<table>
<thead>
<tr>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SONG LIN HUA: Origination of Stone Forests in China ................................................. 3</td>
</tr>
<tr>
<td>F. JASKOLLA, P. VOLK: Use of Cave-Maps for Tectonic Surveys ...................................... 15</td>
</tr>
<tr>
<td>ARRIGO A. CIGNA, P. FORTI: The Speleogenetic Role of Air Flow caused by Convection. 1st Contribution ........................................................................................................... 41</td>
</tr>
<tr>
<td>HERBERT D. GEBAUER: Kurzbericht der Ersten Deutschen Speläologischen Himalaya- Expedition. (Preliminary Report of the first German Speleological Expedition to the Himalaya) ........................................................................................................ 53</td>
</tr>
</tbody>
</table>

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ORIGINATION OF STONE FORESTS IN CHINA

Song Lin Hua

ABSTRACT

The stone forests are widely distributed in the tropical and subtropical climatic areas. The stone forests may be divided into hilltop stone forest, hill slope stone forest and the stone forest in the depressions or valleys. The conditions for stone forest development should be (1) thick and pure limestone, (2) gentle dipping of limestone formation, generally less than 15°, (3) a lot of vertical joint and fissure networks, (4) the soil covering on the limestone surface inhomogeneous, thick in the fissures and thin on the rock top surface, and (5) the soil should be wet and contain rich organic materials and CO₂.

In the above conditions, the stone teeth may develop to the stone forest. If lack of organic soil, low humidity and stable depth of soil erosion zone, the stone teeth is only been developed.

1. INTRODUCTION

The stone forest is defined as the group of stone pillars with over 5 m high. If less than 5 metres high, it is generally named stone teeth. The stone forests broadly distribute in the palaeotropical and subtropical climatic

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Fig. 1: Distribution of Stone Forests in South China
STONE FORESTS

areas, such as in Lunan and Kunming of Yunnan Province, Puding and Meituan, Guizhou Province, Xingwen of Sichuan Province, Luota, Huayuan and Yongshun in Hunan Province (Fig. 1). The stone forests not only make the natural scenery more beauty, but also attract great numbers of karstologists and geographers to look into the origin of the forests.

There are a lot of hypothesis to explain the development of the stone forests. Ma Xirong (1936) suggested that it was resulted from the surface dissolution of limestone. Jie Xieyi (1966) described the development of stone forest should be with the conditions of: (1) very thick limestone; (2) the dipping of limestone formation must be near horizontal or gentle, generally the dipping angle is less than 10 degrees; and (3) it develops in the vadose zone and commonly occurs in the watershed or near watershed areas. In “Karst Research of China” (1979), the author pointed out that the stone forests should be developed in the conditions of thick and gentle folded limestone, rainy and humid palaeoclimate and the palaeolandforms suitable to water vertically dissolving the limestone. Ren Meie (1980) stated that the stone forests are the collections of stone pillars separated by the dissolution along the fissures in horizontal and thick limestone, distribute on the slopes of basins nearly the water divide zones and are palaeotropical karst features. Chen, Song, and Sweeting (1985) recognized that the forests are dominantly produced by the subsoil erosion and retransformed by the dissolution of rainwater.

In the last few years, the author have investigated the stone forests in Lunan, Xingwen, Huayuan, Meituan, Yongshun and Lengshuijiang. Some conclusions may be worked out.

2. LITHOLOGY AND GEOLOGICAL STRUCTURES FOR STONE FORESTS DEVELOPMENT

The stone forests are dominantly developed in the thick pure limestones (Table 1). The Lunan Stone Forest mainly develops in the lower Permian Maokuo limestone, the maximum thickness of the bed may reach up to 30 metres and more. The Xingwen stone forest distributes in the third section of Maokuo (Pm3), the biodetritus limestone with 5 metres of maximum bed thickness. The stone forest in Buermen Park, Yongshun County, Hunan Province, is developed in Ordovician dark pink limestone with 1-3 m layer thickness. Only the Xiaopaiwu forest in Huayuan County distributes in the dolomitic limestone with about 2 metres of single bed thickness.
Table 1 Chemical compositions of limestone the stone forests developed in

