicinity of gas blister caverns, the host rock is often densely fractured as a result of which the rock pieces tend to flake off faster around the gas blister caverns. For this reason we may often overestimate the original, genuine size of a given gas blister cavern due to its expanded diameter.

Conditions for gas-lifted under-crust (subcrustal) gas blister caves to be formed

Gas blister caves do not evolve by the draining, but the expelling of the fluid lava because of the accumulating gases below viscoelastic crusts of basaltlava flows or lava lakes.

In the hot molten, liquid basaltic lava, gas bubbles can migrate to join together. Under a decreasing lava static pressure the joined gas bubbles expand, and if they have sufficient time for it, they expel a considerable volume of the surrounded fluid lava. Close to the surface of basaltlava flows or lava lakes, the accumulating gases can swell up the viscoelastic parts of the cooling lava surface crust, but this lava crust does not allow the expanding gases to escape from below. If the up-swelled, arched surface crust solidifies before sinking back, a cave remains below it, with a cupola-shaped roof.

The expansion of the accumulating and joining gas blisters generally do not only extend upwards, but downwards to the lower molten parts of the flow and in a lateral way below the viscoelastic crust. When the surface crust is more viscous the gases can arch it only to a small extent, and the rest of the gases expand downwards to form caverns.

The roof of gas blister caves usually collapses a short time after its formation, because it has less stable thin walls which are cracked by the contraction of cooling origin.

Gas blister caves originated below uplifted thin fragile surface can preserve for a longer period if they are buried with several thin subsequent lava flow layers which provide an appropriate stability for their roof.

8. The forming of sea caves and their morphology in basalt lavas of different structures

Besides the given sea abrasion conditions, the morphology of sea caves is also determined by the various basalt lava structures.

Columnar jointed basalt lava

For abrasion caves to be formed, jointed stone segments are especially favourable: those that constitute colonnades with vertical or near-vertical joints, or above which there is entablature. Due to abrasion in the colonnade, the cave grows rapidly and large, often a few m^3-pieces of the columns are likely to fall into the sea, especially in times of storms. The basalt columns are most likely to break where cracks are perpendicular to the long axis of the column or where crystal segments, the causes of the cracks, are located.

The stoping of the cave, however, is most probable to cease in the entablature. Here the lava is far more irregular and has a more dense crack-network; and owing to jointed feature of the stone segments there is a larger chance for the formation of parts more resistant for static hold and engraved with cracks typically diverging upwards. Consequently it is in the entablature where the often dome-like vaulting of the abrasion cave is formed, while their near-vertical sidewalls are constituted by the uncovered colonnade.
I studied these types of caves in Iceland: in Arnarstapi and Hellnar, and on the coast of Reynishöfn.

Irregular-jointed basaltic lava

In these caves, made up of far more irregular and densely fractured stone segments, it is the downward diverging cracks that cause the internal stone segments to flake off. Because the cracks run into several diverse directions even on a small area of study, the expansion of a cave—occurring as a result of flaking—is more haphazard in terms of speed and direction than it would be in the case of regularly fractured lava. Hence, the morphology of these caves, too, is irregular.

If solid basalt lava with such irregular crack-network is cut through another dominant fracture perpendicular to sea waves, abrasion along the cut will be more efficient and will build a cave with a narrow and more regular ground plan, and located perpendicular to the coastline. The cave will be built by the ‘concentrated’ quarrying of the irregular-jointed stones of the new fracture.

I investigated these types of caves in Iceland: in Hraunsvík, Dritvík and the coastline of Dyrhólaey.

Formation by abrasive opening of a former cavern and its further formation

On the Páskahraun lava fields of the island of Heimaey, Iceland, sea abrasion opened a lava tube near the coast and it has continuously shaped it ever since. On the same island, a 52-m high cliff, built of compound pahoehoe lava, revealed a tumulus cave on its peak, exposed as a result of sea abrasion and due to a collapse caused by a crack running parallel with the coastal cliff. Due to the abrasive force, tree moulds were revealed in Ísafjördur, and gas blister caves in Dyrhólaey.

In basaltlava delta

The examined sea cave in Dyrhólaey is likely to have formed in a hyaloclastic lava delta sequence, where the coexistence of several geologic prerequisites created ideal conditions for the development of the sea cave which inwardly hollows out. These geologic prerequisites are the following:

Compact, but jointed lava layers in small dip angle and in a sufficient thickness, which means that the layers are thin enough for the abrasive agents to break them up, but they are sufficiently thick to stabilize the cave's roof and sidewalls. These lava layers were broken up from below by the pressure of the invading seawater accompanied by the wedging action resulting from the air compressed into the layers' joints, where the air escaped from with an explosive violence. The up-breaking of the lava layers is proved by the chimney which opened in through them.

Rather thick hyaloclastite layers, in which the effective and rapid excavation of the sea cave took place.

