# ARENITIC CAVES IN VENEZUELAN TEPUIS: WHAT DO THEY SAY ABOUT TEPUIS THEMSELVES?

**Roman Aubrecht[1,2], Tomáš Lánczos[3], Ján Schlögl[1], Lukáš Vlček[4], Branislav Šmída[5]**
[1]*Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina – G, SK-842 15 Bratislava, Slovakia, aubrecht@fns.uniba.sk*
[2]*Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, SK-845 28Bratislava, Slovakia*
[3]*Department of Geochemistry, Faculty of Natural Sciences, Comenius University, Mlynská dolina – G, SK-842 15 Bratislava, Slovakia, lanczos@t-zones.sk*
[4]*Slovak Speleological Society, Hodžova 11, SK-031 01 Liptovský Mikuláš, Slovakia, lukasvlcek@gmail.com*
[5]*Speleoclub of Comenius University, Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina – G, SK-842 15 Bratislava, Slovakia, brano.smida@gmail.com*

Geoscientific research was performed in the two largest sandstone cave systems in the world – Charles Brewer Cave System on the Chimantá Massif and Ojos de Cristal Cave System in the Mt. Roraima, both in South American table mountains (tepuis). These cave systems consist of subhorizontal caves. The research revealed that erosion of non-cemented layers and lateritization of arkosic arenites (hydrolysis of feldspars and micas) played a substantial role in their genesis. Softer beds in which the caves were initially formed show a lack of cementation or cementation by kaolinite. The hard overlying and underlying beds, as well as the "finger-flow" pillars which penetrate the uncemented arenite beds, are cemented by opal and quartz cements. The "finger-flow" pillars indicate that the main diagenetic phase was represented by descending silica-bearing fluids. The pillars originated when the fluid flow reached a coarse-grained arenitic bed, where the continuous fluid front splited to narrow channels. This caused lithification of the arenitic material in the channels and the rest of arenites in these beds escaped from lithification (softer beds) and was easily erodable.

This unusual way of arenite lithification in tepuis infers new views on their genesis and on the geomorphological evolution of the north of South America. Tepuis were formed from hard quartzites and sandstones of the Mataui Formation, which are underlain by arkoses of the Uaimapué Formation. These are the uppermost formations of the Roraima Supergroup which is the Paleoproterozoic detritic cover of the Archean Guyana Shield. From the speleogenetic and geomorphological observations it is evident that the main lithification phase of the Mataui Formation which caused their hardening to quartzites was represented by descending silica-bearing fluids which did not penetrate to the underlying arkoses which remained almost unlithified. The question is: what was the source of these fluids? A new theory concerning the origin of tepuis is presented in this paper. According to this theory, tepuis originated in places where there was an intensive descending fluid flow, most likely emanating from surface water reservoirs, such as rivers or lakes. This continuous flow carried $SiO_2$ from the lateritized surface beds. Thus, the underlying part of the Roraima Supergroup was impregnated with $SiO_2$ and strongly lithified. These indurated parts of the formation remained as tepuis, while the remainder of the formation was removed by erosion. The softness of the underlying, non-lithified sediment below the tepuis caused undercutting of their margins thus maintaining the walls vertical.

## 1. Introduction

Discoveries of large arenitic caves in famous Venezuelan table mountains (tepuis) were unexpected. Caves in silicate rocks are not so ubiquitous as caves in much more soluble material, such as limestones or gypsum. The previously most accepted model for the genesis of the sandstone caves was based on the arenization concept presented first by Martini (1979). The term "arenization" involves the dissolution of the quartz cement in arenitic rocks, with subsequent erosion and winnowing of the loose sand material. However, recent data from the research in the largest sandstone cave systems in the world – Charles Brewer Cave System on the Chimantá Massif and Ojos de Cristal Cave System in the Mt. Roraima (Aubrecht et al. 2008, 2011, 2012) showed that the dominant role of quartz and/or quartz cements dissolution is questionable. Geological and geomorphological research showed that the most feasible way of speleogenesis is winnowing of unlithified or poorly lithified arenites which remained as isolated "pockets" among hard-lithified quartzites and sandstones. Another frequently observed phemomenon, which contributes to the formation of the cave systems is weathering of aluminosilicate minerals, i.e. lateritization. While the latter is related to the recently ongoing processes, the first mentioned speleogenetic factor was related to the processes which created the tepuis themselves. Analysis of this process and the consequences resulting from it are the main aim of this paper.