<table>
<thead>
<tr>
<th>Site</th>
<th>Formations</th>
<th>Compositions (%)</th>
<th>CaO</th>
<th>MgO</th>
<th>R₂O₃</th>
<th>SiO₂</th>
<th>loss</th>
</tr>
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<tr>
<td>Lunan, Yunnan</td>
<td>Maokuo (P₁m₁)</td>
<td>31.95</td>
<td>20.60</td>
<td>0.62</td>
<td>0.29</td>
<td>46.54</td>
<td></td>
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<tr>
<td></td>
<td>Maokuo (P₁m₂)</td>
<td>56.12</td>
<td>0.05</td>
<td>0.32</td>
<td>0.29</td>
<td>43.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maokuo (P₁m₃)</td>
<td>55.33</td>
<td>0.08</td>
<td>0.10</td>
<td>0.04</td>
<td>43.22</td>
<td></td>
</tr>
<tr>
<td>Luota, Longshan,</td>
<td>Maokuo (P₁m₄)</td>
<td>50.70</td>
<td>1.12</td>
<td>0.67</td>
<td>6.66</td>
<td>40.85</td>
<td></td>
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<tr>
<td>Hunan</td>
<td>Maokuo (P₁m₁⁺²)</td>
<td>53.13</td>
<td>1.11</td>
<td>0.10</td>
<td>0.33</td>
<td>43.82</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>55.89</td>
<td>1.38</td>
<td>0.06</td>
<td>0.51</td>
<td>39.01</td>
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Most of stone forests are developed in the gentle or horizontal limestone or dolomitic limestone, such as the dipping angle of Maokuo limestone in Lunan is about 10° or less. Stone forest limestone in Xingwen varies in the range of 7-17°. Ordovician limestone in Buermen Park is less than 10°, the dipping angle of dolomitic limestone in Xiaopaiwu is less than 20°. It has been discovered that the high and huge stone forest is generally developed in the block of gentle limestone and the dipping angle less than 15°, while the shorter and smaller one in the limestone with the dipping higher than 15°. There is no possibility for stone forest to develop in the high dipping limestone (Group of Luota Karst, 1984).

The development of stone forest is closely related to joints and fissures. In the process of folding by the geoforce, the rigid limestone rocks is easily broken as to form the vertical opening, joints and fissures which are nearly right crossed each other, or conjugated joints or fissures. For example, the Lunan stone forest is controlled by the net of joints and fissures of N20°W, N50°W, N.60°E and EW with 80-90° dipping angles. Xingwen stone forest is affected by N60-70°W, N35-25°W, N5-30°E and N70-80°E. The stone forest in Buermen Park is restricted by N45°W, N80°E and N65°W joints and fissures. Also Luota forest is dominantly controlled by the joints of N50°W and N30-40°E.

3. MAIN TYPES OF STONE FORESTS

According to the covering conditions of the stone forests may be divides into 3 groups: (1) bared stone forest; (2) covered stone forest and (3) buried stone forest. Based on the geomorphological occurrence of stone forests, it may be classified: (1) stone forest on the hill top (hilltop stone fo-
rest); (2) stone forest in the depressions and valleys and (3) stone forest on the hill slope. There three types are described as follows:

(1) Stone forests in the depressions and valleys

The depression and valley-stone forests are characterized by the big dimensions, large distributing areas and stone pillars perfectly separated. Take Lunan stone forest for example, the Dashilin, Xiaoshilin and Mother-son going for a walk etc are all developed in the karst depressions covered by one metre or more Quaternary sediments and with many karst dolines, sinkholes and subsurface drainage systems. The Sword Peak Pond is a typical karst natural lake. During the rain season, the water could be drained out by the underground drainage system, the groundwater table will rise up, sometime, the depression is flooded: for example, the tourist path in Unique Scenic spot depression was covered by over one metre of water. Another example is that there is a surface stream in the Xiaopaiwu karst depression which the stone forest develops in (Fig. 2).

Fig. 2 - Stone forest in Xiaopaiwu karst depression, Huayuan, Hunan Province.
(2) Hilltop stone forest
The pillars are grown up on the complete base (Fig. 3). The height of the individual pillar is short, generally about 10 metres or little more, sometimes reaching up to 30 metres. The cover on the base rock is less than 1 m. Commonly, the covering sediment is short, such as the New Stone Forest in Lunan.

(3) Hill-slope stone forest
The features are between the stone forests of depressions and hilltop. It is closely related to the stone teeth.

Fig. 3 - The stone pillars on one base.
The main mechanism of the stone forest development is the subsoil erosion by soil water to enlarge the fissures and separate the rocky block.

