Small-scale modelling of arenitic caves in South American tepuis: Make your own tepui at home.

Roman Aubrecht[1,2], Tomáš Lánczos[3], Ján Schlögl[1], Marek Audy[4] and Petronela Filipčíková[3]

Affiliation: *[1] Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, 842 15 Bratislava, Slovakia.*
[2] Institute of Earth Sciences - Geophysical Division, Slovak Academy of Sciences, Dúbravská cesta 9, 845 28 Bratislava, Slovakia.
[3] Department of Geochemistry, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, 842 15 Bratislava, Slovakia.
[4] Czech Speleological Society, Tyršova 332, CZ-679 06 Jedovnice, Czech Republic.
corresponding author - e-mail: aubrecht@fns.uniba.sk

Abstract

South American table mountains (tepuis) host the largest arenitic cave systems in the world. To explain speleogenesis in these insoluble rocks, two theories were introduced: a) arenization theory implying selective weathering of quartz cements and releasing of sand grains, b) selective lithification theory implying lithification by descending silica-bearing fluid flow. The latter presumes that the descending fluid flow becomes unstable on the interface between two layers with different porosity and splits to separate flow channels ("finger flow"). The arenites outside these channels remain unlithified. There is also a so-called "funnel-flow" which occurs at inclined layers. This works for cross-bedded arenites.

To verify the latter theory, small-scale modelling was performed, using sands and sodium-silicate solution. For experiments with contrasting grain-size, fine to medium sand fraction was used (0.08-0.5 mm), along with coarse (0.5-1.5 mm) fraction. For experiments with cross-bedded sediments, only the fine fraction has been used. The sands were layered and compacted in a transparent plexiglass boxes. Sodium-silicate solution (so-called water glass) was left to drip for several hours to the top of the sediment.

Results of this small-scale modelling mimic the real diagenesis by descending silica-bearing fluids and match the real phenomena observed on the tepuis. The resulting lithified constructions in horizontally layered experiments with contrasting grain-size closely remind many geomorphological features observed on tepuis and inside their caves, e.g. "finger-flow" pillars, overhangs, imperfectly formed (aborted) pillars in forms of hummocks hanging from ceilings, locally also thicker central pillars that originated by merging of smaller fluid-flow channels. The models with cross-bedding display close similarity with triangular-shaped shelters and caves observed in aeolian sediments on Akopán Tepui.

The modelling showed that selective lithification theory can explain most of the geomorphological aspects related to the speleogenesis in tepuis, whereas the arenization theory can explain only particular problems.

Keywords:

1. Introduction

Huge cave systems were discovered in last two decades in the arenitic rocks (Matauí Formation – Mesoproterozoic) forming South American table mountains called tepuis. The largest systems are Ojos de Cristal (Roraima Sur) System discovered in 2002 (Šmída *et al*. 2003), Churí Tepuy System with the largest cave Cueva Charles Brewer discovered in 2004 (Šmída *et al.* 2010; for summary information about both systems see also Aubrecht *et al*. 2012) and Imawarí Yeuta System discovered in 2013 (Sauro *et al*. 2013b). Members of our team came with a new explanation of their genesis. It implies selective lithification of arenites by descending solutions enriched in silicic acid released during lateritization of overlying sediments rich in alumino-silicates. The down-penetrating solutions in sediments (e.g. sands and soils) locally split to separate flows (preferential flows) that are determined by various factors (for detailed information see: http://soilandwater.bee.cornell.edu/research/pfweb/educators.htm). In this case, the most important are the processes causing wetting front instability at the contact of fine-grained sand layer with underlying coarse-grained sand layer, where the wetting front splits to several channels forming so-called "finger-flow". On the other hand, instability at the inclined layers forms so-called "funnel-flow".

After lithification of beds with contrasting grain-size, "finger flow" pillars are created, standing between the lithified beds of finer-grained arenites. The remaining coarse-grained sediment between the pillars remains weakly lithified, or completely unlithified. Disruption of the rock massif and penetration of flowing water causes winnowing of the loose arenite and creates caves. Collapse of superposed winnowed horizons may lead to formation of volumetrically huge subterranean spaces (Aubrecht et al. 2008, 2011, 2012). Presence of "finger-flow" pillars is diagnostic for this type of speleogenesis (Aubrecht et al. 2013a).

Cross-bedded layers affected by "funnel-flow" display poorer diagenesis than other layers due to increased velocity of the fluid flow. Observations on the Akopán Tepui showed that the weaker lithification results in forming of triangular-shaped shelters and small caves.

