TOWARDS UNDERSTANDING THE STRUCTURE OF KAUMANA CAVE, HAWAII

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Abstract

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

Introduction

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

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

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

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

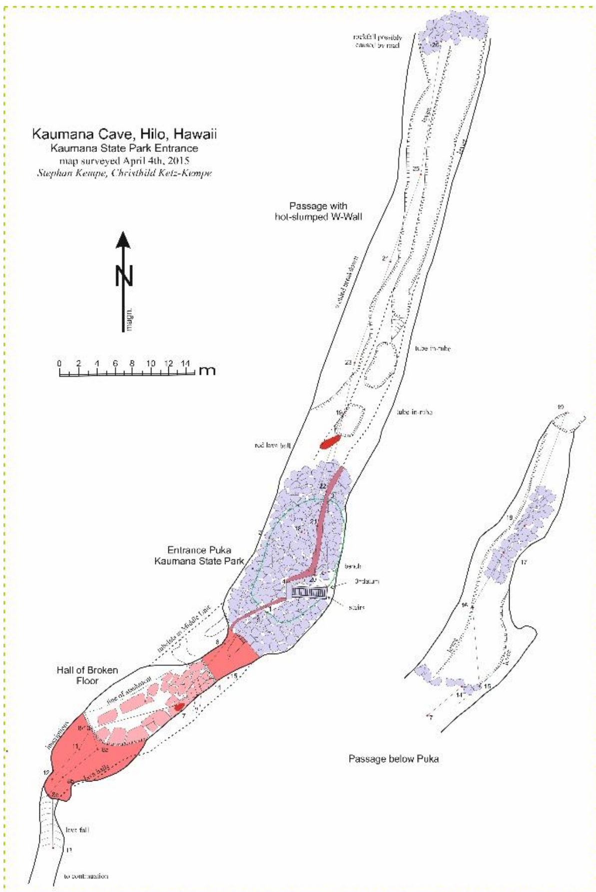

Figure 1.

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

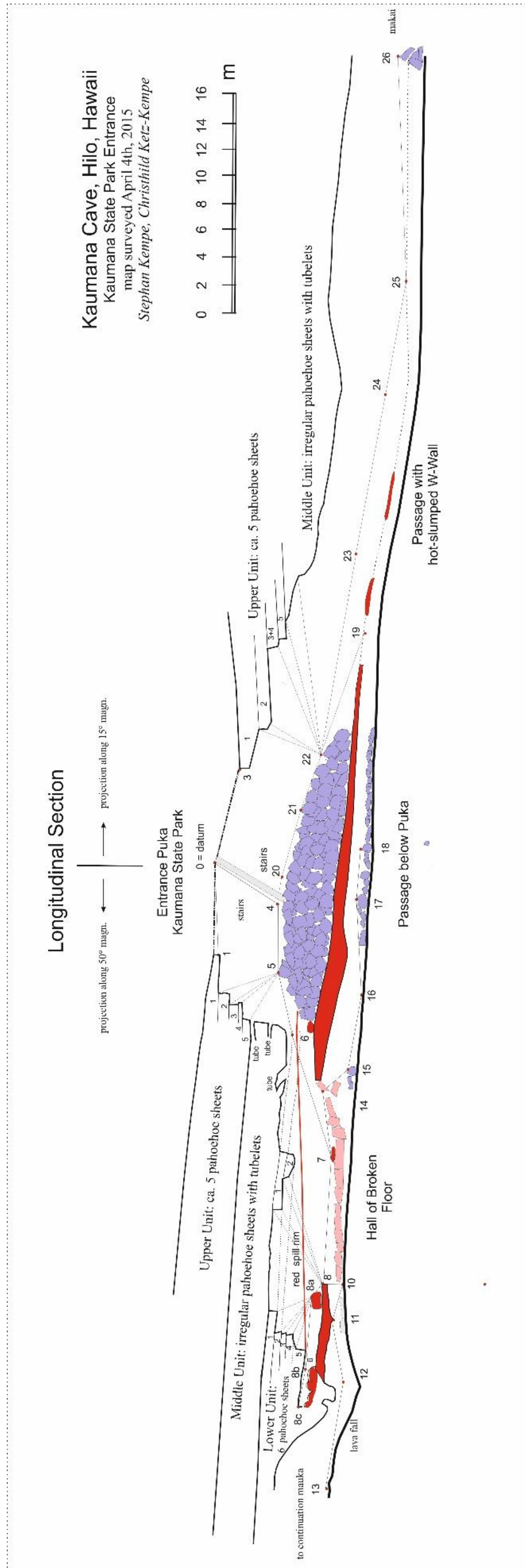

Figure 2.
Longitudinal section of of Kaumana Cave in the vicinity of the County Park Entrance. Colors as in Fig. 1.