Author paid attention to the relationship between the soilwater hydro-dynamics and the stone forest development during the investigation of the Xingwen stone forest. The weathered and corroded limestone is gradually covered by residuary materials or soil which contains abundant humus and CO₂. When the rainwater with little CO₂ drops on the ground surface, it will absorb the CO₂ of soil air and released directly from the biogences on one hand, on other hand, it penetrates downward in the soil. The penetrating water takes two ways, one moves down as the soil water, the other, as the surface water, moves in the contact zone between the limestone surface and soil (Song, 1985). The surface flow is the main dynamic factor to enlarge the vertical joints and fissures, while the erosion ability of the surface flow will be greatly lessen after flowing the distance of about 2-3m. In the section of strong erosion, the fissures and joints are rapidly enlarged and widened. In the part of less erosion ability, the water way is narrow. Therefore, the subsoil erosion feature is like a long funna. Due to the space of fissure narrowing in the vertical direction, a part of soil water will flow to the contact and mix with the saturated surface flow. So the mixing flow will get new erosion ability to corrode the limestone, and the feature like the string of beads may be discovered (Fig. 4). If the elevations of two neighbour soil-filled pits is different, the soil water might flow from the higher one to the lower one through the fissure or joint. In the rainy season, a temporary underground water saturation zone is formed and a rather horizontal subsoil tube would be developed (Fig. 5). Though under the gravitation the velocity of vertical penetrate flow is higher than that of horizontal flow and the horizontal flow is temporary. The erosion of horizontal flow containing high CO₂ content is very strong.

The slope erosion makes much soil with great humic and organic materials in the depression bottoms. The speed of stone forest development in depression is 10 times higher than that of the forest on the hilltop (Yan Qingtong, 1982), that means that even if stone forests on the hilltop and in the depressions may simultaneously develop the size of stone forest but the hilltop is smaller than the depression-stone forest normally 20-30 m, max. 35 m high. Generally, the base of hilltop stone forest is exposed, the main mechanism is the rainwater erosion. Sometimes, the weathering is stronger
than the stone forest development. Thus, the Xingwen stone forest on the hilltop is the residual one with only 1 or 2 pillars on one hill.

The erosion of rainwater on the top of stone pillars has created the solutional cups, bows, basins, small gully and flute the depth of the both is from several mm to 1 m. The rainwater erosion is playing important role or shortening the stone forest. From this point of view, the speed of stone forest development is determined by the soil water and surface water but not by the rainwater.

Fig. 4 - Subsoil erosion pits like the string of 2 beads.
5. STONE TEETH AND STONE FOREST

There are some different point of view about the relationship between stone teeth and stone forest. Someone state that the stone forest is developed from the stone teeth (Zhang Shuyue, 1984). The others argued that it is possible for stone forest developing from stone teeth, but also stone teeth may develop from stone forest.

In fact, the relationship between stone teeth and stone forest is very
complicated. The hypothesis of stone forest developing from the stone teeth is correct, but it only takes place in the position with gentle dipping and thick limestone with a lot of vertical joints or fissure nets, and covered by the organic and humid soil. The Lunan stone forest is a good example. In the place where the cover is very thick and the soil is well conservated, the depth of subsoil water erosion is stabilized, le limestone is homogeneously dissolved under the soil though the intensity of the erosion in the joints and fissures is comparable high. Hence, it is possible just the stone teeth develops. If the soil inhomogeneously covers the limestone and soil ground surface is contineously lowered down, the strong erosion zone gradually goes down too. The thickness of soil layer is not uniform everywhere, that means in the joint and fissure zone, the soil is thick but in other part thin. In the evolution process of stone forest, the joint and fissure are

Fig. 6 - The evolution stage of the stone forest
1. original fissured limestone
2 and 3 subsoil erosion to enlarge the fissures and form the stone teeth
4. stone forest development
gradually and strongly enlarged and deepened. The erosion intensity in the thin soil cover zone or the composed places is weak. The large fissure is the main water moving way, there is generally developing the sinkhole or shaft. Thus, the stone teeth may evolve to the stone forest (Fig. 6).

In the place of the dipping more than $15^\circ$, the joints or fissures probably are developed well but they are not vertical on the ground surface. With the enlarging of joints and fissures, the upper part of limestone block is commonly cut off and the heigh of the limestone block is restricted. In other words, the stone teeth is the principle karst features.

If the soil contains high content of calcareous materials, the soil water is already saturated before it reaches on the contact surface of limestone with soil. Thus the joints and fissures are widen very slow and it is very difficult for stone forest to develop.

