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Sea cave development in an alternating sequence of nearly horizontal basaltic hyaloclastite- and compact lava layers in Dyrhólaey, Iceland

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Abstract

The most frequent postgenetic lava caves develop in rocks of sea cliff exposed to sea abrasion. Many impressive examples of sea caves can be found on the Icelandic coast. In some particular places of Dyrhólaey the cliff consists of a nearly horizontal layered basalt lava delta sequence of 10-15 cm thick compact, jointed lava flow layers and intercalated easily eroding hyaloclastite layers of 50-100 cm on average. This lava delta sequence creates ideal conditions for the sea cave enlargement. Here, the effective upward, inward, and sideways enlargement of the cave takes place in the looser volcanic hyaloclastite layers. The stability of the cave's roof and sidewalls is due to the layers of compact lava flows. As a result of cave enlargement of this kind, the cave's inner cross section is higher and wider than its entrance.

Keywords: sea cave, basaltic lava delta, alternating sequence, hyaloclastite, compact lava layer, Dyrhólaey, Iceland.

INTRODUCTION

For the development of sea abrasion caves there needs a special coexistence of several conditions that allows the differential erosion of the coastal sea cliff sections. Among these conditions, directions and numerical density of joints, and the different resistance of the rocks of which the cliffs are composed have a primary importance (MOORE 1954, ZENKOVICH 1967, SUNAMURA 2000, BUNNELL 2004).

In some particular places on rocky coasts of basalt volcanic terrains, where the sea cliff consists of an alternating sequence of resistant, nearly horizontal compact basalt lava layers and interbedded, less resistant volcanic tuffs (e.g. hyaloclastites), there is a bigger chance for a sea cave to develop.

The aim of this study is to present how sea caves can form under the abovementioned ideal conditions, on the basis of the morphogenesis of the sea cave at Dyrhólaey, Iceland (Photo 1). This sea cave formed in a basaltic lava delta where hyaloclastites and compact lava layers piled up in an alternating, nearly horizontal sequence.

THE SITUATION OF DYRHÓLAEY AND THE EXAMINED SEA CAVE

Dyrhólaey is situated at the southernmost point (63^{o} 23') of Iceland (Photo 1/a,b). As regards its origin, Dyrhólaey is a submarine volcanic hill which rose above the sea level during a hydrovolcanic eruption of Surtseyan type (THORDARSON – HÖSKULDSSON 2006). Dyrhólaey – which represents the remains of a larger hydrovolcanic cone - consists of hydrovolcanic tuff, which capped by compound pahoehoe lava on the eastern side of the island (THORDARSON – HÖSKULDSSON 2006).

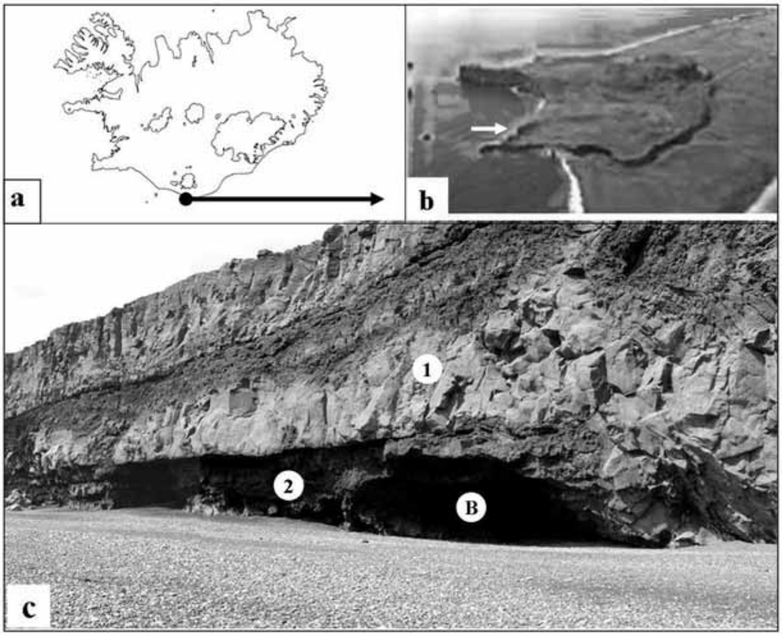

Photo 1. a.) The situation of Dyrhólaey at the southernmost point of Iceland b.) Oblique aerial view of Dyrhólaey taken from the East. On the right side of the picture there are offshore bars which connect the former island with the mainland. The white arrow shows the place where the photo of section "c" was taken c.) An approximately 60 m long section of the southern cliff of Dyrhólaey with the entrance of the sea cave. Legend: 1: thick pahoehoe lava flows 2: the lava delta sequence B: the entrance of the sea cave in the lava delta.