Inwards from the cliff face the compact lava layers become gradually thinner, while, in compliance with it, the hyaloclastite layers become thicker. Because of these reasons the inner side of the alternating lava delta sequence was abraded more effectively than its outer side, therefore the cave's inner cross section is higher and wider than the first passage section.

The stable roof of the cave comprises two different compact lava layers which resisted the abrasive agents and, for this reason, did not break up.

The stability of the sidewalls is caused by the remnants of the compact lava layer segments which remained in the sidewalls after the layer's up-breaking, and subsequently cropped out in some places forming ledges.

By the quarrying of the basalt volcanic agglomerate, or looser structured (aa) lava from between the host compact basalt

Volcanic agglomerate, debris or aa lava is often washed to the shore as a result of sea abrasion. In this case, the form of the resulting abrasion cave—unlike in the examples we have so far seen—will not depend on the crack direction of the enclosing lava volume, but on the shape of the loosely structured debris once surrounded by lava flow; i.e. with the abrasive removal of the debris the shape of the cave will reflect its mould.

I studied these types of caves in Jeju Island, South Korea and on the coastline of Hraunsvík, Iceland.

In pillow lava

Near Mount Valahnúkar, Iceland, on the rocky coast destruction by abrasive forces, I examined an abrasion cave, revealed in pillow lava, which developed along a larger crack. The hyalo-structured crust shells are the most resistant parts of pillow lava and, due to sea abrasion, the basalt material falls out of the internal radial joints of these round arched shells. The hyalo-structured crust shells, therefore, have a vital role in the stability of the abrasion cave wall acting as a sort of stiffener or net, joining the loose and fractured material and protecting the cave from collapsing. Consequently, under given abrasive circumstances, the direction of the external hyalo-structured pillow lava shells, as well as the direction of joints in the fractured pillow lava will be decisive during the formation of the cave.

In basaltic dyke

In the hydrovolcanic tuff, revealed along the coastline of Hraunsvík, Iceland, the lower part of the basaltic dyke is subject to abrasive destruction. The key role of this process is played by abrasive rock boulders, with a diameter of 20 to 70 cm, knocked against the cliffs by sea waves. Above the resulting 'material loss' and on the upper part of the basaltic dyke, fragments separated by contraction cracks (size 8 x 30 cm or 12 x 50) can be expected to be shaken out, they split up along the cracks perpendicular to the fissure, as a result of which the roof of the cave stopes up in the basaltic dyke along the hydrovolcanic tuff.

As a result of the above process it is the basaltic dyke (harder and more solid but made up of blocks separated by contraction cracks) which is washed out faster than the hydrovolcanic tuff, the looser-structured material around the tuff.

9. The formation and morphology of river erosion caves in basalt lava of different structure in the basaltic canyon of Jökulsá á Fjöllum, Iceland

I investigated caves formed in the basalt canyon of the Icelandic glacier river, Jökulsá á Fjöllum, formed in the course of a giant mega-flood some 2500 years ago. My research interest focused on the hydrological, erosion and structural conditions of cave formation and I was also curious to learn how the current morphological features, depending on the structure of the stones, developed due to the erosive river mechanisms.

Under certain given river erosion conditions, similarly to sea abrasion caves, it is the structure of basalt lava stones that determine the morphology of their caves.

In columnar jointed basalt lava

In some parts of the irregularly fractured brecciated zone, less resistant to river erosion and making the upper and lower part of basalt lava flows, the river can deepen its bed more efficiently. As a result of this and on condition that the above row of columns does not collapse, there are low-roofed, longish caves formed on the sidewalls of the canyon parallel with the dipping direction of lava flows.

Above these caves there are colonnades made up of columns with a diameter of 50 to 80 cm, also detached by cracks—perpendicular to the length of the columns and pre-shaped due to the periodic contractions—along which the columns may disconnect and some of their segments might fall out. This way the roof of the cave stopes up and expands in the colonnade. If, due to full loss of material, the columns fall out in the entire length of the cave, the roof of the expanding cave will be made up of the more resistant parts of the entablature located over the colonnade.

In the entablature, the directions of the contraction cracks do not run parallel, therefore in this zone the columns are crooked, which raises the chance for this area to develop statically more resistant parts. For this reason, the basalt lava flow segments, most resistant to river erosion, are entablature structures. This is neatly illustrated by the fact that the surfaces of erosion-made terraces of the Jökulsárgljúfur canyon coincides with the upper border of entablatures; while the more rapid withdrawal of the canyon sidewalls during the floods occurred in the colonnades deepened from below by the brecciated zones.

By washing out relatively fractured segments of sub-volcanic material

Some 200 metres from the western bank of Jökulsá á Fjöllum and in the abandoned riverbed left behind by the ancient flood, there hides the Kirkjan cave. It was formed inside a cone-shaped magmatic/sub-volcanic intrusion revealed by the jökulhlup devastating the area 2500 ago; and came to being when the less resistant, densely fractured stone segments—located earlier beneath and above the dome-like colonnade—were washed out by the flood.

