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PROMINENT ACHIEVEMENTS IN CAVE STUDIES IN HUNGARY

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The papers in the present number of Karszt és Barlang (Karst and Cave) provide, in thematic groupings, the activities of Hungarian speleologists and their most important results. The reviews show that the development of speleology — as of any other science — progresses through continous and meticulous foundation work and just occasional discoveries of great importance. For this reason, the final output is equally dependent upon the many, many speleologists in the background as well as the gifted or lucky researcher who finally compiles the sensational new theory. More than a thousand reports and studies have been published by our cave exploration groups to supply evidence to the importance of that background work. The present paper, however, emphasises the other side of cave exploration; it provides a summary of the prominent achievements which fundamentally influenced the development of the individual branches of speleology or received international attention because of their particularly interesting nature. This article summarises just the Hungarian results.

I would like to underline that it is a subjective judgement to decide that something is prominent and in this case I made the judgements. The list is naturally incomplete and rather a selection of extracts. I apologise to those whose important discoveries are not included in this paper. Certainly the description of the activities of some scientists means repetition of parts of other articles, but the reader is kindly asked to pardon this, as the viewpoint from which they are cited here is different.

The karstification process

The role of climate and vegetation in karstification by cold waters

In the late 1950s the accumulation of information on the evolution of tropical karst features called attention to the contradictions in views on the rate of karst denudation. Previously (in the first place according to Corbel's school) the opinion was widely held that karstification is faster in a cold climate, since the aggressivity of water containing carbonic acid is inversely proportional to temperature. The concept seemed to be supported by measurements: rivers under cold climates transported ten times more dissolved $CaCO_3$ that those in warm belts. Why is it then that karst features are better developed in the tropics than under cold conditions?

The contributions of László Jakucs (1971, 1977) and Dénes Balázs (1964, 1965, 1969, 1971) to the settlement of this issue are of great significance. They revealed the fundamental role which the vegetation on the limestone surface plays in controlling the rate of karst denudation. While the free atmosphere contains only 0.03 per cent carbon dioxide, soils — as a result of their dense vegetation — commonly have CO_2 contents of 1 to 10 per cent. The amount of soil CO_2 depends on the activity of biological processes in the soil mantle, which makes infiltrating rainwater much more aggressive under the abundant vegetation of the tropics than in the temperate or polar belts. This is the reason why the dissolution of limestone is quicker under a soil cover. D. Balázs (1969) conducted laboratory experiments and L. Jakucs (1971, 1977) made field measurements to test the above statement.

L. Jakucs and D. Balázs also contributed to solving the contradiction mentioned in this introduction. The poverty of tropical rivers in dissolved $CaCO_3$ is explained by the fact that only the amount of $Ca(HCO_3)_2$ in equilibrium with the atmospheric carbon dioxide at that temperature can be retained in water, and the excess of $CaCO_3$ dissolved in karst groundwater is precipitated in caves or at springs. This precipitation is limited in the case of polar karsts.

The rate of denudation is also influenced by the amount of precipitation, which is greatest in the tropical belt. Consequently — although the $CaCO_3$ contents of rivers are lower — the amount of $CaCO_3$ transported during unit time is larger.

Top: A bat-mother with her baby (by Cs. Forrásy)
Bottom left: Lapiés near Aggtelek (by P. Borzsák)
Above it: Typical plant of the lapiés: Potentilla arenaria (by E. Siklósi)
Bottom right: Karst water tracing, Aggtelek Karst (by G. Salamon)

Recognising the role of vegetation in karstification, Jakucs arrived at a novel and surprising statement: forest clearance and the destruction of vegetation cover (involving sooner or later the erosion of the soil mantle) do not promote, but instead reduce, the rate of karstification. (It should be noted that this observation was made as early as the fifties by H. Kessler in connection with the investigation of karst waters in Albania and his report attracted much attention in professional circles.)

The selective karst corrosion of dolomite

Much of the dolomite which occurs in Hungary — particularly along structural lines — is heavily disintegrated and altered to dolomite flour. This weathering cannot be explained by sub-aerial mechanical processes, since the disintegrated rock remained in situ and preserved its original stratification and bedding. The phenomenon is due to the impact of hot waters ascending along faults *(Pálffy M. 1920; Scherf E. 1922; Brugger F. 1940; Jakucs L. 1950)* and depositing aragonite (or anhydrite) in the pores of the dolomite. During the cooling of the rock this transformed into calcite (or gypsum) and the increase in volume disintegrated the dolomite into debris.