If the soil water erosion zone is very stable after the stone forest developed, the base of the forest is erosed for a long time and the stone pillars will fall down. On the base of the fall pillar will develop new stone teeth.

REFERENCES


USE OF CAVE-MAPS FOR TECTONIC SURVEYS

Franz Jaskolla*, Peter Volk**

ABSTRACT

Results of the author’s investigations show the useful application of cave-map-data for tectonic assessment.

Considering speleological features, cave genesis, and structural differences, it is possible to select of the cave map’s pattern various jointing and stress systems. By 7 selected cave maps, representing areas of different tectonic history (W-Germany, Austria and Switzerland) it will be demonstrated that three types of kinematic joint-systems can be identified (fundamental, orthogonal- fold- and shear-system).

Therefore, tectonic models are expected to become more valuable. It must be stated that future tectonic investigations in karst-areas should include the additional use of cave maps.

1. INTRODUCTION

Basing on extensive activities of private people and organisations, a broad and detailed knowledge on the course and construction of numerous caves throughout different karstic regions is existent.

Although very important basic information are collected, often the naturale sciences neglect them as something like ‘‘hobbyscience’’ — a fact, which is proven by literature, specially in geology.

Nevertheless, detailed surveys of caves and numerous descriptions on the situation of passages can be applied advantageous as an additional information source (BAYER, 1985).

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** Dr. Peter Volk, Gesellschaft für Angewandte Fernerkundung - GAF -, Leonrodstr. 69, D-8000 München 19.
With this presentation, we want to demonstrate the relationship of mapped passage traces and tectonic elements and the impact specially on microtectonics. Starting point is an investigation of VOLK (1982) which outlines the improvement for microtectonic models considering measurements of joints in cave systems.

2. FUNDAMENTALS

2.1. THE DEVELOPMENT OF ENDOKARST (BÖGLI, 1978)

Karst phenomena are an essential and unique characteristic of all carbonate rocks. Fundamentally, the genesis of caves within endokarst is depending on the intensive solubility of carbonate in presence of acidulated water and an extensive jointing (TRIMMEL, 1968).

2.1.2. PHREATIC STAGE

Corrosion is the most active process under phreatic conditions (rock formation is beneath the karst water table) if vugs or capillary active planes are existent (BÖGLI, 1978).

Fig. 1: Appearance of tectonic and sedimentary planes in cavity-crosscuts.
Special significance has to be put to the mixing corrosion which appears at intersections of planes keeping different acidulated waters; thereby aggressive CO$_2$ is nascent and enables again solution of carbonates (HÖLTING, 1980, see fig. 2).

Mixing corrosion is the most important fundamental to explain the relationship of passage traces and tectonic elements.

2.1.2. VADOSE STAGE

Vadose conditions appear if the water table declines leaving initial cavities. Processes at this stage are characterized by normal corrosion and erosion of subsurface flows. Sintering is another important phenomenon.

TRIMMEL (1968) demonstrated, that the intensity of sinter deposits is increased within highly jointed zones; this fact, again, can be used for tectonic investigations.

2.1.3. COLLAPSE

This desintegration stage characterizes a final step in the development of cave systems (BÖGLI, 1978). Of course, the suitability of those areas for the task in mind is decreased.

Fig. 1 summarizes the appearance of sedimentary and tectonic planes in cavity crosscuts with respect to the evolution stage.

Fig. 2: Development of elliptical shaped passages due to mixing-corrosion at intersections of joint (conc. CO$_2$ (1)) and bedding plane (conc. CO$_2$ (2)).
2.1.4. THE GENESIS OF PASSAGES - BASIC CONSIDERATIONS

As it was sketched before, most of the caves are originated and controlled by tectonics. Concerning the network caverns, however, a genesis by bedding planes was supposed without any influence of tectonic planes (BÖGLI, 1978).

But considering typical cross sections (e.g. Breathing Cave and Höllloch, see fig. 18 and 19) and cavity crosscuts (BÖGLI, 1978, p. 280, plate 3), a crucial influence of tectonic elements can be postulated. A strongly marked orthogonal pattern, elliptic crosscuts and very long plane passages underline this supposition. A considerable influence has the already mentioned mixing corrosion (fig. 2).

