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Venezuelan sandstone caves: a new view on their genesis, hydrogeology and speleothems

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ABSTRACT

Caves in arenites of the Roraima Group in Venezuela have been explored on the Chimantá and Roraima plateaus (tepuis). Geological and geomorphological research showed that the most feasible method of caves genesis was the winnowing and erosion of unlithified or poorly lithified arenites. The unlithified arenitic beds were isolated by well-cemented overlying and underlying rocks. There is a sharp contrast between these well-lithified rocks and the loose sands which form the poorly lithified to unlithified beds. They are only penetrated by well lithified pillars originated by vertical finger flow of the diagenetic fluids from the overlying beds. Such finger flow is only typical for loose sands and soils where there is a sharp difference in hydraulic conductivity. The pillars exhibit no signs of further dissolution. The caves form when the flowing water accesses the poorly lithified beds through clefts. Collapse of several superimposed winnowed-horizons can create huge subterranean spaces. Futher upward propagation of the collapses can lead to large collapse zones which are commonly observed on the tepuis. Dissolution is also present but it probably plays neither a trigger role, nor a volumetrically important role in the cave-forming processes. The strongest dissolution/reprecipitation agent is condensed air moisture which is most likely the main agent contributing to growth of siliceous speleothems. As such, it can be active only after, but not before the cave is created. Siliceous speleothems are mostly microbialites except for some normal stalactites, cobweb stalactites and flowstones which are formed inorganically. They consist of two main types: 1. fine-laminated columnar stromatolite formed by silicified filamentous microbes (either heterotrophic filamentous bacteria or cyanobacteria) and 2. a porous peloidal stromatolite formed by Nostoc*-type cyanobacteria. The initial stages of encrusted shrubs and mats of microbes were observed, too, but the surrounding arenitic substrate was intact. This is strong evidence for the microbial mediation of silica precipitation.*

Keywords: speleology, tepuis, Venzuela, sandstone caves, siliceous speleothems, microbialites, cyanobacteria, stromatolites, hydrogeochemistry.

1. INTRODUCTION

Caves are common in limestone terrains. Karstic phenomena can easily evolve in limestone or other rock materials with good solubility, e.g. gypsum. Most definitions of karst use dissolution as the main factor that determines the true karstic processes. Solubility of silicate rocks is generally very low and caves which formed in silicate rocks are often attributed to pseudokarst, because most workers believe that mechanisms other than dissolution play the main role in their formation. Tectonic phenomena (fracturing, faults, etc.) are considered as the main factors. However, in the recent past, several publications have applied the term karst to silicate caves that occur either in granites (WILLEMS et al., 2002; VIDAL ROMANÍ & VAQUEIRO RODRIGUES, 2007) or, more frequently, in sandstones (see the reviews in WRAY, 1997b, 1999). According to these authors, dissolution, although slow, is the main process that forms the caves. For sandstone rocks, the term "arenization" was introduced by MARTINI (1979). This term involves both the dissolution of cements in the arenitic rocks, together with the subsequent erosion and winnowing of the loose sand material. If the "arenization" theory was true, most of the sandstone caves could really be attributed to karst as dissolution is considered there to be trigger process of the cave formation. The main proof that dissolution is important in silicate caves are silica speleothems which occur in most of the silicate caves. They are mostly composed of opal-A (cf. AUBRECHT et al., 2008), which slowly turns to opal-CT and then to microquartz (chalcedony). The question remains, whether silica dissolution is so important that the silicate caves can really be ranked among the karstic ones. Initial results of several speleological and scientific expeditions to the Venezuelan Gran Sabana, where large caves evolved in the sandstone plateaus called tepuis, are presented. Tepuis are the key area where sandstone "karstic" phenomena can be studied and where the term "arenization" is widely used (e.g. URBANI, 1986). Alternative views on the genesis of sandstone caves are presented here, based on geological, geomorphological, hydrogeochemical and speleological observations.

2. GEOLOGICAL SETTING AND THE CAVES STUDIED

The studied area is located in the Venezuelan Guayana of northern South America (southeastern Venezuela, Bolivar State), in "the corner" formed by the borders of Guayana to the east and Brazil to the south (Fig. 1).

The wider area of the Gran Sabana is built up by rocks of Guiana Shield which represents the northern segment of the Amazonian Craton in the South America. It covers an area of nearly 900,000 km^2 between the Amazon and Orinoco rivers (CORDANI et al., 1988, in VOICU et al., 2001) and underlies the territory of five countries (Venezuela, Guyana, Suriname, French Guiana and Brazil).

The tepuis are formed by the rocks of the Roraima Supergroup, consisting principally of sandstones derived from the Trans-Amazonian Mountains to the north and deposited in braided, deltaic, and shallow-marine environments (REIS et al., 1990, in SANTOS et al., 2003) in a foreland basin. The supergroup mostly forms tabular plateaus, cuestas and hogbacks that abruptly rise above the Palaeoproterozoic basement. Its thicknesses ranges from 200 m to ~3000 m. Local sedimentological studies show that depositional environments range from alluvial fans to fluvial braided deposits plus lacustrine, aeolian, tidal, shallow-marine deposits and some shallow water turbidites (REIS & YÁNEZ, 2001; SANTOS et al., 2003), although sandy continental deposits predominate. The supergroup is composed (from the bottom to top) of the following units (formations): Arai, Suapi (Uiramută, Verde, Pauré, Cuquenán, Quinô), Uaimapué and Mataui (REIS & YÁNEZ, 2001). The tepuis developed mainly within the uppermost of these – the Matauí Formation. The best age estimate for all but the uppermost Roraima Supergroup is 1873 ± 3 Ma, determined by U-Pb analyses of zircons from a green ash-fall tuff of the Uaimapué Formation (SANTOS et al., 2003).

Figure 1: Location of the studied table mountains.