## 2. Geology of the studied area

The main morphological feature of Guyana Highlands, encompassing southern Venezuela, Northern Brazil and Guyana are its tepuis. These are table mountains characterized by steep cliff walls and relatively flat mesetas, composed of Precambrian quartzites and sandstones covering the Guyana Shield. More than 100 table mountains can be found in the area. They provide important habitats for a great variety of endemic flora and fauna.

From a geological viewpoint, the caves and surface areas analyzed herein are situated in the Venezuelan Guyana, in the northern part of South America (southeastern Venezuela, Gran Sabana). This area comprises Archaean rocks of the Guyana Shield which is the northern part of the Amazonian Craton. The Guyana Shield has a Proterozoic sedimentary cover named Roraima Supergroup which is formed mainly by clastics derived from the northern Trans-Amazonian Mountains. Sedimentological studies showed that the depositional environments ranged from alluvial fans to fluvial braided-river deposits together with lacustrine, aeolian, tidal, shallow-marine deposits and some shallow water turbidites (Reis and Yánez 2001; Santos et al. 2003). Sandy continental deposits are dominant here. The thickness of the group ranges from 200 m to approximately 3,000 m, and it consists of the following lithostratigraphic units arranged in stratigraphic order: Arai Formation, SuapiGroup, Uaimapué Formation and the Mataui Formation (Reis and Yánez 2001). Tepuis developed mainly in the uppermost, Matauí Formation formed by quartzites and sandstones, whereas the underlying Uaimapué Formation is mainly formed by arkoses. Their age was determined as 1,873 ±3 Ma (late Paleo-Proterozoic). This was achieved by U-Pb analyses of zircons from a green ash-fall tuff of the Uaimapué Formation (Santos et al., 2003). Since most of the previous authors accepted the theory that quartz dissolution requires a long time, the recent landscape, including commencement of the cave-forming process, is considered to be inherited from the Mesozoic period (e.g., Cretaceous – Galán and Lagarde 1988; Briceño et al. 1991; Piccini and Mechia 2009).

## 3. Methods

Our geological, geomorphological and speleological observations were focused on phenomena relevant to the solution of the speleogenetic problems. This mainly centered on the differential physical and mineralogical properties of the various kinds of arenites on the tepuis surfaces and caves in the Matauí Formation, and also on morphological aspects of the various stages of speleogenesis and its final manifestations on the surface.

Along with geomorphological observations, petrological and mineralogical analyses were performed on the rocks of the Matauí Formation. This mainly encompassed petrography of thin-sections of the arenites under polarized light, as well as SEM observations. Mineralogical composition of the samples was determined optically and also by X-ray diffraction analysis (XRD).

## 4. Results of geomorphological, petrographical and speleogenetic research.

Erosion and rockfalls, which recently prevail in the Charles Brewer and Ojos de Cristal cave systems (for position of the tepuis see Fig. 1) have concealed their true speleogenetic processes. The trigger and structural factors acting during initial stages of the cave evolution are now mostly obliterated in the mature parts of the cavern systems. Therefore, many of the most important clues resulted from caves which are still in their initial stages of evolution.