At present Dyrhólaey is connected to the mainland by two large offshore bars (Photo 1/b) formed from the abrasion products of the rocks of Dyrhólaey and the surrounding coast. These bars together with Dyrhólaey form a tombolo of polygenetic type (ZENKOVICH 1967).

The Icelandic word “ey” (means island) implies that Dyrhólaey was regarded by the former name-givers as an island.

Dyrhólaey has an area of almost 1.3 km^2, which breaks down into the ocean with 120, 80, 50 and 20 m high vertical abrasion cliffs (Photo 1/b).

The sea cave under examination described below (Photo1) is situated at the southern part of the “island” (Photo1/b), at the bottom of a 20 m high cliff (Photo 1/c), about a 30 m distance from the shoreline and 2-3 m above the average sea level.

THE EVOLUTION OF THE HOST HYDROVOLCANIC LAVA DELTA SEQUENCE OF THE SEA CAVE

At the first stage of the evolution of Dyrhólaey, during the violent surtseyan hydromagmatic eruption, hyaloclastites deposited in great thickness as a result of the magma/water interaction in the hydrovolcanic vent (WHITE – HOUGHTON 2000). At the later eruption stages, because of the growing volcanic edifice, the vent became isolated from the seawater, so the explosions were getting gradually weaker, turning into Strombolian and finally Hawaiian type. As a result of this, at the last stage of the eruption pahoehoe lavas were discharged and reached the shoreline (THORDARSON – HÖSKULDSSON 2006) and there interacted with the seawater. As the basaltic lava flows into the ocean, hydrovolcanic explosions may occur and a lava delta can build up encroaching upon new areas in the ocean (MATTOX – MANGAN 1997, SCHMIDT – SCHMINCKE 2000).

My field observations suggest that the examined sea cave at Dyrhólaey is likely to have formed in a hydrovolcanic lava delta sequence of the abovementioned kind. In the area of the lava delta, depending on the amount of seawater infiltration into the evolving lava delta sequence, where the pahoehoe flows only meet small amount of water compact lava layers formed, while in another part of the lava delta, where the pahoehoe flows, meet larger amount of seawater, the ensuing hydrovolcanic explosions produced fragmented hyaloclastite deposits. After some time, in particular places of the lava delta, the hyaloclastite layers and the compact lava layers piled up in an alternate sequence. In the last stage of the eruption this lava delta sequence got covered with thick pahoehoe lava (Photo 1/c).

After the formation of Dyrhólaey, the rocky cliffs of the island started to retreat because of the abrasive agents of the ocean. The rate of abrasive destruction can be inferred from the example of volcanic island Surtsey of the same origin as that of Dyrhólaey, which has decreased in size by almost half (from 3 to 1.5 km^2) as a result of sea abrasion since its creation in 1967 (GU& MUNDSSON – KJARTANSSON 2007). Because of the recess of the sea cliff, the alternating layers of compact lavas and hyaloclastites in the lava delta sequence revealed where the sea abrasion operated with greater efficiency, compared to the surrounding cliffs material, and quarried a sea cave into it.

THE MORPHOLOGY OF THE SEA CAVE

The examined sea cave’s length is 21.3 m. The entrance is 16.4 wide, and 2 m high. The width of the cave’s passage gradually narrows inward to 3 m, but in its inner room the cave hollows out to 8 m in width and 4.4 m in height. The longitudinal axis of the sea cave is almost perpendicular to the direction of the cliff face.

