SMALL-SCALE TERRACES AND ISOLATED RIMSTONE POOLS ON STALAGMITES IN CAVES EXHIBIT STRIKING SIMILARITY TO LARGE-SCALE TERRACE LANDSCAPES AT HOT SPRINGS

DROBNE SIGASTE TERASE NA STALAGMITIH SO PRESENETLJIVO PODOBNE VELIKIM TERASAM, KI RASTEJO OB TERMALNIH KRAŠKIH IZVIRIH

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Abstract
Wolfgang Dreybrodt & Franci Gabrovšek: Small-scale terraces and isolated rimstone pools on stalagmites in caves exhibit striking similarity to large-scale terrace landscapes at hot springs

We report on sinter terrace forms on the centimetre scale observed on the top and at the base of a stalagmite in Škocjanske jame (Škocjan caves). These exhibit connected rimstone dams, forming a net-like pattern with active water pools inside. The form is similar to those seen at the large travertine terraces, which form by precipitation of calcite from spring waters highly supersaturated with respect to calcite. In contrast to these patterns we have also found isolated sinter basins with dimensions of a few centimeter on stalagmite-like structures in the cave Dimnice, Slovenia. Similar basins a few meters wide are a tourist attraction in Pamukkale, Denizli, Turkey. The observed features have grown from supersaturated solutions of calcium carbonate in laminar flow. Large-scale landscapes originate under conditions of turbulent flow. Some ideas are presented why, in spite of the clear difference in flow, the shapes are similar on all scales.

Keywords: Rimstone pools, precipitation, Škocjanske jame (Škocjan caves), Dimnice.

INTRODUCTION
Travertine terraces exhibit complex landscapes with water pools separated by networks of rimstone dams. These occur on scales of several tens to hundreds of meters. Examples are in Huanglong, Sichuan, China or in Pamukkale, Turkey. In cave passages terraces with pools up to several meters are common on sloping flowstone. On stalagmites one finds similar forms with pool dimensions of centimeters down to millimeters.

These beautiful and intricate patterns look similar, independent on their scale and result from precipita-

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tion of calcite from supersaturated water flowing down stream from some source.

Because of their striking geometrical properties and apparent self-similarity these features have recently attracted attempts to find models, which can reproduce such shapes. By assuming a feedback between the hydrodynamics of flow and the precipitation rates Veysey (2006), Goldenfeld et al. (2006), Chan and Goldenfeld. (2007), Hammer et al. (2007), and Veysey and Goldenfeld (2008) presented a dynamical theories of pattern formation of rimstone terraces with statistical properties similar to those in nature. Using linear stability analysis of the underlying dynamical system Chan and Goldenfeld. (2007) showed that on inclined planes with turbulent flow a linear instability on all scales is the cause for scale invariant formation of rimstone terraces.

Hammer et al. (2007) reduced the complexity of the underlying differential equations by assuming that the precipitation rates are proportional to the flow velocity. This way, the flow over a given surface is first calculated and in a second step this result is used to obtain the new surface. By iteration of this procedure simulation of rimstone patterns could be obtained as they evolve in time.

In this paper we report on observations of rimstone terraces on the cm scale, which we have observed in two caves of Slovenia. Both have grown on stalagmite-like structures and exhibit striking differences.

THE STALAGMITE IN ŠKOCJANSKE JAME (ŠKOCJAN CAVES)

The Škocjanske jame (Škocjan Caves) developed near the contact between impermeable flysch and carbonate rocks od Kras plateau (SW Slovenia). The genesis and the present day hydrology are dominated by its allogenic recharge Reka river, which re-emerges about 35 km SW near the Bay of Trieste. The total length of the Škocjanske jame system is 6,200 m, while its main geomorphic feature is an underground canyon, 2,600 m long, 10 – 60 m wide, and up to 146 m high. The observed stalagmite grows on the left bank of the river in the middle part of the canyon called Putic's hall. The height of the ceiling above the stalagmite is about 70 m, while the roof

![Fig. 1](image_url)

**Fig. 1:** a) An example of small terraces on the cm-scale from Mammoth Hot springs Complex at Yellowstone National park, Wyoming, USA. The picture has been taken at a vertical distance of 2 meters. b) Digitized trace of rimstone dams from Fig. 1a. c) The simulated terrace forms calculated for statistical comparison with the features shon in Figs. 1a and 1b. (from Veysey (2006); see also Veysey & Goldenfeld (2008)).
thickness is about 120 m. The data is taken from the laser profiles recorded during the survey in 1996. The location of Škocjanske jame is shown on Fig. 2. Fig. 3 shows the generalised profile and map of the cave with the approximate position of the stalagmite. The excerpt presents the cross-section of the canyon taken at the site of the stalagmite.