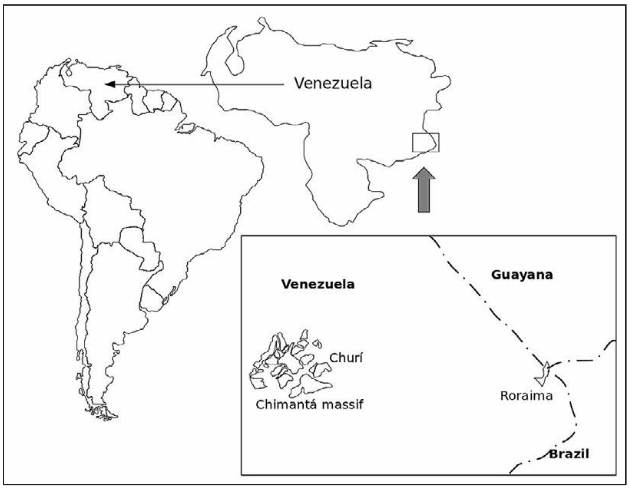

*Figure 1. Location of the examined tepuis.*

The sandstone surfaces of tepuis are very uneven and bizarre, which we interpreted as originated due to an inhomogeneous lithification of the Proterozoic arenites. This is especially apparent in areas where arenite beds form overhangs. The overlying and underlying beds are hard, well-lithified sandstones to quartzites, so that sampling was possible only with strong hammering. However, the beds inbetween are considerably soft, consiting of sands or soft sandstones, so that it was almost impossible to take solid samples for petrographic microscopic study, even after digging 30 cm deep by hand. This contrast in hardness was also verified by Schmidt hammer measurements (Aubrecht et al. 2011, 2012). These soft beds are penetrated by perpendicular pillar-shaped bodies (Fig. 2). These are narrower in the middle, but they have funnel-like widening at either end, with the lower funnel often less developed than the upper one. They are relatively hard rocks, ranging from sandstones to quartzites. In our interpretation, the origin of these pillars is purely diagenetic and their presence proves that the softness of the beds is due to a poor lithification and, therefore, it is primary rather than being secondary, related to weathering (see the discussion between Sauro et al. 2013 and Aubrecht et al. 2013). The pillars are considered to originate by a “finger flow” mechanism (cf. Aubrecht et al. 2008, 2011, 2012, 2013). The main factors influencing diagenetic variability were the differing hydraulic properties of the sediment in different layers which influenced its hydraulic conductivity.

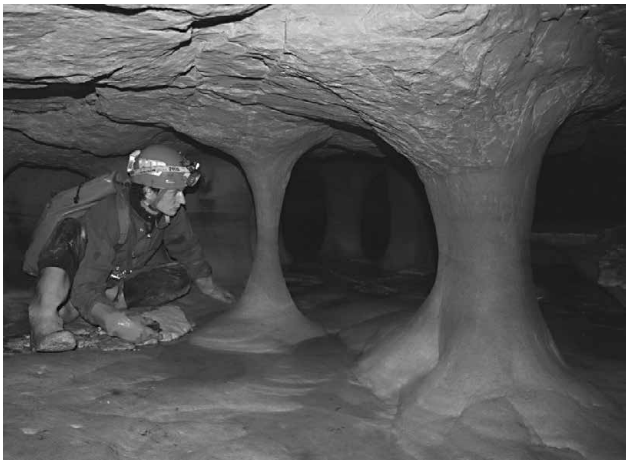

*Figure 2. Well preserved “finger-flow” pillars in the uncollapsed main corridors of Cueva Cañon Verde revealing their origin from descending silica-bearing fluid flow (note the similarity to leaking thick syrup).*