Jakucs (1971, 1977) also pointed out the process of selective cold water karstification contributing to the weathering of dolomite. His starting point was that dolomitic rocks usually have a surplus amount of $CaCO_3$ compared with the Ca content of chemically pure dolomite. This surplus Ca takes the form of calcite and cements the rhombohedral crystals of mineral dolomite ($CaMg[CO_3]_2$) in the texture of the dolomite rock. During the karstification of this rock the dolomite crystals and the cementing calcite dissolve simultaneously *(Markó, 1961)*, but the degree of solubility is lower for the latter than for the former. This finally leads to mineralogical separation and further to loosening the bonds between the dolomite grains, and the rock weathers in situ. With this concept, *Jakucs* also explained why the usual karst features are not characteristic of impure dolomites: selective karst corrosion is predominant and dolines and lapiés fields only develop in compact, chemically pure dolomites, where the dissolution of dolomite crystals is not preceeded by the selective dissolution of calcite.

The karst corrosion effect of carbon dioxide of metamorphic origin

The chemical analysis of the Buda thermal springs revealed a strange contradiction. The dissolved carbon dioxide content of spring waters was found to be proportional to the temperature of thermal waters. On the other hand — according to now accepted views — ascending hot spring waters originate from the deep circulation and hence warming of cold karst water, which descends in the mountains and flows in convection currents under the Great Hungarian Plain *(Vendel M. and Kisházi P. 1964)*. We would expect the concentration of dissolved CO_2 in the ascending waters to be almost equal or — because of dripstone formation — less than that of infiltrating waters. However, infiltrating waters at 10 °C contain 198 mg per litre CO_2, while in waters at 20 °C, 264 mg per litre is found and in those at 60 °C 466 mg per litre. This paradoxical situation was solved by *P. Müller (1971)*.

The carbonaceous rocks of the Great Plain basement, buried and metamorphosed at depth, release (by the estimation of *P. Müller, 1971)* at least 1 ton CO_2 annually from every square km, and this is dissolved in the water flowing over the basement. The actual amount of CO_2 dissolved depends on the time the waters spend underground. (By C^{14} dating, it is known that the Buda hot springs waters infiltrated into the rock ca 15,000 years B.P. It is to be noted that the C^{14} dating of 15,000 years ago is only correct if the water has not been mixed with other.) But the warming of water is also proportional to the time spent underground, and this explains the ratio of CO_2 contents and temperatures. The basic conclusion on karst corrosion drawn from Müller's argumentation is that limestone solution does not only take place from descending waters near the surface, but may also be by thermal waters of metamorphic origin, which ascend from great depths and become aggressive with CO_2 acquired at depths of over a thousand metres.

As the metamorphism of carbonaceous rocks also takes place in orogenic belts and along the margin of subductive oceanic plates, this process may also be characteristic of other karst regions. This could explain the formation of giant caves (e.g. Hölloch and Dachstein) below the karst water table (in the saturation zone).

Origin of caves

Mixing corrosion theory of cave formation by hot springs

The morphological features of caves in the Buda (and partly in the Pilis) Mountains are fundamentally different from those in sinkhole caves with stream; they have horizontal and vertical labyrinths, blind chimneys reaching up in a dendritic fashion, spherical niches, no net flow direction and a relatively regular trellis pattern of equal-rank passages. The idea of an origin by hot water, to explain some of these features (blind chimneys and spherical niches) originated long ago *(Pávay-Vajna F. 1930; Kessler H. 1936; Jakucs L. 1948)*, but several important properties were not explained (for instance, why ascending thermal waters did not become aggressive). A unified theory for the reason of all cave features was missing for the Buda Mountains. *P. Müller* (1974) undertook to create one.

The CO_2-bearing thermal water flows through densely jointed and faulted dolomite (with a rectangular fissure system) and then emerges through limestones and marl along the Danube bank, at the foot of the Buda Mountains. The narrow fractures of the dolomite only allow percolation flow. The flow extends over a large area, but the resulting depression in the permeable rock directs it towards springs. Thus, in the vicinity of springs (from the fractures in the limestone overlying the dolomite) waters converge from various sources, with various temperatures and chemical compositions (CO_2 contents). It has been proved that through the mixing of such solutions the water becomes aggressive (or more aggressive if unsaturated waters mix). Since a karstified rock is highly permeable, the cold karst water percolating downwards from the surface may reach great depths, and mixing with warm water may occur in an extended vertical zone. Consequently, thermal spring caves form through temperature mixing and concentration mixing corrosion along the tectonic fissures.