Fig. 4 shows the stalagmite from the location described in Fig. 3. Its height is about 1.50 m and its diameter 2 m at its base. At the steeply inclined walls the surface shows some smooth wavy structures. But where the speleothem exhibits areas of smaller inclination, a wealth of structures appears. The top of the stalagmite is a flat circle with about 1 m diameter. Fig. 5 illustrates the rich structure decorating this horizontal part of the stalagmite. Pools of various sizes, all filled with dripping water are the basic structural element. They are separated by rimstone dams. At the bottom of the pools one finds crystalline calcite particles. At the side of the stalagmite the speleothem continues its growth as flowstone with changing slopes. At these parts rich structures are

**Fig. 2:** Map of Slovenia with the locations of Škocjanske jame cave system and Dimnice cave.

**Fig. 3:** Plan and extended elevation of Škocjanske jame with the position of discussed stalagmite. The shadowed rectangular excerpt shows a cross-section of the underground canyon at the position of stalagmite. The height of the ceiling is about 70 m, the roof thickness is 120 m. Source: Slovenian cave cadastre.
A topic of future work could be an intense documentation of the statistical properties and the scales of such features and to measure the corresponding slopes,

do dominating, as can be seen in Fig. 6, which gives views at different parts of the speleothem, all looking very similar.

The size of the pools depends on the slope. Structures become smaller with increasing slope.

This is clearly demonstrated in Fig. 6, which gives a closer view to the terrace forms. A flat structure of large elongated rimstone pools with average length of about 8 cm and an average width of 2 cm is surrounded by steeply sloping walls. These also exhibit rimstone structures of smaller pools of about 1 cm width. From these observations one could speculate that the slope of the underlying surface controls the size and the shape of the rimstone dams.

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The cave Dimnice located in SW Slovenia is about 8 km long and almost 180 m deep (Fig. 2). It belongs to the contact karst of Matarsko podolje, where the series of blind valleys evolved along the flysch - limestone contact. The cave has two entrances, both shafts of about 40 m depth. These are connected with a series of large, well decorated dry galleries. The deeper parts of the cave consist of smaller stream passages. Water in the cave originates from the nearby sinking stream. The observed speleothems are located in Vilinska dvorana (Fair’s Hall) close to the main entrance. Fig. 7 depicts the details. On the slope consisting mostly of loose gravel some unique speleothems are found. A series of globular mounds about 1 m in height exhibit active growth with water supply from the cave roof about 20-25 meters high (the data is taken from the cave map in Slovene cave cadastre). The upper parts are covered by caps of white calcite, which show dendritic structures. These features are illustrated in Fig. 8.

Basically the structure is stalagmite-like with diameters of several ten centimetres. Such radii can grow only with a feed rate of about 10 drops per minute to the apex of the stalagmite (Dreybrodt 1988, 1999; Romanov et al. 2008a, b). When we visited the cave a thin layer of water covered the speleothems. Much more interesting features are growing below the white caps of calcite at the top. Fig. 9 illustrates step like structures at the steep side, which consist of various small pools filled with water. Fig. 10a gives a view from the top of the stalagmite. Various rimstone dams of rectangular or polygon shape, with almost straight walls are seen. A close up view of
Fig. 9: Step-like structures at the steep side consisting of various small basins filled with water (Photo: F. Gabrovšek).

Fig. 10: a) Top view of the stalagmite. b) A close up view of some isolated basins (Photo: F. Gabrovšek).

Fig. 11: Vertical distribution of rimstone pools the shape and size of the pools changes with increasing slope (Photo: F. Gabrovšek).

Fig. 12: a) Rimstone dams at Pamukkale, Turkey. b) Patterns similar as in Dinmice cave occur on large scales as isolated ponds at Pamukkale (Photo: F. Gabrovšek).
some basins in Fig. 10a is presented in Fig. 10b. All rimstone dams, some with rectangular shape are isolated and do not touch each other. At the time of our visits they were filled with water. The bottom of these pools is covered by calcite crystals with a diameter of a few millimeters. The widths of the dams are in the order of about ten centimeters.