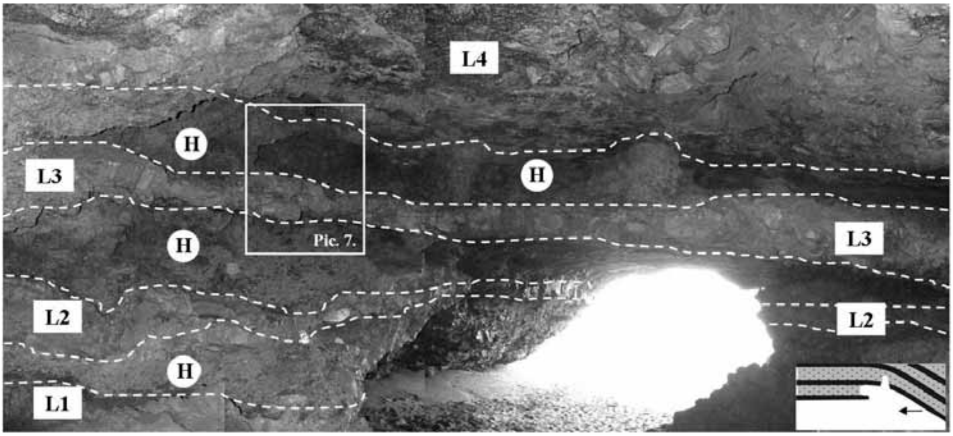

Photo 2. The interior view of the sea cave form inside. The picture was taken looking at the entrance at a view angle of 145 o. The different lava layers (L1-L4) and hyaloclastite layers (H) are bordered by broken lines. The white frame shows the place where Photo 7 was taken. In the lower right corner of the picture, there is a schematic longitudinal cross section (see in Fig. 1), where the black arrow shows the direction of the picture's view.

On the cave's sidewalls the dark grey compact lava layers (Pic.2, 3, 4, 7) are clearly distinct from the interbedded hyaloclastite layers (Pic.2, 3, 7) of light brownish colour, which colour is given by the light brown detritus between the originally dark grey hyaloclastite particles. These layers of different structure built up an alternate sequence in the body of the host lava delta (Photos 2, 3, 7).

In the cave there are 4 layers (L1-L4) revealed out of the compact lava layers of the lava delta, in a thickness of 10-15 cm on average (Photos 2, 3). These flat (in some places undulating) lava layers dip inwards the cave in 10, 15, 20^{o} on average, and they are divided by joints due to cooling and contraction. Two different lava layers comprise the roof of the cave (L3, L4) (Photos 2, 3, 4). The 3rd lava layer from the bottom (L3) comprises the roof of the first narrow passage section of the cave (Photos 2, 3) in a dip angle of 15^{o}. The upbreaking of the 3rd lava layer (L3) revealed the 4th lava layer (L4) (Photos 2, 3, 4), which now comprises the roof of the spacious inner room of the cave in a dip angle of 10^{o}. The same lava layer (L4) gradually inclines down in a dip angle of 35^{o} towards the cave's ending, and terminates it where the layer reaches the bottom (Photo 4; section 6, Fig. 1).

The cave reaches its maximum height (4.4 m) at the chimney, which opened in the roof that comprises lava layer (L4). At its opening the chimney's diameter is 0.8 m, and it reaches up as high as 1.5 m (Photo 5; section 6, Fig 1; section c, Fig. 2).

Where the abrasion eroded the slack scoria layers away, the bedding planes of the lava layers that comprise the roof revealed. As a result of this, flow wrinkles came to sight in a bottom-view of lava layer L3 (Photo 6). The good state of preservation of these flow wrinkles proves an earlier loose connection between the hyaloclastite and the overflowing lava layer.

Between the compact lava layers the interbedded hyaloclastite layers have a rather slack structure and their material can easily be broken by hand. Because of the slack structure of the hyaloclastite layers, the abrasive forces easily quarried hollows into them, between and parallel with the compact lava layers, in a height of 0.5-1 m and depth of 0.2 – 1.8 m (Photos 3,7).