Stratigraphic analysis of the Kaumana Entrance profile

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

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

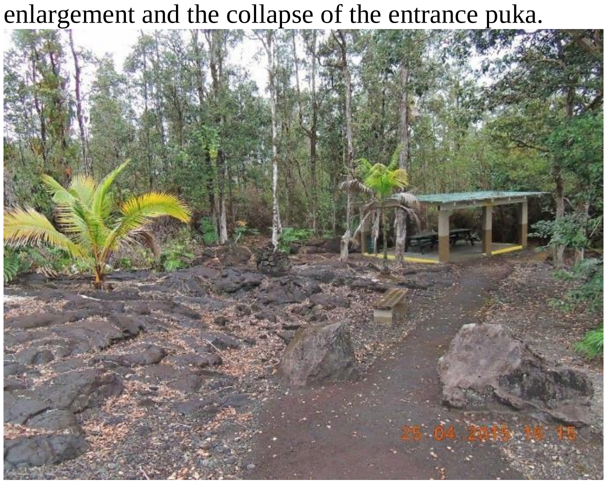

Figure 3.
Surface pāhoehoe sheets of the Upper Unit around the entrance of Kaumana Cave.

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

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

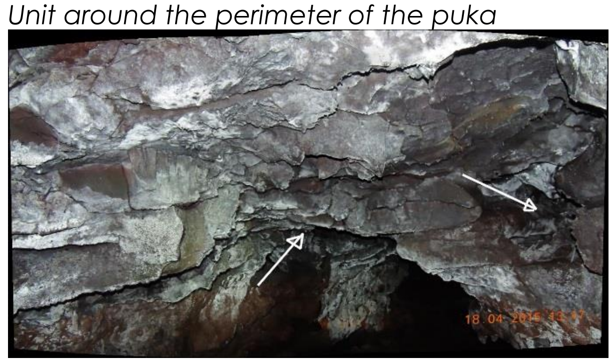

Figure 5.
Panorama view of the irregularly structures Middle Unit mauka at St. 6. Tubelets marked by arrows.