The history of discovering and documenting the sandstone caves in the tepuis began in 1971 when Brewer-Carías led the first expedition to Cerro Autana (BREWER, 1972, 1973, 1976; COLVEÉ, 1973). Later he also led the multidisciplinary expedition that explored and discovered the abysses (simas) and caves in the Sarisariñama Massif (BREWER, 1973; SZCZERBAN & GAMBA, 1973; SZCZERBAN & URBANI, 1974; BREWER, 1974). Later, quartzite caves in Auyán Tepuy were documented by PICCINI (1995). The longest sandstone cave system, Ojos de Cristal was recently discovered in 2002 on the Roraima Tepui (ŠMÍDA et al., 2003). In the same year, the volumetrically largest sandstone cave was discovered in the Chimantá Tepui – Cueva Charles Brewer (ŠMÍDA et al., 2005a, b). The last two caves, together with smaller caves later discovered in Chimantá – Cueva Cañon Verde, Cueva de Arañas and Cueva Bautismo del Fuego are the subject of the present study. Simultaneously, surface weathering phenomena have been studied on the Chimantá, Roraima and Kukenán tepuis.

3. METHODS

The geological and speleological observations were focused on the differential weathering of various sorts of arenites of the Matauí Formation on the tepui surfaces and in the caves.

Four sites with different lithification and erosion phenomena in arenites were sampled in detail for petrographic analysis (thin-sections and SEM), the results of which will be published later. Sampling of siliceous speleothems was equally important. A limited number of samples were collected for study by petrographic thin-sections, to prevent excessive damage to the speleothem decoration of the cave. Fresh speleothem surfaces in growth position, as well as surfaces of broken speleothems (some etched by hydrofluoric acid), were coated with a thin gold film and observed in a JEOL JXA 840 A scanning electron microscope, with an accelerating voltage of 5 kV. The mineralogical composition of the speleothems was determined optically and by X-ray diffraction analysis (XRD). Analyses were performed with a DRON-3 analyser, using $Co_{K\alpha}$ of the wavelength λ: 1.79021 Å, filter Fe, voltage 30 kV, intensity 15 mA, diaphragms 1;1;0.1, or $Cu_{K\alpha}$ of the wavelength 1.54178 Å, filter Ni, voltage 40 kV, intensity 20 mA, diaphragms 1;1;0.5.

Speleothem surfaces were also sampled for microbiological analyses by scraping with a sterilized knife. Part of the samples were fixed in agar for further cultivation (about 20 samples – results not included); and about 40 samples were fixed in formaldehyde (for microscopic observations only).

The hydrogeochemical fieldwork consisted of sampling, field parameter measurements and colourimetric analyses. Part of the samples (in 50 ml quantities) were used for colourimetric analyses performed the same day in the base camp, the next part (15 ml) was sealed in plastic containers and transported to Slovakia for further determination of $\delta^{18}O$ and $\delta^{2}H$. Samples were filtered in situ using a filter with mesh diameter of 0.45 μm. Every sample was doubled. The field parameter measurements consisted of pH and electric conductivity (EC). At the beginning, acidity and alkality measurements were made by titration, but all the measured amounts were below the detection limits of these methods, therefore, this method was later abandoned. For colourimetric analyses, the Merck Spectroquant Multy portable colourimeter was used. The following parametres were measured: Fe, SiO_2–Si, Al, PO_4^{3}–P, NO_3–N.

4. RESULTS AND INTERPRETATIONS

4.1. Genesis of the sandstone caves

In the studied caves, erosion and rockfalls are the most obvious and recent evidence of their formation rather than dissolution (Pl. I, Fig. 1). The sandstone beds have angular edges; the caves are full of fallen angular blocks. The signs of dissolution e.g. smooth edges of sandstone beds or bizarre patterns formed by etching (Pl. I, Fig. 2) are too rare to explain the recent stages of the caves evolution. However, to be ranked among karstic features, prevalence of dissolution is not required; the most important factor is its role as a trigger of cave genesis. The question then remains, what was the trigger factor, which determined how the sandstone caves in the tepuis originated and the place where a cave can be formed? Observations of surface geomorphology of the tepuis and the subterranean spaces provide some clues. The sandstone surfaces of the tepuis are very bizarre, due to the very inhomogeneous lithification of the Proterozoic arenites, which is obvious from initial observations. This is especially visible in the places where the arenite bed forms overhang (Pl. I., Figs. 3–6). The overlying and underlying beds are hard, well-lithified rocks, forming sandstones to quartzites (difficult to sample with a hammer, requiring a lot of force). However, the beds in between are only slightly lithified or completely unlithified, being soft sandstones to sands (it was not possible to take any lithified sample for petrographic microscopic study, even digging using hands up to 30 cm below the surface). These very weakly lithified beds are divided up by perpendicular pillar-shaped bodies, narrower in the middle part, but widening, funnel-like towards the top and bottom, with the lower funnel usually less developed. These are again well-lithified (sandstones to quartzites). This combination of overhangs and pillars forms the dramatic decoration of most of the tepuis surfaces (Pl. I, Figs. 7–8). The origin of these structures can be interpreted as being purely diagenetic. The mean factor influencing the diagenetic variability is the sediment grain size, which influences its hydraulic conductivity. The diagenetic fluids most likely penetrated vertically from the overlying strata. In finer-grained sediments the diagenetic fluids filled the intergranular spaces evenly and thus formed diagenetically well-lithified beds, resistant to weathering. If a coarse-grained arenite with higher hydraulic conductivity occurred below a fine-grained bed, a process named "finger flow" started, i.e. the fluid flow accelerates due to gravity and is divided into separate, finger-like flows. This process has been described in detail by various authors working with transport processes in the unsaturated zone of sandy aquifers and soils (e.g. BAUTERS et al., 1999; LIU et al. 1994). According to LIU et al. (1994), if these finger flows are generated in originally dry sandstones they are conserved as preferential pathways for infiltrating solutions. This is how the pillars originated in the unlithified sands. The upper, narrowing downwards funnel shape of the upper part of the pillar originated from acceleration of the flow, until it was slowed down when it reached the less permeable bottom. This slowing-down is displayed by the reversely oriented funnel shape of the pillar bottom.

The poorly lithified beds form distinct horizons in the tepuis geomorphology. They can be traced and correlated laterally for long distances. The overlying and underlying beds protect the unlithified sand from rainfall but they are easily eroded when accessed by water streams flowing horizontally. When the overlying, protecting beds are weathered, broken, or dissected by clefts water can penetrate as deep as the unlithified beds and a horizontal cave can form. Indeed, our observations show that pillars are present in most of the caves and in their galleries, which are still in the younger stages of their evolution (Pl. II, Figs. 1–2). These usually possess low ceilings and strictly keep to one distinct layer. If several superimposed winnowed horizons evolve, the second, collapse stage follows, leading to formation of much larger subterranean spaces (Pl. II, Figs. 3–4). Relic finger-flow pillars were also observed in the marginal, uncollapsed parts of the larger galleries (Pl. II, Figs. 5–6). In the Cueva Charles Brewer, the galleries are typically 40 metres wide, but can be much larger.