The diagenetic fluids most likely penetrated vertically from the overlying strata as a descending diagenetic fluid flow. In finer-grained sediments, these diagenetic fluids filled the intergranular spaces evenly and resulted in the formation of diagenetically well-lithified beds, resistant to weathering. In coarse-grained arenites with higher hydraulic conductivity below the fine-grained beds, the evenly distributed descending diagenetic front divided into "fingers", where the fluid flow accelerated and formed separate, finger-like flows. This process has been described in detail by various authors working with transport processes in unsaturated zones of sandy aquifers and also in soils (Liu et al. 1994 and Bauters et al., 2000). A similar process is seen in snow penetrated by descending water as it leaks from melted snow above (Marsh 1988 – Fig. 2). Liu et al. (1994) considered that when these finger flows are generated in originally dry sandstones they are conserved as the most preferred method of infiltrating solutions. This is the way pillars originated in the unlithified sands. The downward diminishing funnel shape of the upper part of the pillar originated from flow acceleration, which continued until it decelerated when approaching the less permeable bottom. This retardation process is manifested in the reversely oriented funnel shape in the lower part of the pillar.

Observations in the Charles Brewer and Ojos de Cristal cave systems show that pillars are present in most of the caves and in their galleries, which are still in younger stages of their evolution. These usually possess low ceilings and strictly maintain one distinct layer. However, relic finger-flow pillars were also observed in the marginal, uncollapsed parts of the larger galleries.

When several superimposed winnowed horizons evolve together, a second collapse stage follows, leading to formation of much larger subterranean spaces. Galleries in the Charles Brewer Cave System are typically 40 metres wide, but they can also be much larger. The largest chamber found in the cave is Gran Galería Karen y Fanny. This is 40 metres high, more than 355 metres long and 70 metres wide, giving a volume of approximately 400,000 cubic metres.

The final stages of cave evolution often lead to huge collapses, and these are evident also on the tepui surfaces. This process most likely led to the creation of the large abysses in the Sarisariñama Plateau (Sima Mayor and Sima Menor).

Mineralogical and petrological analyses showed that softer beds in which the caves were initially formed lack cementation, or only kaolinite cementation is present, while the hard overlying and underlying beds and the "finger-flow" pillars are cemented by opal and quartz.

Some workers, e.g., Sauro et al. (2013) argumented against differential diagenesis by the metamorphic overprint of the entire Matauí Formation. They suggested that the metamorphism is evidenced by presence of pyrophyllite and pressure dissolution of quartz. Pressure dissolution also takes place in higher degrees of diagenesis and it can be neglected as a metamorphic indicator. Concerning pyrophyllite, although it is mentioned as a metamorphic indicator in the literature (anchizone to epizone) it does not explain presence of vast quantity of kaolinite in the soft arenitic beds that did not react with quartz to form pyrophylllite. Instead, pyrophyllite without kaolinite is present in hard lithified arenites (Aubrecht et al., 2013 – Fig. 3). Literature studies revealed that there is some evidence that pyrophyllite may also originate by hydrothermal alteration at lower temperatures (e.g., Ehlman and Sand 1959; Bozkaya et al. 2007; Bauluz and Subías 2010). The most important information is that some part of the aluminosilicate mineral phases existing at atmospheric pressure and 25 °C shows that $H_4SiO_4$ concentration is the critical factor in kaolinite/pyrophyllite transition (Aubrecht et al. 2013 – Fig. 4). Here, increased $H_4SiO_4$ concentration can theoretically cause the transformation of kaolinite to pyrophyllite without increased temperature or pressure (Aubrecht et al. 2013).

Lateritization, which also contributes to cave-forming processes, is important, but as we are now focused to the very early diagenetic processes that affected the Matauí Formation, it is beyond the scope of this paper.

## 5. Interpretation of the descending silica-bearing fluid flow: a new view on the origin of tepuis

Summarizing the results of the speleogenetic research, several important points were discovered concerning the origin of the tepuis. Although the research elucidated many aspects of the speleogenetic process, it also created new questions and problems. The most conspicuous finding was that the Matauí Formation is formed not only of quartzites but that its arenites show various degrees of lithification. Our research provided evidence of variability in vertical profiles. But what about the lateral variability? Are tepuis with a dominant presence of hard-lithified quartzites typical examples of the Matauí Formation? What about the larger, missing portion of the formation which was removed by erosion? Why are tepuis usually isolated islands rising up from the flat Gran Sabana? And also, why there are no "ruins" of tepuis formed by accumulations of quartzite boulders dispersed throughout the Gran Sabana?