To support the new theory, small-scale modelling of the arenitic caves by descending silica-bearing fluids was performed and discussed with competing arenization theory, which implies dissolution of recrystallized siliceous cement forming quartz overgrowths along the grain boundaries and subse-

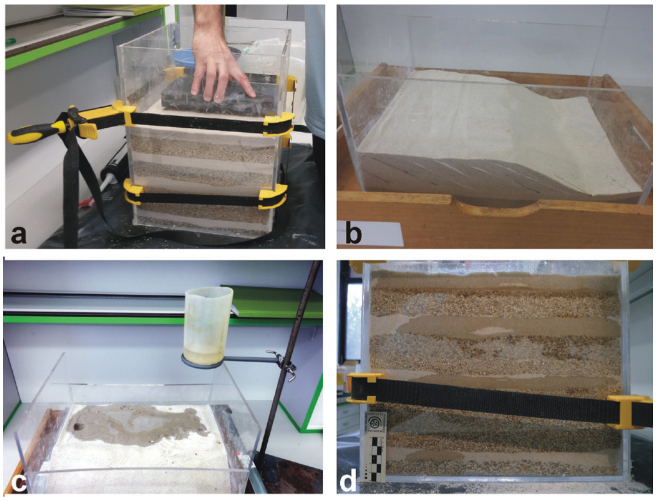

Figure 1. Photos documenting preparation and performance of the experiments. (a) Layered sand of various grain size sedimented and compacted in a plexiglass vessel. (b) Preparation of cross-bedded fine-grained sands. Cross-bedding is emphasized by thin kaolinite laminae (white). (c) Sodium silicate solution is dripping onto the cross-bedded sand. (d) Downward penetration of the wetting front in experiment using horizontally layered sands with contrasting grain-size. The wetting appeared in all three fine-grained layers, when it for the first time appeared as fingering on the vessel wall in the second coarse-grained layer. The wetting front in the first coarse-grained layer (its upper part) is till even and stable.

quent releasing and winnowing of sand grains (Martini 1979, 2002, 2004).

2. Material and methods

To verify the theory about selective lithification by descending silica-bearing fluids, experiments were performed, using layered sands with contrasting grain size and cross-bedded fine sands (Fig. 1). A commercially available sodium silicate ("water glass") solution (concentration cca 36 %) was selected as a medium that best mimics lithifying silica-bearing fluids. After several experiments with firm vessels from transparent material, the best results were achieved with silicon-glued plexiglass boxes that were constructed directly in the lab.

For the experiments with contrasting grain-size sands, the vessels were filled with various layers of fine-grained sands (0.08-0.5 mm), along with coarse fraction (0.5-1.5 mm. The sands were layered and compacted (Fig. 1a) with the coarser fractions forming the thickest layers (5-10 cm). The fine-grained layers were thinner (2-3 cm). For experiments with cross-bedded sands, only fine-grained fraction was used (0.08-0.5 mm) mimicking wind-borne sand. The cross-bedded layer was formed between two horizontally- layered levels. The cross-bedding was increased by thin kaolinite intercalations each 1 cm (Fig. 1b). Sodium-silicate solution was left to drip for several hours to the top of the sediment and to soak inside (Fig. 1c).

The resulting lithified arenitic constructions were photodocumented and compared with field documentation and photos on the surface of the Churí and Akopán tepuis (parts of the Chimantá Massif) and Roraima Tepui, as well as in their cave systems (Churí Tepui Cave system and Ojos de Cristal Cave system).

Figure 2. Lithified results of the modelling using layered sands with contrasting grain-size. (a-b) Most of "finger-flow" pillars developed in the central coarse-grained layer and less in the lower coarse-grained layer. The upper coarse-grained layer has been filled and lithified completely. Many of the pillars display uneven thickness and locally bulbous thickening in the lower part. (c) Earlier experiment performed in a firm plastic vessel. "Finger-flow" pillars were developed only in the central, 10cm thick coarse-grained layer. Bottom part and some pillars were destroyed during tumbling the material out of the box. (d) Due to rapid flooding, most of the pillars merged to one central pillar in this experiment. However, the original merging pillars are still discernible in the coarse-grained layers. Only one small pillar remained isolated in the lower layer (right of the lower part). (e) Most of the pillars again merged to one central pillar in this experiment, but a relict cavity with flat bottom and vaulted top still remains (middle right). (f) Thickest and largest pillars developed in the lower coarse-grained layer in this experiment. In this layer also an aborted pillar is visible (bottom center). Two upper layers were more filled by the lithifying liquid, but some small pillars are still visible, mainly at the margin of the upper coarse-grained layer. Number of pillars diminished downward but their size increased.