PLATE I

1 Gran Galería de los Guácharos (Cueva Charles Brewer); one of the top ten largest natural subterranean spaces in the world. In its latest evolution it has been shaped by rockfalls which obscur the initial stages of formation.

2 Dissolution pits on an arenitic block in the Cueva Charles Brewer. The dissolution was most likely mediated by microbes.

3–5 Overhanging arenitic beds showing differential weathering due to variable lithification: o – overlying bed strongly lithified quartzite, u – underlying bed of the same lithology, p – strongly lithified quartzite pillars formed by descending finger flows of diagenetic fluids, s – poorly lithified to unlithified sands, h – honeycomb-like weathering of the sandstones.

6 Two superimposed poorly lithified horizons (pale grey) separated by well-lithified quartzites (dark). Increased view of the same as fig. 3.

7–8 Spectacular surface features of Monte Roraima, displaying rows of finger-flow pillars.


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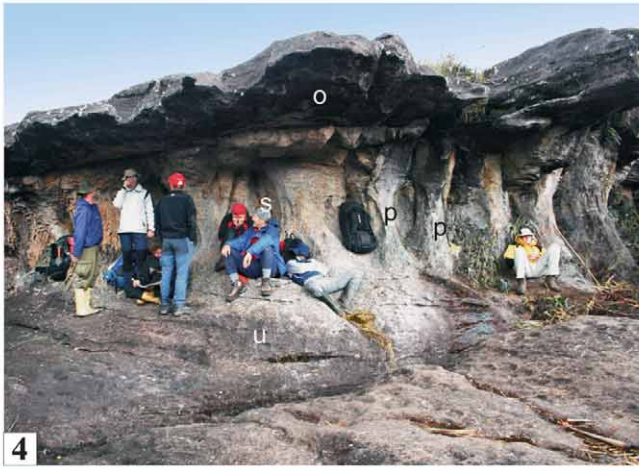

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PLATE II

1–2 Beautifully preserved finger-flow pillars in Cueva Cañon Verde (Chimantá Massif) – an initial stage of the cave-forming process. The unlithified sand has been winnowed; only strongly lithified quartzitic elements remaining. Note the smooth surface of the ceiling, floor and pillars, free of any signs of dissolution, indicating that there was a strong contrast between the lithification of both constituents.

3–4 Galleries of the Cueva de Arañas showing progressive evolution by collapse of the floors between two superimposed winnowed horizons forming a larger cave. The finger-flow pillars are preserved at the margins of the galleries.

5–6 Small-scale finger-flow pillars preserved at the margins of a larger, highly-developed cave (Ojos de Cristal System, Roraima).


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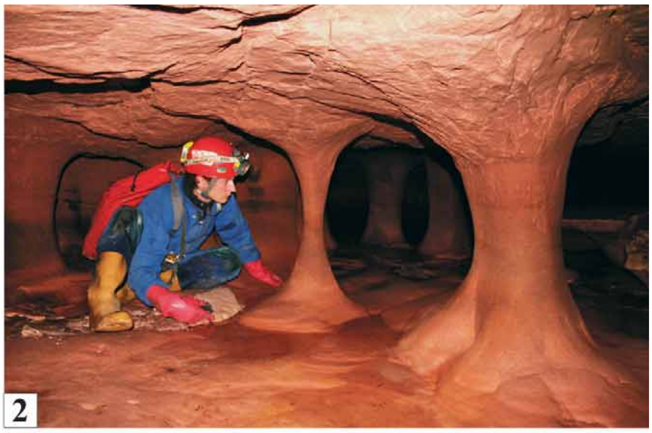
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The largest chamber found in the cave, Gran Galería Karen y Fanny, is 40 metres in height, more than 355 metres in length, and 70 metres wide: a volume of about 400,000 cubic metres. Final stages can lead to huge collapses, which are observable on the tepui surfaces (Pl. III, Figs. 1–2). One of the largest collapse zones separates the Akopán Tepui from the Churí Tepui in the Chimantá Massif (Pl. III, Fig. 3). The whole zone is sunken and the sandstone mass is dissected into large blocks which are variously inclined. Obviously, they were "undercut" by winnowing of the unlithified sand layers and then collapsed. Any other process, like dissolution, arenization (dissolution of cements and release of the sand grains), or weathering, were unable to create such a huge collapse zone. The linear course of this zone betrays the fact that it is related to fault tectonic activity (cf. BRICEÑO & SCHUBERT, 1992), but it could not solely be responsible for the collapse. It is more likely that it just triggered the collapse by enabling drainage of the flowing water and transport of the solid material from the unlithified strata. On the basis of these observations, winnowing of the unlithified or weakly lithified sands, not only plays the triggering role in formation of the sandstone caves in tepuis, but it also influences their subsequent evolution. Although dissolution also occurs there, (as witnessed by the presence of numerous siliceous speleothems), it has a subordinate role as a cave-forming process.

4.2. Hydrogeochemistry of the caves

Water samples were taken from underground streams in caves, as well as from streams, ponds, swamps and springs on the surface. The sampling and field analyses were performed in three campaigns, following the three periods of the expedition. The first campaign performed on the top of the Chimantá Massif, the second inside the Cueva Charles Brewer and the third on the surface and caves of Monte Roraima. Detailed information about the analyses and results is given in LÁNCZOS et al. (2007). Although the extent of the measured parametres was restricted due to the logistics, some conclusions about processes controlling the chemical composition of the water can be presented.

Acidity was only successfully measured in samples taken on the surface of the Chimantá Massif, but other samples are supposed to have very similar pH values. This assumption is supported by the pH values from 3.8–6.5 reported by MECHHIA & PICCINI (1999) based on sampling on the Auyan Tepui. The low pH values are the result of rainwater interaction with the quartzite rock which does not cause significant H^+ cation consumption. The other factor preserving low pH could be the presence of organic acids also indicated by the yellowish colour of the waters on tepuis and carbonic acid originating from decaying organic material in swamps and jungles on the surface of the table mountains. Slightly higher pH values in two samples taken in small swamp ponds (5.48 and 5.64) were presumably caused by carbon dioxide exsolution in the swamp ponds heated by the sun during daytime.