The theory explains why thermal caves are associated with recent or fossil springs and why they have large vertical extent. The model also accounts for the other morphological features in the thermal caves of Hungary *(Müller P. 1974)*. Müller's theory was supported by measurements in a presently developing underwater spring cave labyrinth, the Molnár János Cave.

A model of shaft or pothole formation purely by corrosion

Karstic shafts, as studied in Hungary, show certain distinctive characteristics, but their explanation in a single comprehensive theory has been lacking for long and even today there is no universally accepted answer to many questions. Shaft or potholes (term used in England) are vertical caves, but most of them are independent of passable horizontal stream caves, according to the examples of Alsó-hegy (North Hungary). At present they do not function as ponors and their positions do not indicate earlier ponor or sinkhole functions. They reach down to several hundred metres' depths, and they consist of a chain of offset shafts connected by narrow passages and broadening downwards. Their entrance is mostly found in a ponor, but in the side and not on the bottom of the doline.

Previous theories say that shafts (potholes) are secondary karst features and their origin was ascribed to upward extension from the ceiling of horizontal caves *(Cholnoky J. 1916; Kessler H. 1933)*. These models, however, only explained the downward widening of shafts, but did not account for their other properties. Although *Jakucs (1971, 1977)* first raised the idea of shaft (pothole) formation as an independent, primary karst corrosion phenomenon, the first unified theory without contradictions and considering all the features of shafts is associated with *I. Sárváry* and *P. Müller (1970)*. They supplied evidence that shafts form simultaneously with dolines and make genetic units with them. Their theory identifies the following stages in shaft development *(Fig. 1)*.

1. Karstification begins over the exposed limestone surface, and embrionic dolines emerge. The solution of rock is confined to a shallow zone some

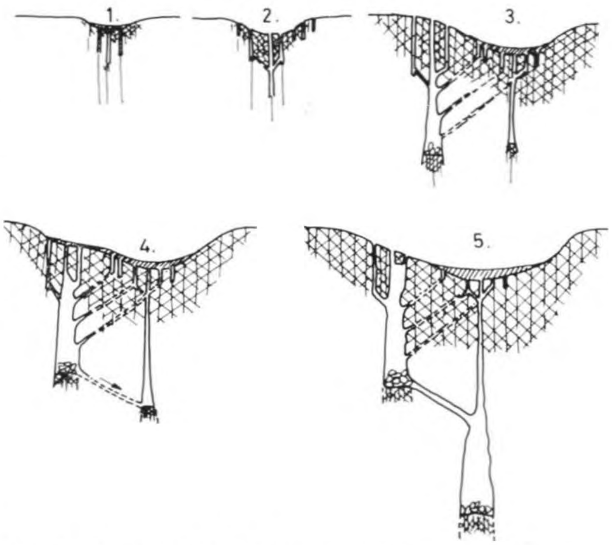


Fig. 1 Stages in shaft formation by Sárváry (1970)

metres below the surface, since waters become saturated at greater depths.

At places where there are fractures at least a millimetre wide in the rock, water sinks rapidly (without causing solution) and the corrosion effect is located at the bottom of the crack. The fissure with low hydraulic resistance produces a hydraulic cone of depression around itself, and drains the percolation water in the nearby capillary fractures into the larger fissure. Water flow in the fissure, therefore, increases and the mixing of waters of various concentration makes it more aggressive. As a consequence the solution zone is lowered in the area around the fissure.

2. This process starts at several points in the doline and the fissures deepen at various rates. At any one time, the deepest fissure drains, through the depression created, the other downward reaching openings. Thus the mixing-corrosion mechanism outlined under 1. and the increases in flow go on at an ever increasing speed.

The rate of shaft widening suddenly increases when the depth limit is reached at which ascending air cannot warm up the rock and melt the snow of the shaft. This way the amount of water necessary for corrosion is available all through the year.

3. Since the hydraulic cone of depression of the embrionic shaft exerts a draining effect in its surroundings, the deepening of the doline slows down at this point. As a consequence, the deepest point of the doline shifts away from the shaft. At the new deepest point a new shaft begins to form.