3. Results and interpretations

The final lithified product of the experiments using sands with contrasting grain-size in some cases displayed well-preserved isolated "finger-flow" pillars between well-lithified fine-grained layers (Fig. 2). In other cases, gradual soaking caused merging of some flow channels and forming of thicker pillars which sometimes merged to one central pillar (Fig. 2d-e), with the individual channels still observable at the pillar margin. But even in such cases, some cavities and isolated pillars were still preserved. The cavities have vaulted top and flat bottom (Fig. 2e) just like the caves, which Sauro et al. (2013a) presented as being typical for the horizontal caves in tepuis. Despite being created in small-scale modelling, all types of lithified products closely mimic the structures that were observed on the tepuis, or in their caves, e.g. cavities with flat bottoms and ceilings, supported by "finger-flow" pillars between them (Fig. 3a-c). The "finger-flow" pillars were mostly perpendicular to the layering; but slightly inclined pillars were common, too. Some pillars displayed bulbous

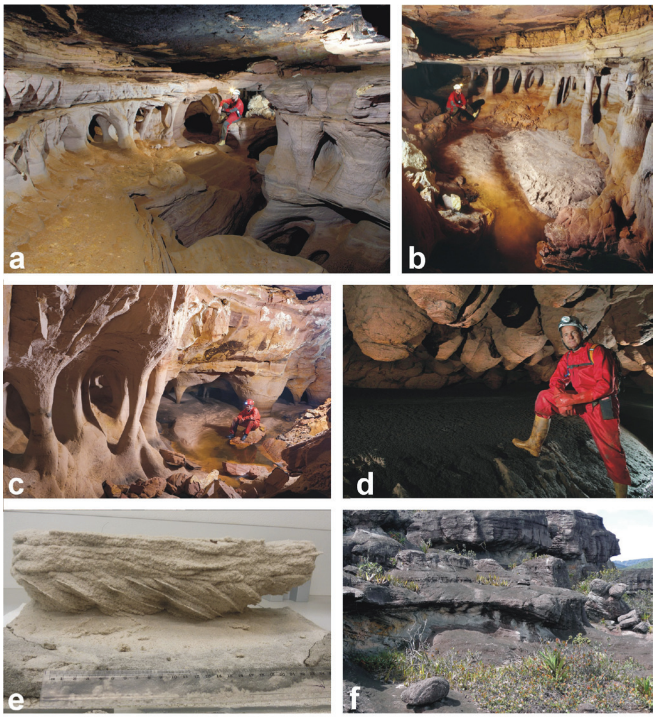

Figure 3. Field photos from caves in the Churí Tepui. (a) Superposed two levels with developed pillars. If origin of the pillars was predisposed by vertical cracks, existence of such superposition would be unlikely. Cueva de las Arañas. (b) Well-developed pillars in Cueva de las Arañas. Tops of some pillars show lithified merging "finger-flow" channels. The bed above the pillars would be again disrupted if they were predisposed by vertical cracks. (c) Well-preserved pillars in Cueva de las Arañas. (d) Aborted pillars ("tetas") hanging below ceiling of Cueva Eladio (Sistema Brewer). (e) Lithified result of an experiment with cross-bedded sands. Note that the top and bottom layers are lithified evenly, whereas the cross-bedded layer between them displays poorer lithification and forms negative relief. (f) Field photo from Akopán tepui showing that the parallel-layered layers are hardly lithified, forming overhangs, whereas the cross-bedded layers form negative relief between them.

thickening (Fig. 2a-b) which is similar to some pillars in Imawarí Yeuta Cave in Auyán Tepui (Sauro et al. 2013b). Some pillars are imperfectly developed in their early stages, forming hummocks hanging from the ceiling (Fig. 2f), which closely mimic similar structures in the tepui caves called "tetas" (tits) by local cavers (Fig. 3d).

The resulting structures of experiments with cross-bedded sands display good lithification of horizontally layered sands and much poorer lithification of the cross-bedded sediment between them (Fig. 3e), showing triangular overhangs, which closely mimic the triangular shelters on the Akopán Tepui (Fig. 3f).

4. Discussion

The experiments showed that many geomorphological features observed on the surface of tepuis and in their caves can be created by small-scale modelling using descending diagenetic fluids. Not all aspects that are observable in the field can be reproduced in this scale. The coarse-grained layers were not thick enough to promote formation of perfectly shaped "finger-flow" pillars with widenings on both ends and smooth surface that might be modified by flowing water. However, the principal processes occurring in this system are obvious.