Variations of EC values and SiO_2 concentrations are apparently controlled by water-rock interactions as well as evaporation-precipitation processes. From the EC – SiO_2–Si relationship some differences in values and their ranges are apparent between samples taken on the Chimantá Massif and on the Monte Roraima (Fig. 2). The extent of the EC values is much narrower but the values are slightly higher in the Chimantá samples than in the Roraima samples. However, the SiO_2–Si concentrations are slightly higher in the Roraima samples. One of the explanations of the higher EC values of the Chimantá samples could be a higher concentration of ions as a consequence of rainwater evaporation due to greater average temperatures and probably also less precipitation in comparison with Roraima as a consequence of their different altitudes. The Chimantá Massif is about 400 m lower (the highest point is approx 2500 m a.s.l., the sample locations are approx. 2200–2300 m a.s.l.) than Roraima (more than 2700 m a.s.l.). These differences are more notable in the case of the underground streams. All the samples except one taken in the Cueva Charles Brewer have the same EC values (20 µS/cm); the SiO_2–Si concentrations are from 0.2–0.23 mg/l, while the Roraima underground stream samples show EC values from 10–18 µS/cm and the SiO_2–Si concentrations from 0.73–1.31 mg/l. The explanation of this difference is apparently the varying cave and underground stream morphology. The Cueva Charles Brewer is a straight 4.5 km long cave with a stream of high current velocity, with a more or less U-formed and smooth riverbed. This morphology results in a relatively small water/rock contact zone, the time of the contact is also rather short and has minimum influence on the chemical composition of the water.

The cave system of the Monte Roraima is rather complicated; the water flows in small creeks with slow current velocities, and the river bed is often covered by sand and/or gravel. Samples from the repository lake of the Río Arabopó and the Tuná Deutá spring located below the examined cave system, were also included in the evaluation. A positive correlation exists between the EC values and SiO_2–Si concentrations. The parameters in the Río Arabopó sample are close to the values expected for rainwater. Therefore, we suppose that this lake collects rainwater from the wider drainage area and represents the water source of the cave system. The Tuná Deutá spring sample characteristics are placed at the opposite end of the relationship and, consequently, it may be considered as the output from the cave system. As all the sample characteristics are situated closely around the positive trend line, we assume that the SiO_2 concentrations and the EC values are controlled by the kinetics of SiO_2 dissolution.

The phenomenon of corrosive precipitation can be recognized in the Cueva Charles Brewer of the Chimantá Massif and the Cueva de los Pemones (Ojos de Cristal System) of Monte Roraima. It is displayed as extremely low EC values (6 µS/cm in the Cueva Charles Brewer and 2 µS/cm in the Cueva de los Pemones), and extremely high SiO_2–Si concentrations (3.05, or 2.3 mg/l resp.) in the samples collected from pools fed by dripping water that condensed on the cave walls. The explanation of this phenomenon is that water vapour condensing on the cave wall acts as a strongly undersaturated agent for the dissolution of different forms of SiO_2. The extremely low EC values are caused by the lack of dissociated salts in the water. Almost the only soluble material in quartz-

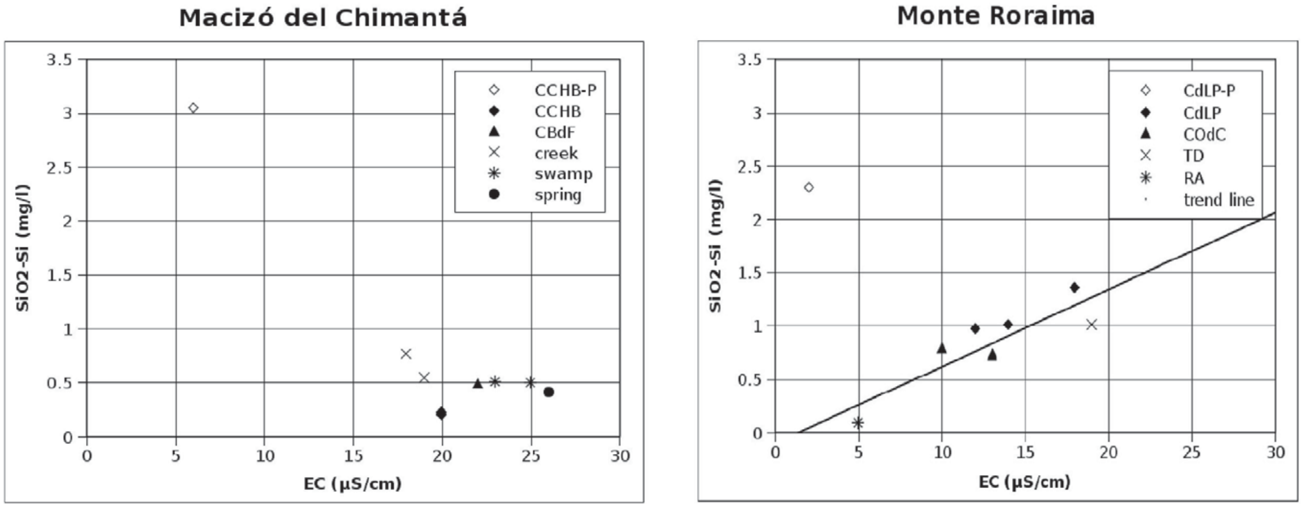

Figure 2: Comparison of EC and SiO_2–Si concentrations and relationships in water samples taken from the Chimantá Massif and Monte Roraima. Abbreviations in the legends: CCHB-P – Cueva Charles Brewer – corrosive precipitation, CCHB – Cueva Charles Brewer, CBdF – Cueva de Bautismo del Fuego, CdLP-P – Cueva de Los Pemones – corrosive precipitation, CdLP – Cueva de Los Pemones, CodC – Cueva Ojos de Cristal, TD – spring Tuná Deutá, RA – Río Arabopó river.

ite is SiO_2 which, when being dissolved under the low pH conditions, exists mainly as the non-dissociated H_3SiO_3 not contributing to the EC. Therefore, the condensed water vapour can be considered as the strongest agent acting on SiO_2 dissolution and reprecipitation. However, as stated in the previous chapter, the dissolution plays a subordinate role in the cave formation, which is also documented by the fact that condensation of atmospheric water vapour can only occur once the cave is already developed.