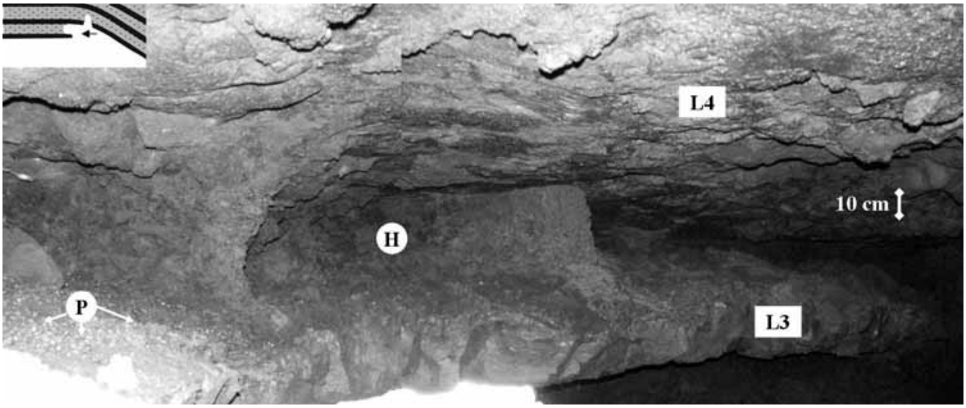

Photo 3. In the interbedded hyaloclastite layer (H), between the lava layer comprising the roof of the cave's first narrow passage section (L3) and the lava layer comprising the roof of the cave's spacious inner room (L4), the abrasive erosion was more rapid. Having been disrupted by the abrasive agents, lava layer L3 cropped out forming a ledge. Lava layers L3 and L4 diverge towards the cave's interior. It indicates that the former hyaloclastite layer between them was gradually thicker towards the interior of the lava delta sequence. Sign P marks the situation of the abrasion pebbles. In the upper left corner of the picture there is a schematic longitudinal section (see in Fig. 1), where the black arrow shows the direction of the picture's view.

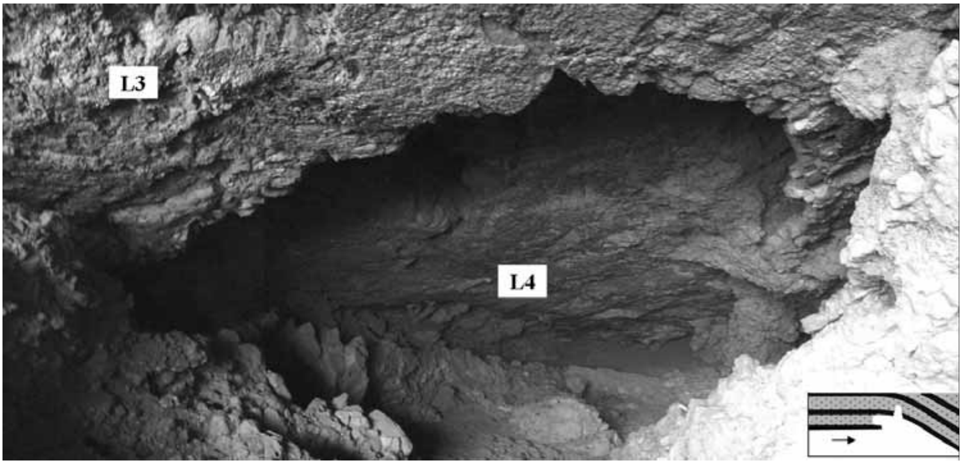

Photo 4. The roof of the sea cave comprises two different lava layers (L3, L4). The cave gradually lowers inwards and finally terminates because lava layer L4 inclines down towards the cave's ending. In the lower right corner of the picture there is a schematic longitudinal cross section (see in Fig. 1), where the black arrow shows the direction of the picture's view.

Because of their better resistance, the compact lava layers cropped out from the sidewalls forming ledges in a width of 0.2-1.8 m (Photos 3, 7). On the surface of the ledge formed from lava layer L3, there are abrasion pebbles (Photo 3, 7), which greatly contributed to the excavation of the loose hyaloclastite cover above layer L3.

