THE “CUEVA DEL VIENTO” ON THE CANARIES, SPAIN

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Abstract

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

Introduction

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

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

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

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

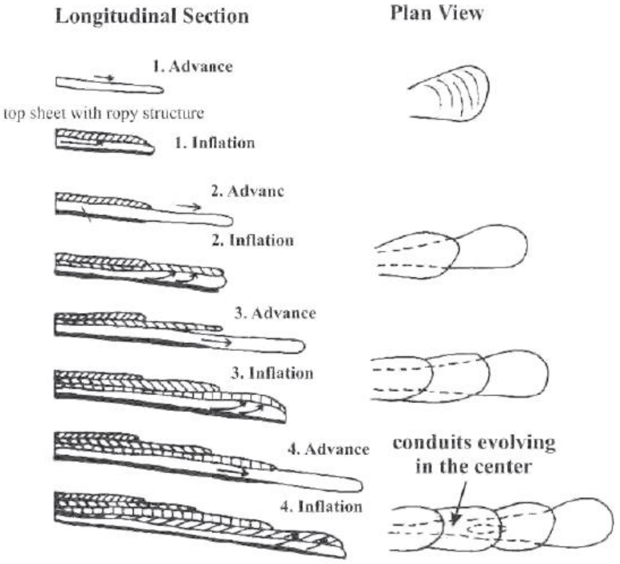

Figure 1: *Many cycles of advance and inflation establish the primary pyroduct roof (Kempe, 2009).*

Study Site

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

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

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

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

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

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

Methods

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

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

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

Results

The cave´s internal structures

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

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

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

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

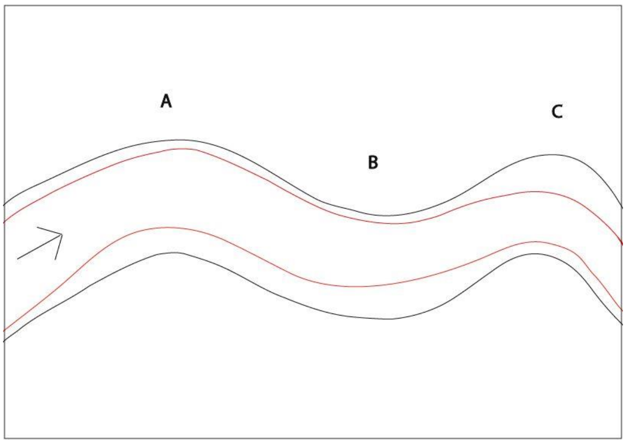

Figure 3: *Accretion due to centrifugal force (A), inertia (B) and meandering (C). The red line shows the line of lava accumulation. At A, in a wide curve, the lava aggregates in the convex side and erodes the concave side. In B, when wide curves follow each other, inertia dominates the accretion processes,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

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

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

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

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

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

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

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

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

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

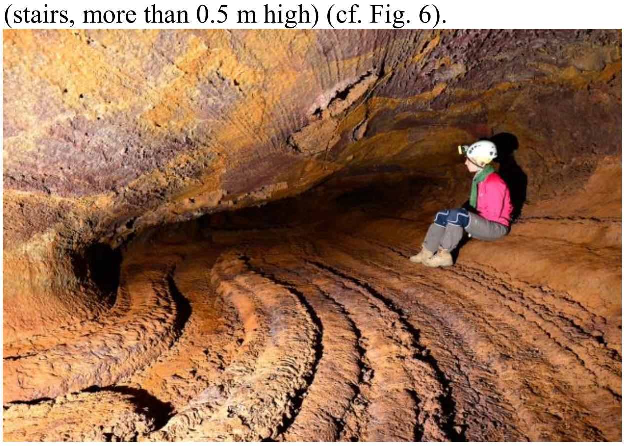

Figure 6: *This view depicts several features: the cooling flow left a series of low levees on the floor (right and left) and the last moving lava formed a low lava tongue (a"lengua"; lower left). At the ceiling small eruptive rings are seen caused by gas that accumulated behind the viscous glazing until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

Petrographical composition

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

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

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

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

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

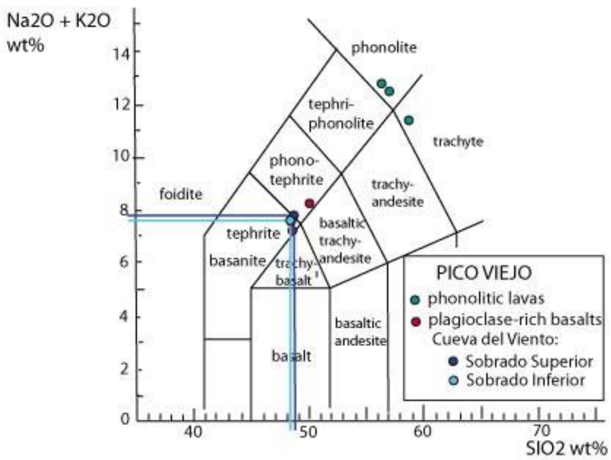

Figure 8: *Position of the Sobrado Superior and Inferior samples in the TAS diagram in comparison to the determination by Carracedo (modified after Carracedo, 2008).*

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

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

Discussion

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

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

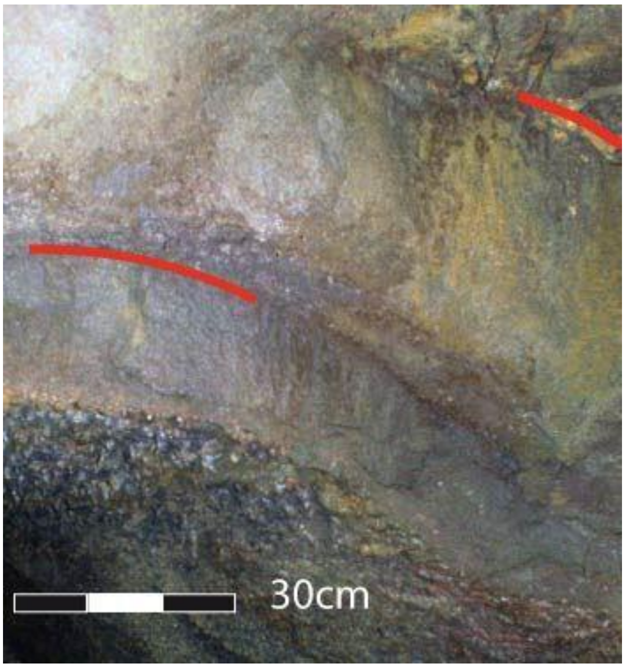

Figure 9: *View of the primary roof exposed by breakdown. Visible are the three lowest sheets of an inflationary primary roof. The sheets are separated by shear planes. (photograph taken in September 2014).*

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

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

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

Perspective

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

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

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

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