The new shaft will naturally be narrower than the previously developed, but it deepens at a greater rate, since the bottom of the doline receives more water than the old channels now in the side of the doline. On the other hand a similar amount of solution causes larger growth at depth.

4. The base of the new shaft sooner or later becomes deeper than the old one, and creates a cone of depression that drains its water. At this point the

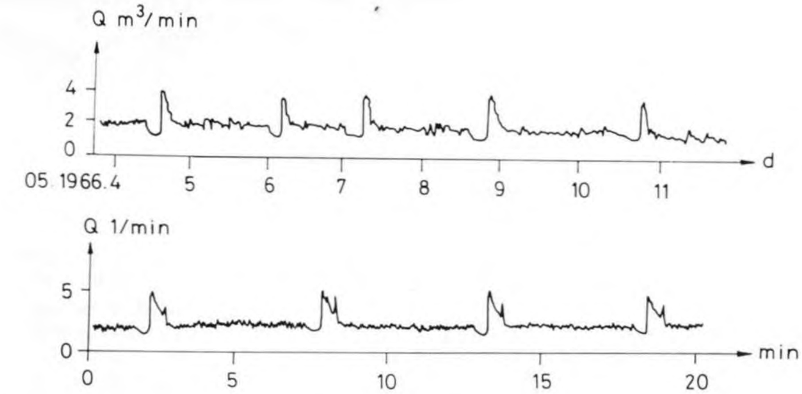


Fig. 2 Original hydrograph for the Lófej Spring of Jósvafő and the changes of flow recorded in the hydraulic pipe model

further deepening of the original shaft slows down and then stops, and its water contributes to the widening of the young shaft. The increased flow of water, and renewed aggressivity by mixing, leads to the formation of a wider and more rapidly deepening shaft.

5. At the bottom of the old shaft, now inactive, with respect to corrosion, debris can accumulate and block access between the shafts for people, but it presents no obstacle to water flow. (The more complex explored shafts are characterised by narrow passages connecting the shafts, and this supports the theory.)

Sárváry and *Müller* have confirmed their theory with examples taken from reality, and also with numerical estimation of the rate of corrosion.

Hydrological processes effecting caves

Experimental simulation of karstic sinks

In the vicinity of Jósvafő there are numerous extraordinary karst springs (with caves), some of which show regular fluctuations of flow independent of precipitation *(Fig. 2)*. This fluctuation (often known as ebb-and-flow) is most striking at the Lófej Spring, where minimum flows (during drought) are 50 litres per minute, but during surges rise to 5,000 litres per minute. (The surges of the nearby Nagytohonya Spring also have outputs up to 5,000 litres per minute.) It is also characteristic of the Lófej Spring that between surges, occurring very often at 12, 24 and 48 hour intervals, a flow pulsing of 150 litres per minute and 0.5—2.0 hour period is observed, and its period is reduced before surges. The surge is immediately preceeded by a state of constant water flow, without pulsing, lasting for 5 to 6 hours *(Fig. 2)*.

The reason for this unusual regime was revealed by *L. Maucha (1967)*, who assumed that this fluctuation in flow is related to the activity of a complex system of sinks. (The idea of the existence of karstic sinks was first raised by *Anker (1962)*, the first evidence was provided by the investigations of *Maucha.)*

Maucha used an electric analogue to show that the system of Lófej Spring consists of two large sinks (A and B) and a small sink connected in parallel (C) *(Fig. 3)*.

Fig. 3 shows that the overflow level of A lies higher than that of B. Sink C connects with sink A through a narrow section and its overflow level is somewhat below that of sink A.

The activity of the triple sink system can be summarised as follows. The water-course feeding the system recharges simultaneously sinks C and A. When water level reaches the overflow height of C, the downsurging water in the descending branch of the sink creates a vacuum in C and drains its total water content (about 30 m^3). This water induces some pulsing in the spring flow (the small amplitude section in *Fig. 2)*.

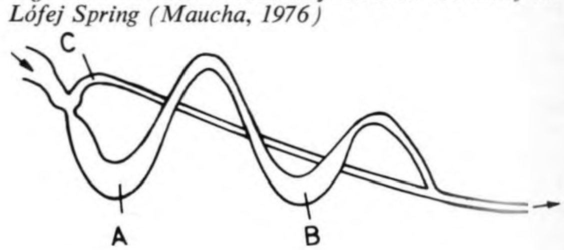
When sink A is full the water overflows into sink B (about 300 m^3); in the meantime pulsing stops as the suction effect emerges at the bottom of sink C. During this period there is only base-flow from the spring, since the flow is consumed to recharge reservoir B (about 270 m^3 — see the minimum section before surges in *Fig. 2)*. When B is being emptied about 500 m^3 water leaves through the spring and this represents the surge itself (surge section in *Fig. 2)*.