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

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

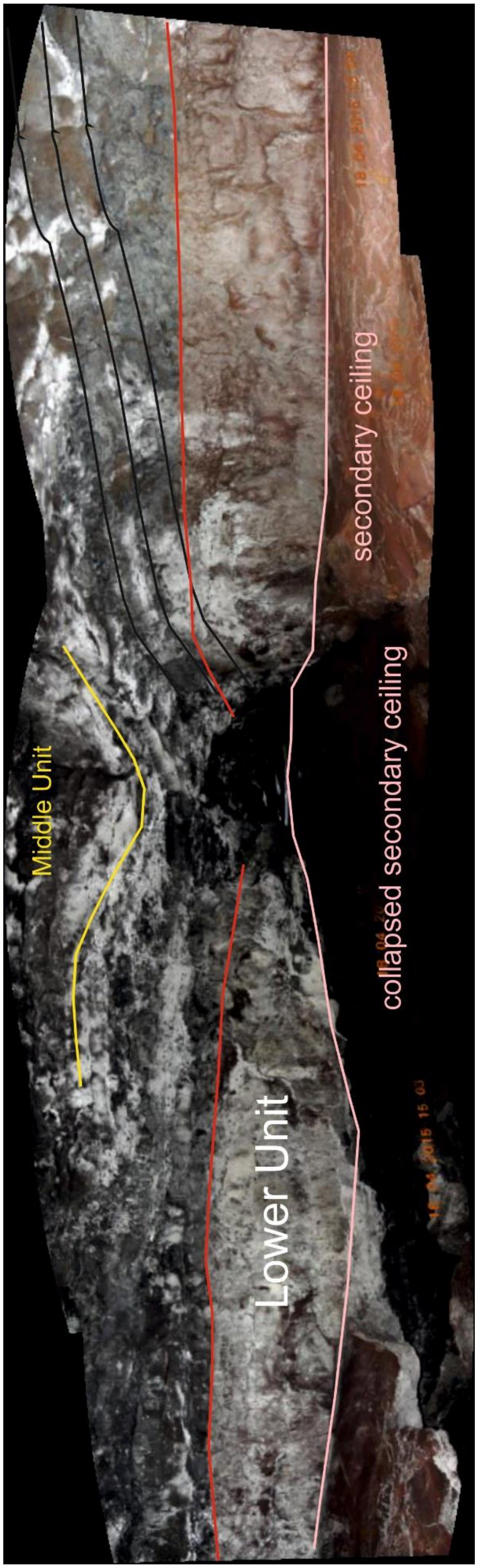

Figure 6.
Makai view of the "Hall of the Broken Floor" (HBR). Note the steeply inclining sheets of the primary roof (Lower Unit; black lines), underlying the Middle Unit (yellow line). Note also the horizontal spill rim of oxidizes red lava above the secondary ceiling that is collapsed in the center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

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

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

Reconstructing the events forming the present cave

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

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

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

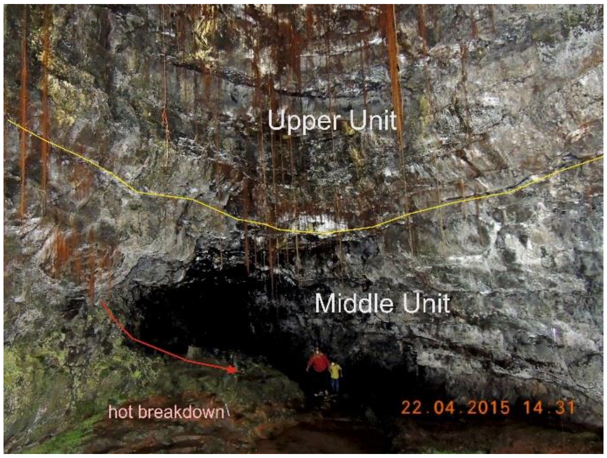

Figure 7.
View makai of the Entrance Puka into the main passage of Kaumana. The cave has been enlarged upward by collapses of the Upper Unit and the Middle Unit. Breakdown blocks from the left wall forced the flow in the cave to the right side, some of them were not only welded but also covered by the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

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

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

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

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

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

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

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

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

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

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

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

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

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

Observations beyond the surveyed section

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

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

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

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

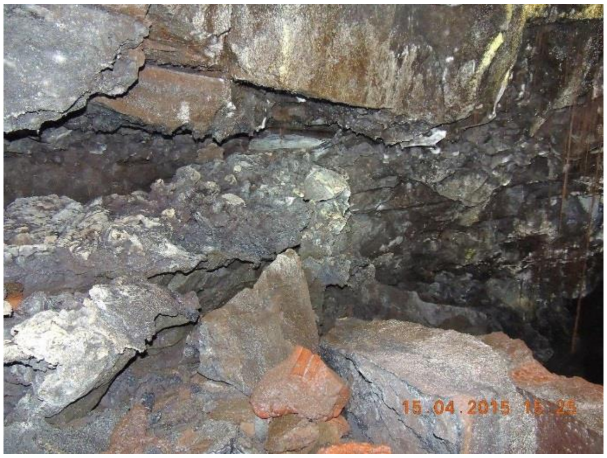

Figure 15.
Outcrop of ʻaʻā rubble behind the collapsed lining near St. 26.

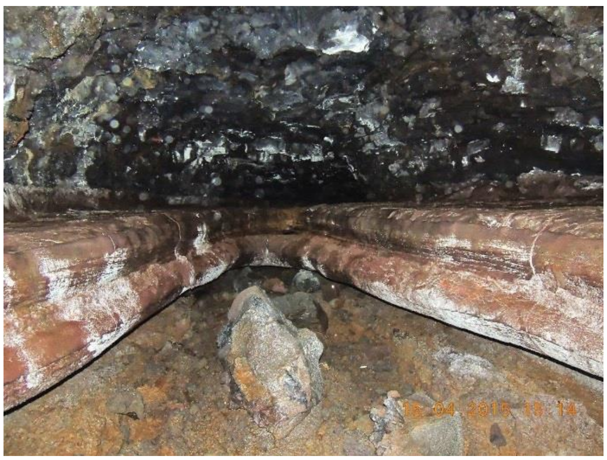

Figure 16.
Closure of secondary ceiling makai of surveyed section.

Reconstructing flow rates

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

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

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

Conclusions

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

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

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

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

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

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