Answers to these questions are currently purely theoretical as the missing, eroded portion of the Matauí Formation can no longer be examined. However, knowledge gathered from our research of this formation's remnants can be grouped under one common image which entails a new theory of the origin of tepuis.

"Finger-flow" pillars in the arenites forming these tepuis indicate that the descending flow of silica-bearing diagenetic fluids provided induration to arenites even to very hard quartzites. This flow penetrated deeply enough to lithify hundreds of metres of arenites in a vertical profile, and the indurated rocks then protected less lithified portions of the formation below. Most of the tepuis are limited by vertical cliffs, and undercutting of these cliffs often occurs because the lower parts of the massifs are less lithified (see also Young et al. 2009 – p. 58–60). Undercutting and the subsequent rockfall would be responsible for creation of the rock talus around tepuis (Montañas al pie del escarpado – see Briceño and Schubert, 1992 – Fig. 4.3). The talus then passes to flat country surrounding the tepuis, without retaining any remnants of quartzite boulder accumulations. However, closer inspection of the talus around Roraima indicates that it is formed by less lithified, soft arenites of the Roraima Supergroup, which most likely underlie the sandstones and quartzites, rather than by fallen quartzite blocks (Fig. 3). Erosion of these soft arenites causes undercutting of the Roraima cliffs and keeps them steep.

*Figure 3. A view on Mt. Roraima (and Mt. Kukenan – left). The mountain consists of quartzites, which form steep cliffs (C) and surrounding talus (T).*

All these observations suggest that the patchy distribution of tepuis in Gran Sabana was formed long ago by vertical lithification of the Matauí Formation. This lithification required a voluminous source of soluble $SiO_2$ and sufficient fluids. Exactly as evident today from the recent lateritization, the best source of $SiO_2$ were the clay and rocks with micas and feldspars above the actually preserved Matauí Formation. These rocks were easily affected by lateritization, which most likely occurred after the Late Carboniferous, when the northern-most part of South America reached the tropical zone (see Scotese 2001). The best source of fluids would undoubtedly have been water reservoirs on the surface, and thus the recent distribution of tepuis may have copied the distribution of ancient lakes and rivers. Alternative explanations for the erosion of the missing portions of the Roraima Supergroup include the inference of Galán et al. (2004 – Fig. 1) that this erosion mainly affected tectonically disrupted parts of the Roraima Supergroup. However, this contradicts the lack of boulder accumulations on Gran Sabana. Moreover, the disrupted parts of the Roraima Supergroup had to be more widespread than the undissected ones, and this is considered most unlikely in this firm, rigid block of the Guyana Shield.

This theory is currently based on a limited set of data and further research is necessary. Although new data may support or refute our theory, it is very satisfying to provoke future research in this area.

## 6. Conclusions

1. The following speleogenetic model can be inferred from the obtained geomorphological and geological results (Fig. 4): Stage 1 – The descending, $SiO_2$-bearing diagenetic solutions caused complete lithification of some beds, whereas other beds with more coarse-grained arenites were only penetrated by narrow channels through which fluids flowed to completely fill some of the lower beds. This resulted in the contrasting diagenesis, where most beds turned to sandstone and quartzite while parts of other beds remained intact. Stage 2 – Hard, isolated beds were broken, and the flowing water which penetrated the poorly lithified beds started initial erosion. Lateritization then began in aluminosilicate-rich beds with the subsequent emptying of spaces by winnowing of sand and other products of lateritization. The empty spaces were then supported solely by "finger-flow" pillars. Stage 3 – Empty spaces collapsed further, thus creating larger caves, and superior propagation of these collapses created large collapse depressions on the surface.