4.3. Genesis of siliceous speleothems

Caves formed in silicate rocks (including arenitic sediments) are characterized by predominantly siliceous speleothems, in which the dominant mineral is opal. Unlike in carbonate speleothems, microbial mediation is much more common in the precipitation of siliceous speleothems. Siliceous speleothems commonly represent small forms, rarely exceeding 2 cm in size. In all the examined caves, peculiar forms of speleothems were found (see also AUBRECHT et al., 2008). They have various shapes and forms and most of them bear the signs of microbial origin (Pl. III, Figs. 4–6). Many of the speleothems are reminiscent of classical stalactites and stalagmites known from limestone caves, but their structure and genesis are different. Apart from variable shapes, the microbial speleothems show identical principal textures, corresponding to the various stages of their evolution (Pl. IV, Figs. 1–2). They consist of two principal zones: 1. laminated columnar stromatolite, consisting of non-porous compact opal, mostly forming the internal zones of the speleothems, 2. a highly porous zone formed of white chalk-like opal, representing the accumulation of microbial peloids, mostly forming the outer zones of the speleothems. In some speleothems, both zones may alternate.

The columnal stromatolite zone consists of finely laminated layers of pure opal, intercalated with some zones of filamentous microbialite, with thin filaments oriented in the direction of stromatolite growth. SEM study of the etched surfaces of the columnal stromatolite showed that it mostly consists of concentric laminae, formed by dense parallel tubes representing the casts of filamentous microbes (Pl. IV, Fig. 3). The microbes are most similar to filamentous cyanobacteria from the order Oscillatoriales (GOLUBIC, 1976). In other places, irregular, larger-scale, double-layered cross-sections of microbe tubes occur (Pl. IV, Fig. 4). They resemble casts after cyanobacterial cells of the genus *Cyanostylon* or *Entophysalis* (GOLUBIC, 1976).

The zone of peloidal microbialites consists of elongated (mostly ovoid) peloids of relatively uniform shape. They are densely packed, arranged in concentric laminae (Pl. IV, Fig. 5). The size of the peloids varies from 0.1 to about 0.3 mm. Microscopic study revealed that the peloids are formed by *Nostoc*-type cyanobacteria (Pl. IV, Figs. 6–7). Fungal hyphae, metazoan and plant remains also subordinately contribute to speleothem construction. In many places, initial colonization of the surface by *Nostoc*-type cyanobacteria was observed, forming mats and shrubs covering the underlying arenites (Pl. IV, Fig. 8). The microbial filaments are commonly encrusted by white silica, whereas the surrounding arenites are intact. This is strong evidence that the microbes were not only passively encrusted by silica but the encrustation was microbially mediated, either by their metabolism, or by changing physicochemical conditions. This phenomenon is common in limestones but has not previously been evident for siliceous microbialites.

Some speleothems, e.g. the cobweb stalactites (AUBRECHT et al., 2008) represent mostly inorganic precipitates, encrusting various structures, such as spider threads. There are also large inorganically precipitated stalactites (Pl. IV, Fig. 9) and flowstones. Comparing the size of the speleothems from various caves, there seems to be a dependent relationship between cave and speleothem sizes. Cueva Charles Brewer hosts the largest recorded silica speleothems (up to several dm in size) whereas those in other caves were smaller (cm to dm size).

PLATE III

1 Gradual cave collapses can penetrate as high as the surface. Large collapse zone on Monte Roraima (Brazil part, close to the Venezuela/Brazil/Guyana border stone – Triple point). Finger-flow pillars are still visible under the overhangs.

2 A similar large collapse which formed the famous Lake Gladys (Guyana part of Roraima).

3 Large collapse zone between two tepuis of the Chimantá Massif – Churí and Akopán. This collapse zone was probably also influenced by winnowing of poorly lithified sediments.

4 Large microbial speleothem forms called "champignons" are frequently more than 30 cm in size.

5 Erect, stalagmite-like microbial speleothems called *"muñecos"* (dolls) which are from 10 to 15 cm high.

6 White "ice-cream"-like microbial speleothems which are up to 20 cm high (all speleothems figured in this plate are from the Cueva Charles Brewer).


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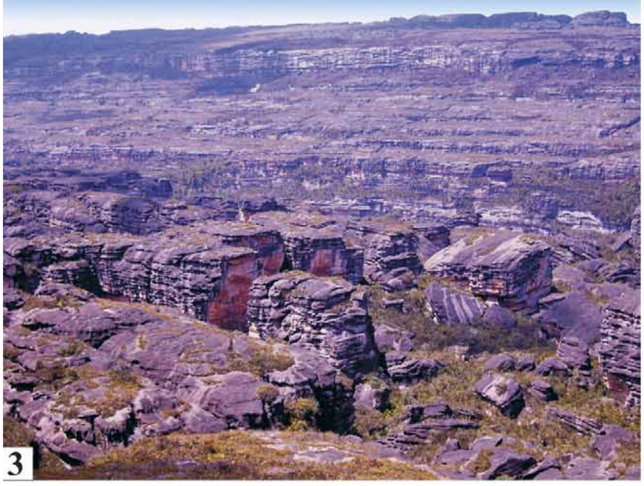
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PLATE IV

1, 2 Slabs of *"muñeco"* (1) and "champignon" (2) from Cueva Charles Brewer showing the common principal inner structure of all the erect speleothem forms, consisting of the columnal stromatolite (c) forming mostly the inner zones, covered by white, chalk-like peloidal layer (p). The scale is valid for both pictures.

3 Etched columnal stromatolite showing longitudinal cross-sections of the encrusted mat of filamentous microbes. On the inner sides of some tubes there are remains of regular septae (arrow), indicating that the filaments were sectioned.

4 Irregular double-layered cross-sections of tubes likely representing casts after microbes similar to cyanobacteria *Cyanostylon* or *Entophysalis*.

5 Concentric laminae of peloids in the peloidal zone.

6 Peloids from the outer, less encrusted part of the "champignon". These are obviously formed by short chains of microbial cells.

7 Some larger cells (arrow), most likely representing heterocytes – a determining feature of the order Nostocales.

8 Silica-encrusted shrubs forming an initial mat of *Nostoc*-type microbes on the quartzite substrate. The substrate is not encrusted by silica which indicates microbial mediation of silica precipitation (Cueva Cańon Verde). Picture width = 5cm.