By washing out cemented basalt gravels and boulders as well as compound and less resistant fractured basalt agglomerate intercalated into solid basalt

The Tröllahellir cave is located on the eastern bank of Jökulsá á Fjöllum. Its formation was triggered by fractured and less resistant basalt agglomerate (found in the surrounding stones that had better resistance but owing to river erosion retreated less rapidly) as well as cemented basalt gravels and boulders formed with more rapid fluvioraptive erosion and, from the resulting material loss, by the falling out of larger basalt blocks separated by contraction cracks.

This is demonstrated by the basalt gravels and boulders (with a diameter of 5-10 cm and 40 cm, respectively) rounded by river erosion and found on the sidewalls and ceiling of the cave. Some segments of the gravels and boulders are welded to, and intercalated into the surrounding basalt, probably the contact zone of the enveloping magma/lava and the river wash. The lentil-shaped Gloppa cave, located at a height of 20 metres near the western bank of Jökulsá á Fjöllumin, developed in a rock formation when the mega-flood washed it from the surrounding stone structure 2500 years ago. The Gloppa cave, similarly to the Tröllahellir cave was formed by the washing out of looser structured basalt volcanic agglomerate that intercalated into solid basalt and accumulated here, as well as the washing out of mixed river gravel and boulder carried by the torrential Jökulsá á Fjöllum. Below a lower tower of the erosion rock pillar, or "erosion rock castle", made up of several peak cones, a smaller cave can be found whose formation was the same as that of the Gloppa cave. Between the two, formerly probably interconnected, caves there is a space (closed from the sides and having the shape of a cauldron) that must have evolved by collapse. Here some astonishingly giant river boulders were trapped as a result of the massive glacier outburst 2500 years ago, and the same boulders are likely to have played a key role in the formation gouging of the Gloppa cave. Although the larger part of the roof in the Gloppa cave keeps stoping up by collapses, some one-third of the ceiling is still constituted by a mix of compound basalt volcanic agglomerate and basalt gravels—cleaving to the basalt walls and welded in the contact zone of the surging hot basalt and therefore having a better resistance—which prevent the collapse of the basalt located above them and full of contraction cracks.

By the opening of gas blisters and further development by erosion, and by quarrying of the connecting pyroclastics

The first section of the cave, discovered on the western part of Jökulsárgljúfur canyon, is an opened up gas blister cave. When the jökulhlup flooded the area 2500 years ago it broke through to a pyroclastic deposit and enlarged the cave significantly both inwards and outwards. The flood revealed the subsurface segments of a former lava fountain, a spatter cone or scoria cone, which must have been formed when the lava flowed on a water saturated area and, due to the increased steam content, it erupted. At the end of the eruption, the new cave was blocked up by the welded pyroclastics, beneath which the gas blister cave could exist - at the site of the steam production and until the point it was revealed by the flood.

10. Crevice caves at the edges of tectonic grabens

On the divergent plate boundary crossing Iceland, internal tensile powers created a major rift zone, which also crosses the Vogahraun lava field, where the internal forces formed a broad graben. In the western fault zone of this graben, produced from this sunken crust, several meter wide and several hundred meter long parallel crevices developed. In this zone, the downward opening 'A' cross sectioned subsurface crevices— created as a result of the tilting down of peripheral thick rock tables of the graben—have extended and reached the size of a cave.

The Grjótagjá cave evolved as a result of a "stoping up" of the upper part of the widening crevice, during which the stone structure, separated with downward cracks in the upper and formerly narrower part of the crevice, collapsed into the lower and wider parts of the crevice diverging in a downward direction. This sort of collapse-originated widening may occur along with the formation of the tectonic graben.

I had the opportunity to investigate a large number of examples for these characteristic Icelandic crevice caves, which evolved in the same way as the Grjótagjá cave on the periphery of sunken grabens of tectonic nature, e.g. in the lava field of Leirhnjúkshraun or, for instance, the Vatnhellir crevice cave at the periphery of the Mygludalir tectonic graben.

Further research objectives:

- To investigate caves formed in aa type basalt lava and different from caves developed in pahoehoe type lava. I have already started this research on Heimaey island, Icelend in the Páskahellir cave when surveying a complicated lava tube system formed in aa lava. on Heimaey island, Iceland. For anyone wanting to research caves formed in aa lava, Etna in Sicily is also worth studying.
- To further study subsurface basalt lava caves
- To conduct a morphogenetic research into basalt lava caves located in Hungary and in the Carpathians.
- To discover and carry out a morphogenetic analysis on new sample areas for basalt lava caves formed by abrasion and erosion.
- Once aware of the morphogenetic features of basalt lava caves, to draw consequences regarding the paleo-environmental conditions prevailing at the time of their formation;
- To draw consequences about the formation processes of lava caves by studying the thin sections of stones collected on the research areas;
- To conduct a comparative study of the different morphogenetic types of basalt lava caves found in various part of the Earth.

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