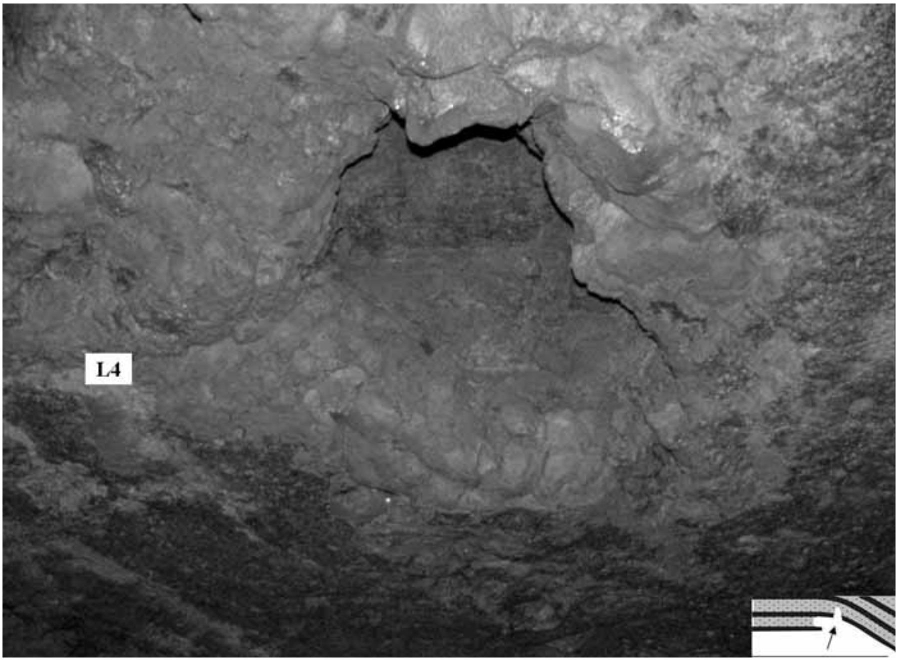

Photo 5. Chimney which was opened by the up-breaking of the roof comprising lava layer L4. At its opening the chimney's diameter is 0.8 m, and it reaches up as high as 1.5 m. In the lower right corner of the picture there is a schematic longitudinal cross section (see in Fig. 1), where the black arrow shows the direction of the picture's view.

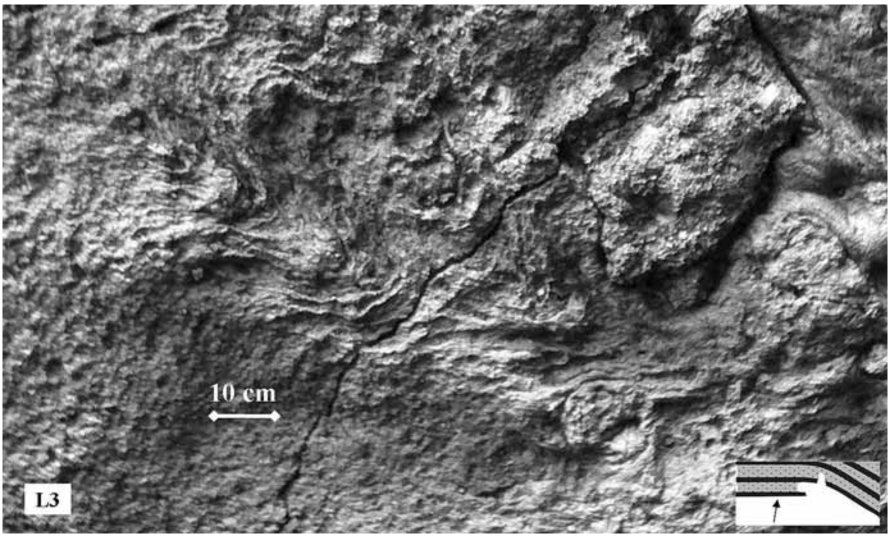

Photo 6. Flow wrinkles in the lower bedding plane of lava layer L3 comprising the roof, which became revealed as a result of the abrasive transportation of the underlying hyaloclastite layer. The good state of preservation of the flow wrinkles proves the loose connection between the lava and the hyaloclastite layer. In the lower right corner of the picture, there is a schematic longitudinal cross section (see in Fig. 1), where the black arrow shows the direction of the picture's view.