As shown in Fig. 11, larger dams are only located where the slope is still moderate. Further down, where the walls of speleothem become steeper, the features become smaller and also attain triangular shapes.

**DISCUSSION**

We have presented two distinctly different landscape patterns of rimstone dams on speleothems on the scale of centimetres. Both may have in common that most likely they originated at low water supply of dripping waters from the roof of the cave. As a consequence, flow was laminar everywhere. Nevertheless the rimstone patterns at the base of the stalagmite in Škocjanske jame (Figs. 4-6) are strikingly similar to large-scale patterns (Fig. 12), when large amounts of water generate turbulent flow over the lips of the dams. Fig. 13a shows such a structure of rimstone dams on Pamukkale, Turkey. Patterns, similar to those observed in Dimnice, occur on large scales as isolated ponds at Pamukkale (Fig. 12b).

When modelling terrace structures various assumptions were considered:

- a) Hammer *et al.* (2007) and Chan and Goldenfeld (2007) considered the growth of terraces under turbulent flow and assumed that the deposition rates depend only on the velocity of flow.
- b) Deposition rates are independent of the distance from the water source to the local position. In other words, the amount of water feeding the terraced is so large that its Ca$^{2+}$ concentration remains unaffected by the amount of calcite deposited on its way down.

However, models assuming growth rates, which depend on the local slope and decrease with distance from the input source (Jettestuen *et al.* 2006) also have been used successfully to create realistic models of rimstone dams.

The features of our observations are created in the chemical systems H$_2$O-CaCO$_3$-CO$_2$, where deposition rates at given chemical composition depend on the depth $h$ of the water layer covering the surface (Buhmann & Dreybrodt 1985; Dreybrodt *et al.* 1997; Baker *et al.* 1998).

For laminar flow three regions are found:
- a) At depth smaller than 0.005 cm, the deposition rates are linearly dependent on the depth $h$, because precipitation is limited by slow conversion of H$_2$CO$_3$ to CO$_2$.
- b) In the region 0.01 cm $< h < 0.04$ cm, rates are only weakly dependent on depth, because both CO$_2$-conversion and diffusion control the rates.
- c) For deeper water films diffusion becomes rate limiting and the rates decrease with increasing depth.

In turbulent flow diffusion is highly enhanced and is no longer rate limiting. Theoretically, if turbulent flow could arise for water depth $h < 0.05$ cm, rates would depend on $h$ as in the case of laminar flow, because CO$_2$-conversion solely is rate limiting (Dreybrodt & Buhmann 1991). With increasing depth, rates increase until they reach a maximum controlled entirely by surface rates. In reality the rates are controlled by a laminar diffusion boundary layer which separates the solid surface from the turbulent core of the fluid. Nevertheless, for $h > 0.1$ cm, the rates increase significantly with increasing depth, until $h = 10$ cm, when a maximum is reached (Liu & Dreybrodt 1997).

Although from this different behaviour in laminar and turbulent flow differences of precipitation patterns should be expected, this does not seem to be the case in nature.

One way out of this problem could be to couple precipitation rates to the depth of the water, which is controlled by flow velocity. Then, the precipitation rates in both laminar and turbulent flow follow similar rules.

For laminar flow the rates increase with water depth until they reach a maximum and decline drastically for a depth of more than several millimetres in the pool. In case of the turbulent flow above the lips of the dams, the rates also increase with depth until they become constant at depths of about 10 cm. In the pools, however, the fluid stays almost stagnant and the rates are significantly lower. This has been observed in the field by Liu *et al.* (1995) and Bono *et al.* (2001).

From this reasoning future modelling could try to couple flow and precipitation rates by a simple function of water depth, increasing linearly with depth, reaching a maximum and then declining to some lower value.
REFERENCES


Liu, Z. H. & W. Dreybrodt 1997: Dissolution kinetics of calcium carbonate minerals in H₂O CO₂ solutions in turbulent flow: The role of the diffusion boundary layer and the slow reaction H₂O+CO₂ reversible arrow H⁺+HCO₃⁻.- Geochimica et cosmochimica acta, 61, 2879-2889.