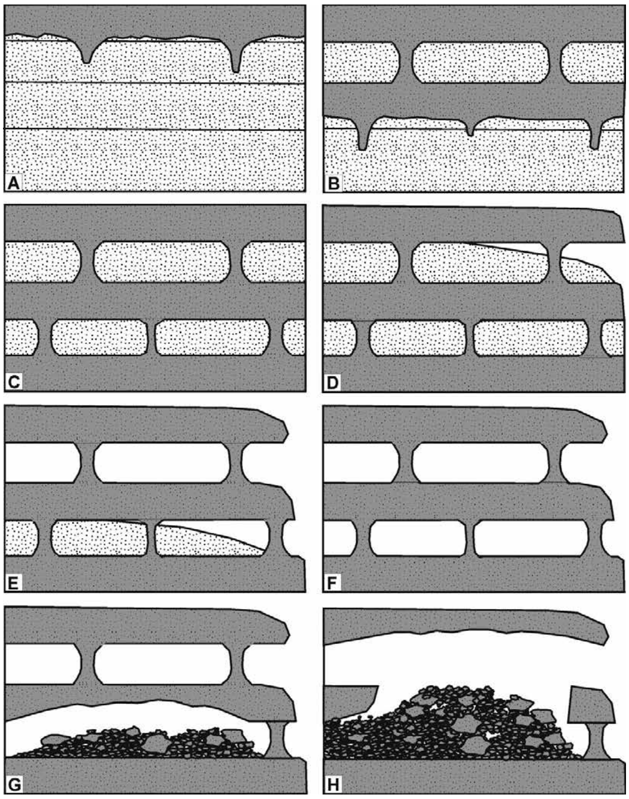

*Figure 4. Schematic overview of the speleogenesis in the arenites of the Roraima Supergroup. Grey – well-lithified arenites, pale – poorly lithified arenites (caves formed by lateritization are omitted). A–B – The gradual diagenesis to arenites caused by descending silica-bearing fluids (Stage 1). C – Two poorly-lithified horizons superimposed on each other. D–E – Flowing water penetrated the vertical cleft (on the right side) causing gradual winnowing of the poorly lithified sediment (Stage 2). F – Two horizons remained empty (two superimposed initial caves), with lithified pillars offering the only support against collapse. G–H – Collapse of both floors, forming a large cave (Stage 3).*

2. A new theory concerning the origin of tepuis can be proposed, based on the fact, that diagenesis by descending silica-bearing fluids appears to be the main phase that indurated the Matauí Formation quartzites (Fig. 5). According to this theory, tepuis originated in places where there was an intensive descending fluid flow, most likely emanating from surface water reservoirs, such as rivers or lakes. This continuous flow carried $SiO_2$ from the lateritized surface beds. Thus, the underlying part of the Roraima Supergroup was impregnated with $SiO_2$ and strongly lithified. These indurated parts of the formation remained as tepuis, while the remainder of the formation was removed by erosion. The softness of the underlying, non-lithified sediment below the tepuis caused undercutting of their margins thus maintaing steep walls. Speleogenesis in the tepuis was a process which most likely began at a later stage, with initial incision of the valleys followed by erosion.