By this model, also the genesis of large caves can be explained taking into account the fact, that faults and lineaments mostly represent broad zones with intensely deformed and jointed rock complexes (JASKOLLA, 1978). Schematically, this is demonstrated by fig. 3. The solution of the

Fig. 3: Scheme for creation of big cavities due to mixing-corrosion. Main reason is the location at intersections of bedding plane(s) and joint- and fault swarms.
carbonate starts within small, mostly linear zones (phase I) which leads summarizing, to large caves (phase III); characteristically they show turbulent walls with small slightly curved elements (BÖGLI, 1978). In this framework, joints must not be split open but can also represent planes able for capillary migration (BÖGLI, 1978, MURAWSKI, 1969).

The background of such a development concerning vadose corrosion was investigated mathematically by FRANKE (ref. TREIBS, 1962). Although he wanted to line out climatical influence and changes on the development of caves, his results support our model significantly.

By this extension on the genesis of caves results an additional basis for the correlation of passage traces and tectonic structures. Therefore, it is possible to use most passage traces as indicators for tectonic structures.

2.2. SOME FUNDAMENTALS ON MICROTECTONICS

In this presentation it is neither possible nor necessary, to discuss in detail the fundamentals and problems of microtectonics.

Nevertheless some indispensable explanations for the understanding of the following demonstration of examples have to be premised.

It was SANDER (1948) who defined the theoretical basis by his cognition, geometric structure of a jointed rock reflects the physical forces acting on this body. Until now, this fundamental consideration was verified deductively by manifold investigations (e.g. ADLER, 1970; SMOLKA 1977; JASKOLLA, 1976, 1978).

Summarizing the results, the following joint system can be distinguished specially when considering carbonate rocks:

- Orthogonal System (BOCK, 1980)

  This type has to appear within all carbonate rocks because it is caused by diagenetic processes. Significantly two swarms of orthogonal joints are existent, differentiated by their degree of regulation. If shear joints can be observed, they have to be explained by a superimposed stress (e.g. folding).

- B-oriented jointed system

  If a horizontal compressive stress is acting on layered rocks, folds will be originated. With respect to the intensivity in time and space also typical joints will results. They show a distinct orientation towards the regional B axis. Besides “parting ruptures” shear joints are generated which enables a characterisation of folds.
Joint system related to faults

Mainly, there are three reasons responsible for such a joint system:
- the compressive stress acting on a rock is exceeding the mechanical boundaries of folding;
- the compressive stress is acting on non-layered, massive rocks;
- dilatation stress is acting on rocks.

Again "parting ruptures" and shear joints will be generated.

It is obvious, that these types may be superimposed on an intensively stressed area - a fact which can impede the association of joint systems significantly. Considering some criterions (e.g. statistical data collection and preparation, synoptic interpretation), however, these problems can be minimized.

2.3. DATA COLLECTION AND PREPARATION

To fulfill the task in mind, it was necessary, to select cave maps which realize the following requirements:
- sufficient accuracy of a survey must be guaranteed;
- detailed crosscut and cross sections have to be available;
- the selected cave maps should represent areas with different tectonic evaluation.

Fig. 4: Part of a cave plan (Binghöhle, fränk. Höhlenatlast C 15, Aufnahme H. Cramer, 1937, 1938) for demonstration of passage traces and joints.
In the framework of our investigations the following experiences could be gathered which are fundamental for an efficient application of cave maps for tectonic investigations:
- the association of passages and tectonics depends on the quality of survey and the description of cave systems; an increasing accuracy enlarges the applicability significantly;
- crossing traces of joints or fractures can be interpreted, if the cross section of passages shows salients on both sides of the walls (see fig. 4);
- a passage is indicated as a tectonic element by plane walls;
- isohypsal contours and their variations are important indicators of tectonic planes (fig. 5); secondary formations (sinter deposits, cave sediments, incasion) have to be considered;
- a separated evaluation due to the different zones in a cave (phreatic -phreatic-vadose - vadose) is necessary;
- the following parts of active maps are not usable: spiral passages (German: "Schneckengänge"), meandering canyons and broad regularly curved passages; due to isotropic large-scale jointing and vadose erosive processes, the tectonic origin is obliterated;

Fig. 5: Example for the importance of isohypsal contours in a cave plan (Lamprechtsfofen, Kat. nr. 1324/1, Höhlenplan Bl. 4, Originalplan nach KLAPPACHER et al., 1976). Note: Lamprechtsdom (h = 117m above entrance) and Steinbachklamm (h = 88m) are bound to one fault plane. Strike and dip can be taken approximately from the contour lines within the Lamprechtsdom.
in addition, big desintegrated cavities are not statistically usable, although they mostly are situated at points of intersection of faults (BÖGLI, 1978, fig. 6).