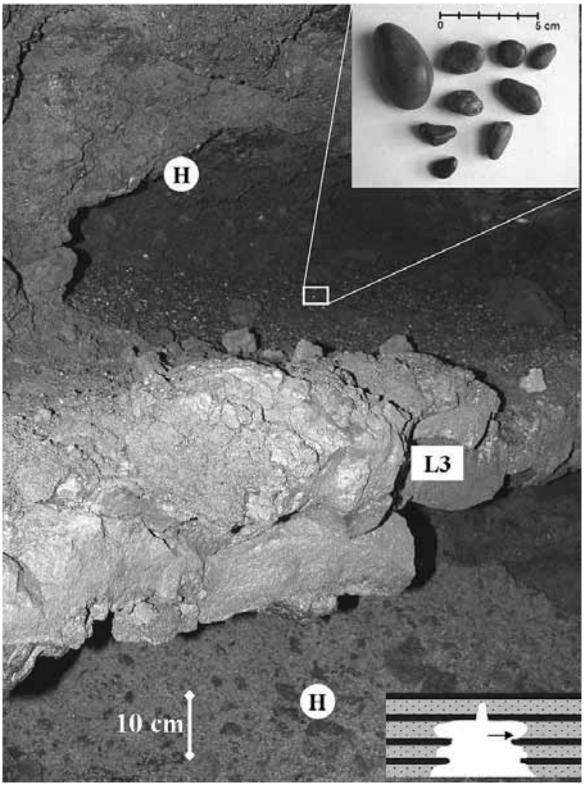

Photo 7. The lava ledge (signed L3 in the picture) was formed by the up-breaking of lava layer L3, which broke in and continued in the host lava delta sequence, and subsequently cropped out from the sidewall as a result of the rapid erosion of the over- and underlying hyaloclastite layers (H). On the surface of the ledge there are abrasion pebbles (see the upper right corner of the picture). In the lower right corner of the picture, there is a schematic cross section (see in Fig. 2), where the black arrow shows the direction of the picture's view.

THE DEVELOPMENT OF THE SEA CAVE

The enlargement of sea caves is particularly rapid during storms or bores, when the storm waves in relatively small time intervals quarry a great amount of material from the cliffs (MOORE 1954). The storm waves can exert a tremendous pressure of 30 tons per square meter on the rocky coasts, which was measured by means of dynamometers (KUENEN 1950).

The evolution process of the sea abrasion cave under examination at Dyrhólaey is detailed below, and can be followed in Fig. 1.

In the beginning of the sea cave formation, an undercut or notch was hollowed, which was enlarging relatively quickly inwards, sideways and upwards in the lower hyaloclastic layer, as high as the overlying compact lava layer was (section 1, Fig. 1; section a, Fig. 2). In this stage of sea cave development the particles slid and rolled by the waves play an important role in widening and lengthening the notch. These abrasive agents subsequently cause a greater width at the bottom of the sea cave (MOORE 1954). The compact lava layer comprising the roof blocked the upward enlargement of the initial cave for a certain time (section 1, Fig. 1; section a, Fig. 2).

However, because of the abrasion of the underlying hyaloclastic layer, causing the cave's further lengthening and widening, the support surface of the lava layer comprising the roof became smaller. It resulted that this lava layer-roof was becoming more and more unstable. The instability was also increased by the lava layer's already existing and new-formed joints and the lava layer's local thin sections revealed by the lengthening and widening of the cave. The seawater rushing into the low and wide cave exerted a great abrupt pressure on the weaker lava layer-roof from below. At the same time, the compressed air having got squeezed in between the seawater and the lava layer-roof pushed into the cracks and joints of the roof. It resulted in a wedging action that broke the blocks of the lava layer-roof apart (section 2, Fig.1). As the wave receded, the compressed air was allowed to escape with an explosive violence, which loosened and carried away the roof's broken material (KUENEN 1950, MOORE 1954, RAMPINO 1982, SUNAMURA 2000). As a result of this process, a considerable part of the slack-structured hyaloclastic layer overlying the former lava layer-roof also collapsed (section 3, Fig.1).

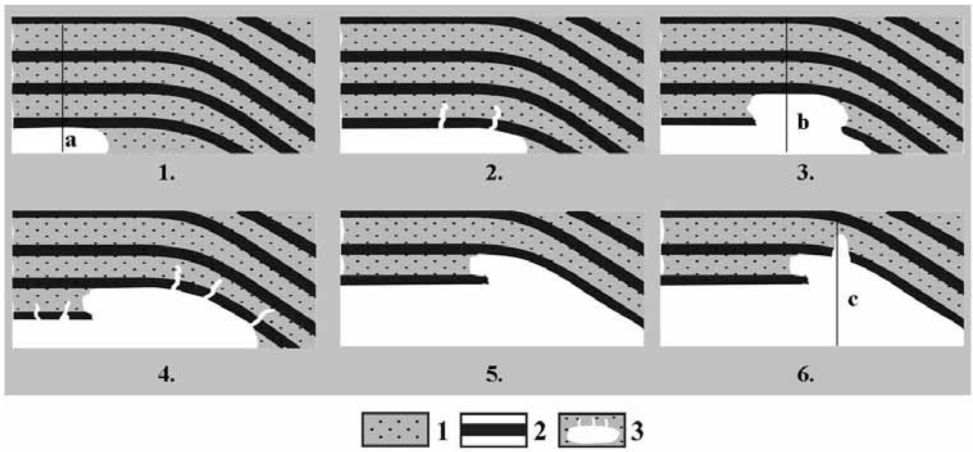

Figure 1. Series of schematic longitudinal sections (1-6) perpendicular to the cliff face demonstrating the development of the sea cave. Legend: 1. hyaloclastite 2. compact lava layer 3. growing sea cave.