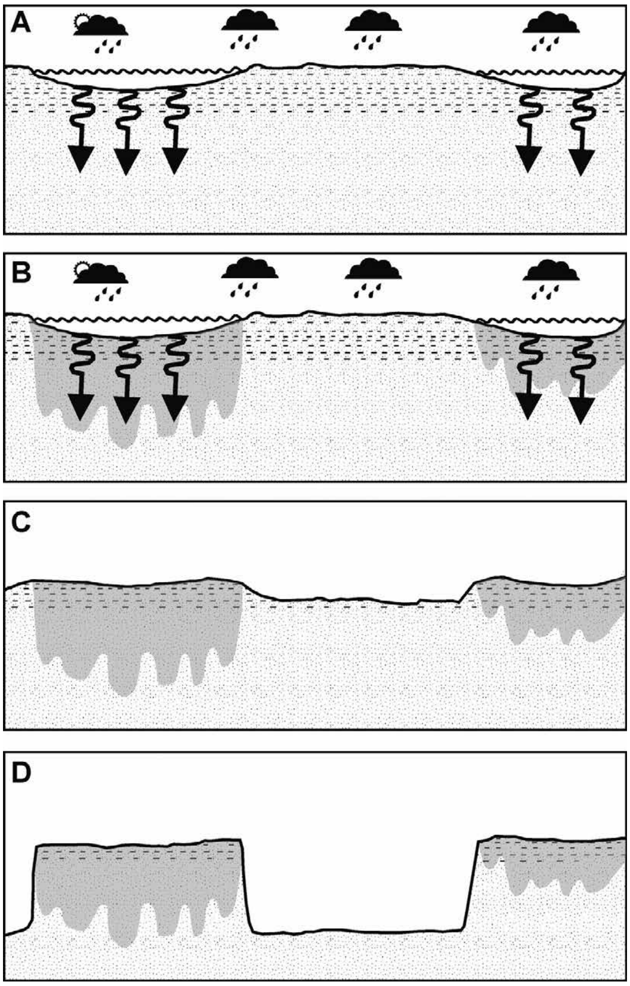

*Figure 5. The newly proposed model of the origin of the tepuis. A – The Roraima Supergroup was originally capped by sediments rich in micas, feldspars or clay minerals which were prone to lateritization. This lateritization may have begun in the Late Carboniferous when the northern part of present South America reached tropical areas (Scotese, 2001). B – The lateritization occurred mostly in the areas with excess fluids, such as rivers and lakes. The descending fluids brought silica from the lateritization zones downwards, causing additional cementation of the Mataui Formation. This cementation was patchy, and concentrated only in the zones with sufficient water. C–D – In the later geomorphological evolution stages, the uncemented portions of the Roraima Supergroup were subjected to erosion and the cemented, quartzitic parts were preserved, together with the softer, uncemented parts protected below them. The steep cliffs of the tepuis are maintained by erosion of the softer, uncemented arenites below with subsequent undercutting of the quartzite layers.*

## Acknowledgements

The authors are deeply indebted to Francesco Sauro and Jo De Waele (Bologna University, Italy) for their review and useful corrections and comments that helped to improve the text of this paper. The research was financed by grants APVV 1-0251-07 and VEGA 1/0246/08.

## References

Aubrecht R, Lánczos T, Šmída B, Brewer-Carías Ch, Mayoral F, Schlögl J, Audy M, Vlček L, Kováčik Ľ, Gregor M, 2008. Venezuelan sandstone caves: a new view on their genesis, hydrogeology and speleothems. Geologia Croatica, 61, 345–362.

Aubrecht R, Lánczos T, Gregor M, Schlögl J, Šmída B, Liščák P, Brewer-Carías Ch, Vlček L, 2011. Sandstone caves on Venezuelan tepuis: return to pseudokarst? Geomorphology, 132, 351–365.

Aubrecht R, Barrio-Amoros C, Breure A, Brewer-Carías Ch, Derka T, Fuentes-Ramos OA, Gregor M, Kodada J, Kováčik Ľ, Lánczos T, Lee NM, Liščák P, Schlögl J, Šmída B, Vlček L, 2012. Venezuelan tepuis – their caves and biota. Acta Geologica Slovaca – Monograph, ISBN 978-80-223-3349-8, 1–168.

Aubrecht R, Lánczos T, Gregor M, Schlögl J, Šmída B, Liščák P, Brewer-Carías Ch, Vlček L, 2013. Reply to the Comment on "Sandstone caves on Venezuelan tepuis: Return to pseudokarst?" Geomorphology (DOI: 10.1016/j.geomorph.2012.11.017).