Against the selective lithification theory stands recently mainly the theory of arenization (Martini 1979, 2004). Our team already disputed several aspects on the pages of Geomorphology (Sauro *et al*. 2013a; Aubrecht *et al*. 2013a). However, the last paper concerning this matter of Sauro (2014) still supports the arenization theory, bringing new possible explanations about the origin of pillars and the caves themselves. According to him, the pillars were pre-disposed tectonically by vertical cracks which limited them and the erosion removed the surrounding, more dissected rocks. In such case, however, it is difficult to explain common presence of undisturbed overlying and underlying beds, or local presence of interbeds that are supported by the pillars. On the other hand, these continuous, well-lithified beds are a typical product of selective descending fluid lithification, as evidenced by the experiments. The vertical cracks model also does not work in the cases of pillars that are still half-embedded in sandstone or sand.

If admitting validity of arenization theory, very complex models must be invented from case to case. On the other hand, the selective lithification model explains most of the aspects, which was proved also by small-scale 3-D modelling presented in this paper.

5. Conclusions

1. Large cave systems were discovered in arenites (quartzites and sandstones) forming the table mountains in northern part of South America.

2. To explain speleogenesis in these insoluble rocks, two theories were introduced: a) arenization theory implying selective weathering of quartz cements and releasing of sand grains, b) selective lithification theory implying lithification by descending silica-bearing fluid flow. The latter theory presumes that the descending fluid flow is unstable and locally splits to separate flow channels (so-called "finger flow"). The arenites outside these channels remain unlithified.

3. To verify the selective lithification theory, small-scale experiments were performed, involving layered sands with contrasting grain size and cross-bedded fine sands mimicking aeolian sediments. As the lithifying medium, sodium silicate ("water glass") solution was left dripping on the sediment.

4. The resulting lithified constructions closely mimic many geomorphological features observed on tepuis and inside their caves, such as "finger-flow" pillars, overhangs, triangular shelters, aborted pillars in forms of hummocks hanging from ceilings. Locally also thicker central pillars that originated by merging of smaller fluid-flow channels were formed, with relic cavities with flat bottom and vaulted top. These are also typical for some tepui caves.

5. The modelling showed that selective lithification theory can explain most of the geomorphological aspects related to the speleogenesis in tepuis, whereas the arenization theory can explain only particular problems.

Acknowledgements

The authors acknowledge the financial support from the project APVV 14-0276.

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. *Geologica Croatica*, **61**(2-3), 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**(3-4), 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, 1-168.

Aubrecht R, Lánczos T, Gregor M, Schlögl J, Šmída B, Liščák P, Brewer-Carías Ch, Vlček L, 2013a. Reply to the Comment on "Sandstone caves on Venezuelan tepuis: Return to pseudokarst?". *Geomorphology*, **197**(1), 197-203

Aubrecht R, Lánczos T, Schlögl J, Vlček L, Šmída B, 2013b. Arenitic caves in Venezuelan tepuis: what do they say about tepuis themselves? In: M Filippi and P Bosák (Eds.). *Proceedings of the 16th International Congress of Speleology*, July 21-28, 2013. Brno, Czech Republic, Vol. **3**, pp. 221-226.

Martini JEJ, 1979. Karst in Black Reef Quartzite near Kaapsehoop, Eastern Transvaal. *Annal of the South African Geological Survey*, **13**, 115-128.

Martini JEJ, 2000. Dissolution of quartz and silicate minerals. In: AB Klimchouk, DC Ford, AN Palmer and W Dreybrodt (Eds.). *Speleogenesis, Evolution of Karst Aquifer*, January 2000 edition. NSA, Inc., Huntsville, Alabama, pp. 171-174.

Martini JEJ, 2004. Silicate karst. In: J Gunn (Ed.). *Encyclopedia of caves and karst science*. Fitzroy Dearborn, London, pp. 1385-1393.

Sauro F, 2014. Structural and lithological guidance in quartz-sandstone caves: evidences of the arenisation process. *Geomorphology*, **226**, 106-123.

Sauro F, Piccini L, Mechcia M, De Waele J, 2013a. 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 (2011), 351-365. *Geomorphology*, **197**(1), 190-196.

Sauro F, Vergara F, De Vivo A, De Waele J, Lira J, 2013b. In the House of Gods on Devil‘s Mountain. Imawarí Yeuta Cave, Auyan Tepui, Canaima National Park, Venezuela. *NSS News*, September 2013, 7, 10-19.

Šmída B, Audy M, Vlček L, 2003. Roraima 2003 expedition. Crystal Eyes Cave. *Bulletin of Slovak Speleological Society*, **34**(2 spec. vol.), 1-190 (in Slovak with English summary).

Šmída B, Brewer-Carías Ch, Audy M, Mayoral F, Bakšić D, Vlček L, Stankovič J, 2010. Churi-Tepui Cave System: Inside the second largest quartzite cave in the world. *NSS News* **68**(7), 16-23.