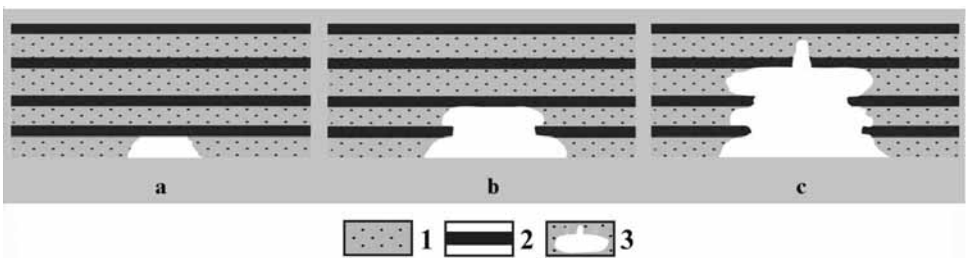

Figure. 2. Series of schematic cross sections (a, b, c) parallel with the cliff face demonstrating the development of the sea cave. Legend: 1. hyaloclastite 2. compact lava layer 3. growing sea cave.

Thereafter, in the revealed hyaloclastic layer, the cave enlarged again relatively quickly, inwards, sideways and upwards. The hyaloclastic layers eroded away more rapidly than the compact lava layers, so the compact lava layers cropped out forming ledges reaching into the cave in 0.2-1.8 m (Photos 3, 7; section b, c, Fig.2). On the wider ledges, abrasion pebbles deposited which probably greatly contributed to the excavation of the loose hyaloclastic layers (Photos 3, 7).

The relatively rapid inward, sideway and upward enlargement continued until it reached the subsequent overlying compact lava layer, which then became the new roof of the growing sea cave (sections 4, 5, Fig.1).

The process described above took place several more times, while the cave's interior became more spacious than the initial passage section (sections 4, 5, 6, Fig. 1; sections b, c, Fig. 2), which was caused by the following reasons:

1. The invading seawater entirely filled the initial passage section up to its roof. It resulted that the compressed air in the cave's interior could not "escape" through the entrance, but pushed into the joints of the sidewalls and the roof of the cave's inner room.
2. The loose hyaloclastic layers in the inner part of the examined alternating lava delta sequence are thicker (Photo 3), while the lava layers are thinner. This caused more efficient erosion in the inner part of the lava delta sequence than in the outer part, because of which the inner room of the cave became larger.

Between the loose hyaloclastite layers the intercalated compact lava layers braced and stabilized the sea cave's roof and sidewalls, and prevented them from collapse (Photos 2, 3, 7; sections b, c, Fig. 2).

If the amount of seawater invading the gradually growing sea cave does not change with time, the pressure exerted by the seawater is distributed on a greater area on the walls of the cave. As a result of this, the sufficient pressure needed for the effective erosion can only exist in storms or bores, when the amount of the invading seawater considerably increases.

The growth of the sea cave was slowed down by the inclining lava layers (Photo 4; sections 5, 6, Fig.1). At present, the ending of the cave comprises the resistant lava layer L4 (Photo 4.). This layer resisted the invaded seawater, whose energy had already been dissipated in the widened beach area on which it had flowed across from the shoreline.

The bottom of the cave's entrance is situated 1-2 m above the average level of the ocean, in a distance of 30 m from the shoreline, with a sandy-pebbly beach between them. The reason for the horizontal and vertical removing of the cave from the ocean might be the isostatic emergence caused by the rapid melt of the surrounding ice caps (EINARSSON 1994), and the deposition of the transported abrasion products derived from the rocky segments of Dyrhólaey and the nearby coasts as well (Photo 1/b).

CONCLUSIONS

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:

1. 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 lava layer L4 (Photo 5).

2. Rather thick hyaloclastite layers, in which the effective and rapid excavation of the sea cave took place.
3. 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 that 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 that remained in the sidewalls after the layer's up-breaking, and subsequently cropped out in some places forming ledges.

The further lengthening of the sea cave was probably blocked by the resistant lava layer L4, which inclines down towards the cave's ending, where it reaches the cave's bottom.

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