9 Inorganically precipitated silica stalactites also contribute to the cave decoration (Gran Galería Karen y Fanny, Cueva Charles Brewer).


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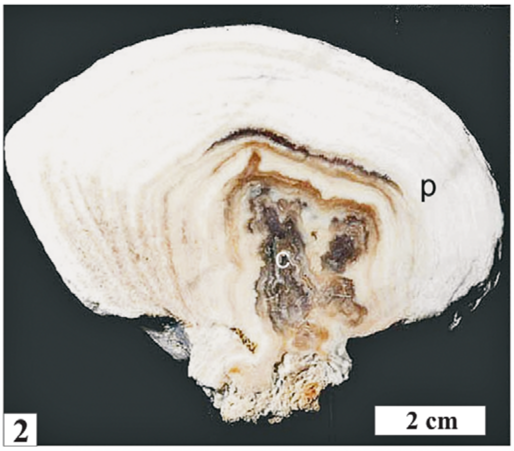
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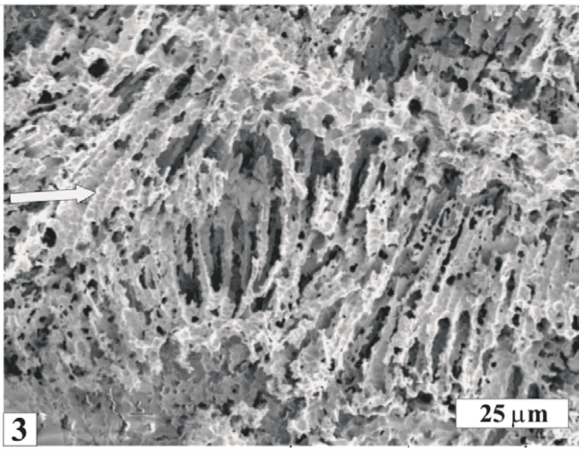
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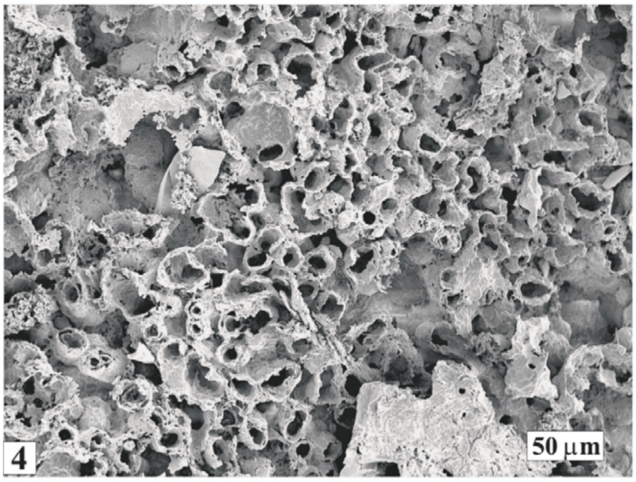
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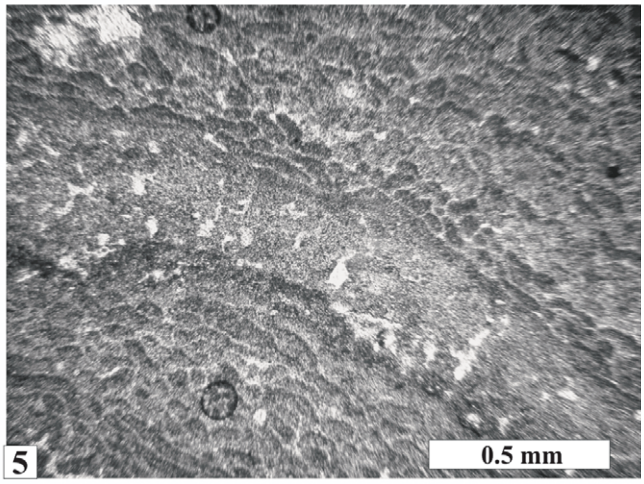
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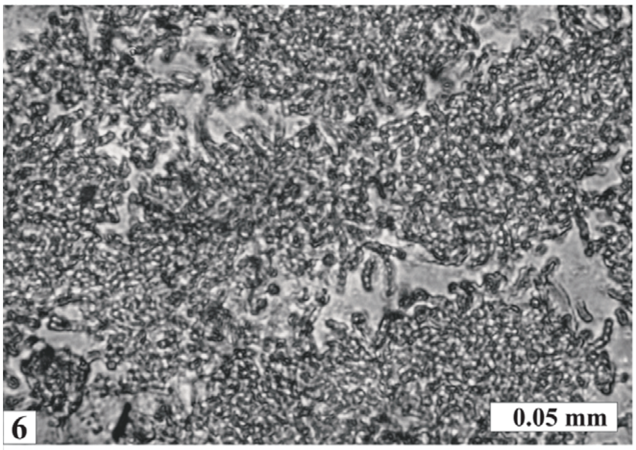
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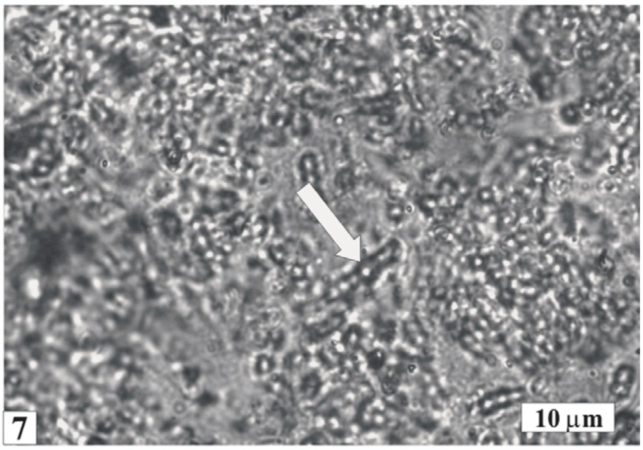
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5. DISCUSSION

5.1. Cave genesis

Caves can only be formed in silicate rocks under special conditions. The most common are lava tubes which form by cooling and hardening of the outer parts of lava flows (LÉVILLÉ et al., 2000; GRADZIŃSKI & JACH, 2001). Caves formed in other silicate rocks are less common, e.g. granites (WILLEMS et al., 2002) or arenites (sandstones and quartzites). Whereas caves in granites are very rare, caves formed in arenites are known from several areas in the world (see the detailed review in WRAY, 1997a), such as South Africa (MARTINI, 1979, 2000) and Australia (WRAY, 1997b, 1999). Proterozoic arenites of the Roraima Group in Venezuela and Brazil are known to host the largest and deepest caves of this type in the world (ŠMÍDA et al., 2003, 2005a, b; RASTEIRO, 2000).