Then the process begins again from the initial stage. This intricate hydraulic mechanism was simulated in the laboratory by Maucha and the correspondence with the hydrograph of the spring was good *(Fig. 2)*.

Fluctuation in joints and the tidal oscillation of karst water table

The periodicity of both the Lófej and Nagytohonya Spring surges shows a similarity to the tidal motion of the seas. It seems that the surplus water which overflowed sink A (and triggered the surge) is related to the tidal fluctuations of the gravity field

Fig. 3 A theoretical sketch of the sink system of the Lófej Spring (Maucha, 1976)



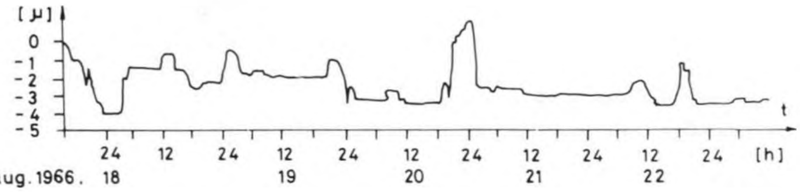


Fig. 4 Tidal changes in the size of a fissure in the Vass Imre Cave

of the Earth induced by the Moon and the Sun. To settle this problem, *Maucha*, with the assistance of *Gádoros* and *Sárváry (1966, 1968, 1971)* conducted precise measurements in the Vass Imre Cave.

The results showed that the rise of the Earth surface during terrestrial high tide (involving growth of this section of the Earth's perimeter) induces horizontal stretch tension in the crust. This results in the considerable widening of vertical north-south joints (the average expansion is 0.5×10^{-3} mm, but in extreme cases the figure may reach 2—5×10^{-3} mm); during low tide, joints rebound into their narrow positions *(Fig. 4)*.

Since karst water is located in the fissures and the caves of the limestone, the periodical changes of the fissure volume necessarily involve the rising and lowering of the karst water table. The average range of fluctuation is 10 cm (exceptionally around half a metre) and this induces minor floods on cave streams. This small flood wave can be observed on the hydrograph of the Little Tohonya Spring which has no feeder sinks. On the other hand, this fluctuation may trigger changes in the sink systems, and so induce surges of several hundreds of cubic metres.

Maucha proved that the extreme values of tidal rock motion coincide with earthquakes and with large-scale and rapid changes in atmospheric pressure, when permanent deformations of 10^{-3} mm dimension are generated in the rock.

Cave formations

Dripstone discoloration and surface morphology

In the Baradla Cave and particularly in the Béke Cave, which is free from sooting by old lamps, researchers observed that the distribution of dripstones of various colour is uneven along the passages. In order to determine any regularity of this distribution *L. Jakucs (1961)* analysed 14,335 dripstones and found that the nature of discoloration is closely related to the surface morphology and the vegetation above the cave.

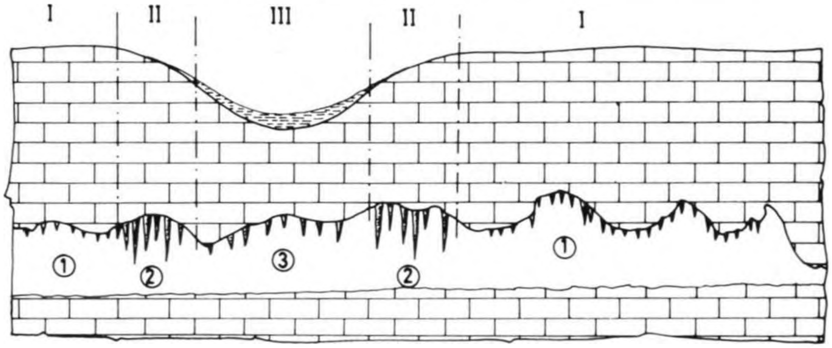
His observations indicate that in cave sections where the overlying terrain is of low relief (and parallel with the horizontal cave with stream) dripstones develop slowly to relatively small size, with uniform colour, and with only slightly contaminated material. Contrasted with these, there are sections where the cave runs under the sides of a doline, and large, inhomogeneously coloured and chemically heavily contaminated dripstones are found. In these latter dripstones, zones of various colour alternate in a concentric pattern. This phenomenon can only be observed under doline sides with less than 8—10 degrees slope. Underground with steeper gradients the amount of inhomogeneous dripstone does not increase within the cave. Under the central parts of dolines, however, dripstones are fewer and smaller, and, in parallel, the proportion of red dripstones increases greatly *(Fig. 5)*