Bauluz B, Subías I, 2010. Coexistence of pyrophyllite, I-S, R1 and $NH_4^+$-rich illite in Silurian black shales (Sierra de Albarracín, NE Spain): metamorphic *vs*. hydrothermal origin. Clay Minerals, 45, 3, 383–392.

Bauters TWJ, Dicarlo DA, Steenhuis TS, Parlange J-Y, 2000. Soil water content dependent wetting front characteristics in sand. Journal of Hydrology, 231–232, 244–254.

Bozkaya O, Yalcin H, Basibuyuk Z, Bozkaya G, 2007. Metamorphic-hosted pyrophyllite and dickite occurrences from the hydrous Al-silicate deposits of the Malatya-Puturge region, central eastern Anatolia, Turkey. Clays and Clay Minerals, 55, 4, 423–442.

Briceño HO, Schubert C, 1992. Geomorfología. In: Huber O. (Ed.): Chimantá. Escudo de Guayana, Venezuela. Un Ensayo Ecológico Tepuyano. Oscar Todtmann Editores, Caracas, 61–74.

Briceño HO, Schubert C, Paolini J, 1991. Table-mountain geology and surficial geochemistry: Chimantá massif, Venezuelan Guayana Shield. Journal of South American Earth Sciences, 3, 179–194.

Ehlmann AJ, Sand LB, 1959. Occurrence of shales partially altered to pyrophyllite. Clays and Clay Minerals, 6, 368–391.

Faure G, 1991. Principles and applications of inorganic geochemistry: a comprehensive textbook for geology students. Macmillan, New York, 626.

Galán C, Lagarde J, 1988. Morphologie et evolution des cavernes et formes superficielles dans les quartzites du Roraima. Karstologia, 11–12, 49–60.

Galán C, Herrera FF, Carreño R, 2004. Geomorfología e hidrología del Sistema Roraima Sur, Venezuela, la mayor cavidad del mundo en cuarcitas: 10,8 km. Bol. SVE, 38, 2–16.

Liu Y, Steenhuis TS, Parlange J-Y, 1994. Formation and persistence of fingered flow fields in coarse grained soils under different characteristics in sands. Journal of Hydrology, 159, 187–195.

Martini JEJ, 1979. Karst in Black Reef Quartzite near Kaapsehoop, Eastern Transvaal. Annals of the Geological Survey of South Africa, 13, 115–128.

Piccini L, Mecchia M, 2009. Solution weathering rate and origin of karst landforms and caves in the quartzite of Auyan-tepui (Gran Sabana, Venezuela). Geomorphology, 106, 15–25.

Reis NJ, Yánez G, 2001. O Supergrupo Roraima ao longo da faixa fronteirica entre Brazil-Venezuela (Santa Elena del Uairen-Roraima Mountain). In Reis N.J. & Monteiro M.A.S. (Eds.): Contribuicao a geologia da Amazonia, Vol. 2: Manaus, Brazil, Soc. Brasil. Geol. 113–145.

Santos JOS, Potter PE, Reis NJ, Hartmann LA, Fletcher IR, McNaughton NJ, 2003. Age, source, and regional stratigraphy of the Roraima Supergroup and Roraima-like outliers in northern South America based on U-Pb geochronology. Geological Society of America Bulletin, 115, 331–348.

Sauro F, Piccini L, Mecchia M, De Waele J, 2012. Comment on "Sandstone caves on Venezuelan tepuis: Return to pseudokarst?" by R. Aubrecht, T. Lánczos, M. Gregor, J. Schlögl, B. Smída, P. Liscák, Ch. Brewer-Carías, L. Vlcek. Geomorphology 132, 351–365. Geomorphology.

Scotese CR, 2001. Atlas of Earth History. PALEOMAP Project, Arlington, Texas, 1–52.

Young RW, Wray RAL, Young ARM, 2009. Sandstone landforms. Cambridge University Press, 1–304.