The existence of silicate caves other than lava tunnels seem to be surprising due to the very low solubility of SiO_2 (HILL & FORTI, 1986; WRAY, 1997a, 1999). Some authors (e.g. URBANI, 1986; WRAY, 1997b) explain the origin and evolution of the quartzite karst by dissolution processes under various climatic conditions, combined with an extremely long exposure time to chemical weathering. Dissolution, as a trigger process and as an important process during cave evolution is necessary for ranking the caves in arenitic rocks with karst phenomena (see the detailed review in WRAY, 1997b). Several theories arose to explain the dissolution mechanism itself. Some of these involve temporarily increased alkalinity of the ground waters due to lateritic weathering (MARKER, 1976), quartz hydration to opal (WHITE et al., 1966), alteration of quartz to opal by microbes (VIDAL ROMANÍ & VAQUEIRO RODRIGUES, 2007) or hydrothermal alteration along fractures and bedding planes (SZCZERBAN et al., 1977). Several authors (e.g. MARTINI, 1979; URBANI, 1986; BRICEÑO & SCHUBERT, 1990) prefer an explanation of karstification by intergranular cement dissolution and subsequent mechanical release and winnowing of sand grains. Weathering is considered to be penetrative, along the grain-to-grain contacts and bedding plains (CHALCRAFT & PYE, 1984; WRAY, 1997b). Some researchers emphasize the influence of biogenic processes (etching by cyanobacteria, fungi and lichens) on weathering of the quartzite on tepuis (GORBUSHINA et al., 2001; BREHM et al., 2005).

The evidence presented herein shows that dissolution is not necessarily the leading factor in cave formation in the Roraima Group. Instead, the lack of lithification of some arenitic strata plays a key role. The unlithified strata were protected from massive infiltration of diagenetic fluids by extensive cementation of the overlying and underlying beds and their subsequent isolation. A horizontal course for most of the caves supports this assumption. Although some workers, like WRAY (1999) expressed their opinion that dissolution is much stronger in beds with higher porosity, which is practically equivalent to a low degree of diagenesis, there are some arguments for not only a low degree of lithification but also a complete lack of lithification occurring in the arenites which can result in cave formation:

1. There is a strong contrast between lithification of the beds prone to erosion and sand winnowing on one side and the surrounding strata and quartzite pillars (cemented by vertical finger-flow of diagenetic fluids) on the other. This assumes that from any dissolution prior to winnowing and erosion, dissolving fluids should have only flown horizontally and the fluid flow should have been limited by the strongly lithified overlying and underlying beds. This horizontal movement would, however, have had to leave some traces (such as horizontal grooves). The dissolution would not leave perfectly clean spaces but, instead, bizzare swarms and nests of residual well-lithified portions of arenites should be expected to fill the space. Only rare cases of honeycomb-like weathering were observed in the poorly lithified strata (Pl. I, fig. 3). Also the pillars would have more bizarre surfaces, and not be perfectly smooth. Our observations indicate the opposite. The quartzite pillars are often perfectly smooth, displaying only the vertical movement of finger flow. Even when completely denuded in the caves, no horizontal grooves or any other such signs are visible. Very few dissolution marks are also visible on the ceilings and floors of such caves.

2. Any attempt to explain a secondary origin of the pillars (after dissolution and arenization) would make the diagenetic history much more complex. This way, the overlying and underlying beds should be still permeable enough to enable fluids to migrate vertically but this is not in accordance with the facts mentioned above.

3. Cueva Charles Brewer is most likely not the only giant subterranean space that occurs in the Roraima Group arenites. Huge abysses in the Sarisarińama Plateau (SZCZERBAN & GAMBA, 1973; SZCZERBAN & URBANI, 1974, BREWER, 1974) or in the Guaiquinima Massif (SZCZERBAN et al., 1977) most likely originated by the collapse of huge caves. The sizes of those caves were proportional to the collapses recently observed. It is unlikely that such huge subterranean spaces could originate solely by dissolution, although it may have lasted from a longer time.

5.2. Genesis of the siliceous microbial speleothems

The microbial origin of many of the siliceous speleothems was recognized by previous workers (e.g. FORTI, 1994; VIDAL ROMANÍ & TWIDALE, 1998; LÉVILLÉ et al., 2000; WILLEMS et al., 2002; URBANI et al., 2005), but very few of them attempted to closely describe the microbes. Siliceous microbialites of much larger forms are known from hot springs and geysers (opal sinters). These also contain abundant microbial assemblages, dominated by cyanobacteria, i.e. phototrophic organisms (JONES et al., 2001; KONHAUSER et al., 2001; KONHAUSER et al., 2003). Phototrophic organisms – diatomaceans – were also found to contribute to the formation of similar speleothems in Japan and the USA (KASHIMA et al., 1987; KASHIMA & OGAWA, 1995). These speleothems, however, occurred close to the cave entrances, whereas speleothems presented in this paper came from the deepest parts of the cave. Therefore, it is surprising that a considerable part of the central compact stromatolite of the speleothems was probably formed by cyanobacteria. Biological investigations