This relationship between surface morphology and dripstone colour is explained by differences in jointing. Under dolines the rock is more densley jointed than below flat terrains which are less affected by superficial karstification. On the sides of dolines the soil mantle is also shallower, or entirely missing. For these reasons, infiltration is faster over these spots and — lacking the filtering effect of soils — the chemical composition of the water reaching the cave shows more serious contamination. The final consequence is the faster growth of more colourful dripstones.

Doline floors are usually sealed by red clay (terra rossa), which hinders infiltration. Therefore, in cave passages below dolines dripstones develop in smaller numbers and to smaller size. At the same time the terra rossa functions as a filter, removing contamination (colouring materials) from rainwater, but — due to its own iron content — stalactites are stained red.

Jakucs (1971, 1977) recognised that in areas where forest clearances took place within the last hundred years (the longest period for which data are available) or where the vegetation was removed from the surface, dripstone formation came to a halt and stalactites received a red coating. After the reintroduction of vegetation, dripstones began to develop pure layers again, devoid of chemical contamination. Consequently the changes in the colour of consecutive concentric layers of dripstones provide evidence for landscape changes above the cave — even back over several millennia.

Fig. 5 Colour and size of dripstone deposits and the relationship with surface morphology above the cave. I: flat terrain; II: doline side; III: doline floor; 1: pure and homogeneous dripstone; 2: inhomogeneous, large dripstone; 3: red dripstone



Theory for the origin of certain types of helictite

Previously they were thought to be rare, but subsequently clustered or isolated helictites have been found in many caves. Their peculiar forms and crystal structures attracted the attention of mineralogists, and various hypotheses were set up to explain the mechanism of their formation. *F. Cser (1967)* and *L. Maucha (1968)* evaluated the proposed explanations, and made mathematical and physical calculations to test them, and arrived at the conclusion that most of the models are burdened with contradictions. They also indicated that study on the minerals in caves could be worthwhile. In particular, their theory on crystals precipitating from the cave air is a novel one.

As shown by the physical-chemical investigations of *Cser*, helictite formation depends on drops of water containing dissolved $Ca(HCO_3)_2$ falling from the cave ceiling. They splash as they impact on the floor or on a stalagmite and the resulting microscopic droplets — due to their small size and friction with the air as described in Stokes' law — remain suspended in the air for a long time as an aerosol. Meanwhile, the water of the droplets partly evaporates, since relative humidity in the cave is always less than 100 per cent. Evaporation results in loss of volume and increased concentration of $Ca(HCO_3)_2$. According to the law of reducing tensions, increased concentration makes the vapour pressure, corresponding to the state of saturation, decrease, and consequently the evaporation of the water (as the solvent) stops, even at a relative humidity less than 100 per cent (the same physico-chemical effect is responsible for the rise of boiling-point in solutions). Consequently drops of water of 10^{-2} to 10^{-4} mm diameter, supersaturated with dissolved calcium bicarbonate and incapable of evaporation are suspended in the cave air.

If such a drop hits the cave wall, crystallisation from the supersaturated solution immediately begins. However, attention should be paid to the situations where splashing droplets are charged with electricity (as proved in the Millikan experiment). If a charged droplet passes a pointed formation, the electric peak effect produces opposite charges on the drop, and the formation attracts the water droplet to itself. As a consequence, the surplus calcium carbonate of the supersaturated water droplet precipitates on the pointed protrusion of the cave wall. The apex of the rhombohedron of the new calcite crystal would trigger further crystallisation.

This theory (also confirmed from the results of experiments) explain the observation that pointed helictites are single calcite (or twinned crystals) and that there is no relationship between their crystallographic axes and the shape of helictites.

In a very demonstative way, *Cser* drew parallel between ice and calcite crystals. Dripstones form in a manner similar to icicles, while helictite formation is analogous to hoar-frost accumulation.

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