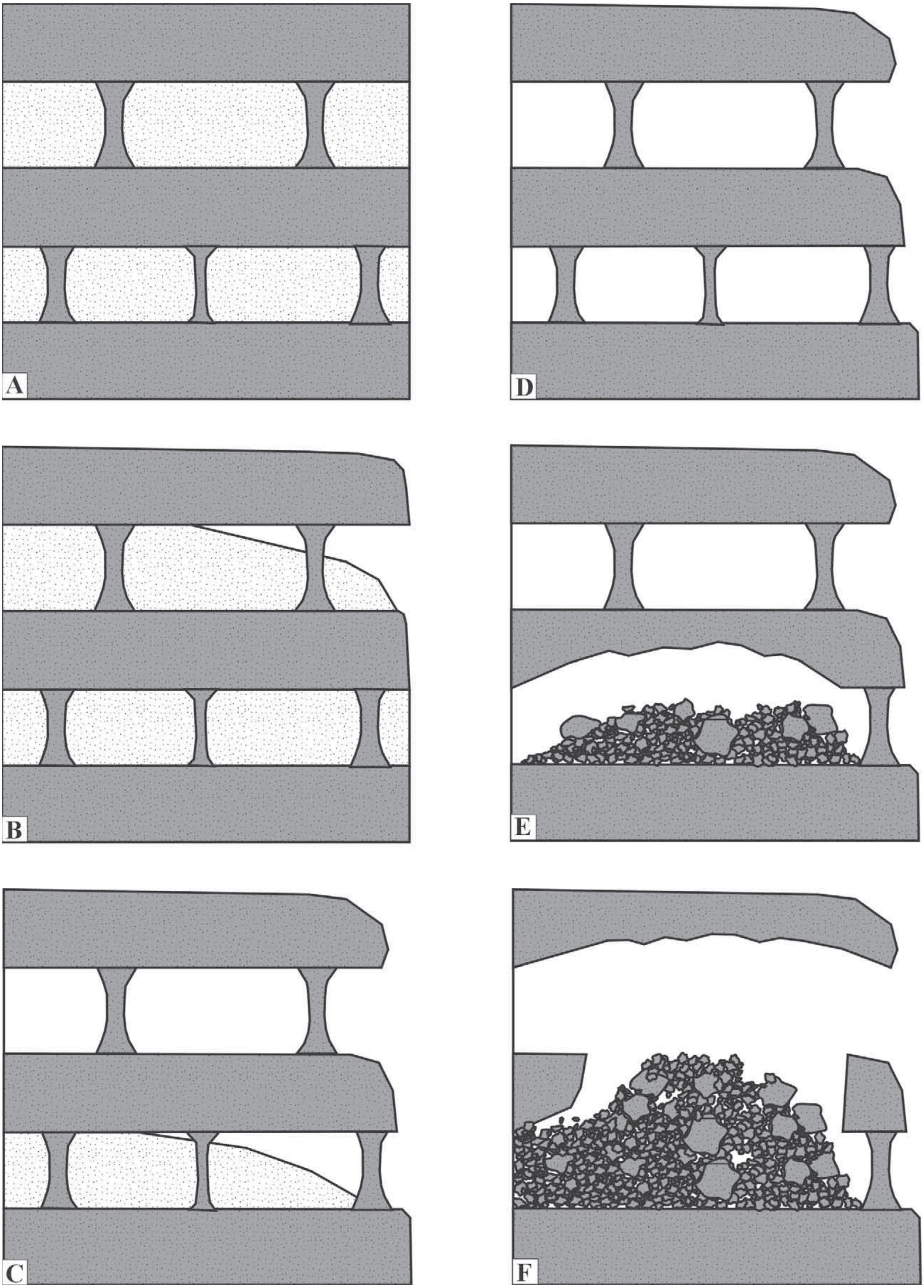

Figure 3: Schematic overview of cave genesis in the arenites of the Roraima Group. Grey – well-lithified arenites, pale – poorly lithified arenites. A – Initial stage with two contrasting poorly lithified horizons superimposed on each other. B, C – Flowing water penetrated through the vertical cleft (on the right side) and caused gradual winnowing of the poorly lithified sediment. D – Two eroded horizons remain empty (two superimposed initial caves), with lithified pillars being the only support against collapse. E, F – Gradual collapse of both stages, forming a large cave.

of the microbes of opal speleothems from similar sandstone caves on the Sarisariñama Plateau (Cueva de los Guacharos – KUNICKA-GOLDFINGER, 1982), mostly showed the presence of heterotrophic microorganisms, the trophic life mode of which was adapted to the decaying excrement of bats and birds guarachos, as well as fruit remnants coming from their diet. The basis of microbe ecology in Cueva Charles Brewer is as yet unclear. The presence of these otherwise phototrophic organisms in caves is not as surprising as it seems to be. Some cyanobacteria do not withstand an excess of solar radiation that can damage their cells (VINCENT & ROY, 1993; QUESADA & VINCENT, 1997). Some of them produce protective pigments in an extracellular sheath (e.g. *Lyngbya estuarii* produces the pigment scytonemine – KYLIN, 1937); others are able to protect themselves against excess light by boring into the substrate, e.g. endolithic boring cyanobacteria *Hormathonema* and *Hyella* (GOLUBIC, 1976). The genera *Fisherella* and *Calothrix* are able to change their mode of life to slow heterotrophy in complete darkness (WHITTON, 1987). Finally, the most convincing fact is that some cyanobacteria, e.g. *Geitleria calcarea* and *Scytonema julianum* have been found inhabiting caves (FRIEDMANN, 1955; BOURRELY & DEPUY, 1973). It is obvious that the cyanobacteria in Venezuelan caves are also adapted to a heterotrophic mode of life.

The reason for the size dependence between the caves and the speleothems is as yet unclear. One of the possible explanations would be that the larger the cave is, the more siliceous material there is to undergo the dissolution/reprecipitation cycle. Larger cave corridors and galleries of the Cueva Charles Brewer have surfaces available for condensation of water vapour that are several times larger than other caves. Such condensation plays the most important role in the cycle of speleothem formation.

6. CONCLUSIONS

1. The main factor in cave formation in the arenites of the Roraima Group is the presence of poorly lithified to completely unlithified bodies within the arenite complexes, which are prone to relatively rapid winnowing and erosion when accessed by flowing waters (Fig. 3). Quartz dissolution also occurs, but it plays a subordinate role in the cave formation. However, it is not yet clear if these facts can also be applied to other caves formed in arenites elsewhere in the world.
2. The low pH values of the water samples are caused by the low neutralization capacity of the quartzite rocks as well as the presence of organic acids and CO_2 resulting from the decay of organic detritus.
3. The chemical composition of the water is controlled by SiO_2 dissolution kinetics in the case of proper cave and/or streambed morphology
4. The strongest dissolution/reprecipitation agent is the condensed atmospheric moisture with extremely low EC and high SiO_2–Si concentration.
5. The siliceous speleothems are mostly represented by cyanobacterian stromatolites. Columnal stromatolitic forms are likely to have been formed by filamentous cyanobacteria from the order Oscillatoriales; the chalk-like peloidal layers were formed by *Nostoc*-type cyanobacteria. Inorganically precipitated siliceous speleothems occur, too. Some of them used spider webs as supporting structures.

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