Considering these criterions we generated maps containing lineaments; they refer to interpreted passage traces and represent the strike of tectonic planes.

Statistical preparation of the data was carried out using the facilities (hard-and software) available at the Department of Photogeology and Remote Sensing at the Institute for General and Applied Geology, University of Munich (HENKEL, 1982).

The following rose diagrams were produced:
- number of lineaments per striking sector (10°);
- total length of lineaments per striking sector (10°);
- mean length of lineaments per striking sector (10°);
  (ratio of number and total length of lineaments).

Basing on these diagrams, tectonic stress system could be interpreted with additional information (description of cave systems, surface geology).
3. THE APPLICABILITY OF CAVE MAPS FOR TECTONIC INVESTIGATIONS - SOME SELECTED EXAMPLES

With respect to the basic joint systems described in chapter 2.2., corresponding examples of existing cave maps were selected. Their location is indicated by fig. 7.

- Orthogonal system: Geisloch near Streitberg/NE Bavaria
  Schönstein - und Brunnsteinhöhle near Streitberg/NE Bavaria
- B-oriented system: Schlüsselloch near Chiemsee/S Bavaria
  Frickenhöhle near Garmisch-Partenkirchen/S Bavaria
- System related to faults: Angerloch near Walchensee/S Bavaria
- Complex system: Lamprechtsofen near Lofer/Austria
  Hölöch/Switzerland.

Fig. 7: Position of caves, investigated in this paper 1 = Geisloch, 2 = Schönstein- und Brunnsteinhöhle, 3 = Schlüssellochhöhle, 4 = Frickenhöhle, 5 = Angerloch, 6 = Lamprechtsofen, 7 = Hölöch.
3.1. THE ORTHOGONAL SYSTEM

With an area of about 6.400 km², the "Fränkische Alb" represent the largest connected karst-surface of F.R.G. Flat-lying carbonate rocks of upper jurassic age offer ideal conditions for development of endo- and exo-karst. Intersected only by a few significant faults, the series are undisturbed. In addition, suitable results of detailed cave surveys are available. The occurrence of the orthogonal system can be demonstrated excellent on most cave.

3.1.1. THE GEISLOCH NEAR STREITBERG/NE BAVARIA

The cave best surveyed in the "Fränkische Alb" is the Geisloch (Franconian cave cadaster, No. c 58). It is running within nearly horizontal layered reef carbonates (dolomites) of tithonian age (Malm E, MAYER, 1972).

The existing cave map (DAUM in: SPÖCKER, 1980) was published in 1972 and shows up two nearly vertical passage system. The detailed evaluation of the passage traces and their statistical presentation confirm this first impression. Significant maxima of lineaments appear at 30° and, with an evident dispersion, between 110° and 150° (fig. 8).

![Fig. 8: Statistical distribution: length of passage traces per striking sector in the Geisloch.](image-url)
Taking into account the fundamentals of microtectonics, an improved interpretation is enable. While former authors (KRUMBECK, 1956) connected joints in this area with the few, regional important faults, the application of an orthogonal joint system (BOCK, 1980) results in a more sophisticated interpretation. A primary joint set representing three strikes at about 30° is accompanied by a swarm of secondary joints representing one. This swarm is characterized by a high dispersion and relatively short striking lengths due to the origin by stress inversion.

3.1.2. SCHÖNSTEIN - UND BRUNNENSTEINHÖHLE NEAR STREITBERG/NE BAVARIA

A few kilometers from the Geisloch, on the slopes of the Wiesent Valley, different cave system are located. They are described as “caves of the lower level”, which indicate as well the location of the mouth as the stratigraphic position within Malm B carbonates. For the demonstration of the suitability for tectonical analysis, the Schönstein - und Brunnsteinhöhle was selected (fig. 9). Obviously cave map and interpreted lineaments (as
traces of joints) offer an orthogonal passage pattern, which coincides surprisingly with the results obtained and described by BOCK (1980). This preliminary interpretation has to be relativized by use of statistical distribution of the number of evaluated lineaments (fig. 10). Two aspects have to be discussed comparing the results of the interpretation of the Geisloch:

- the differences of the orientation of the maxima and
- the angle of about 70° between the two maxima.

Concerning the last, rheological parameters of the thin-stratified carbonates may be responsible, expressing increased incompetent behaviour. The deviation of the strike direction, however, reflects differences in the stratigraphic development. MEYER (1972, 1974) proves, that due to facies differentiation an orientation of the dolomit reefs of Malm B of approx. 170° has to be suspected. The interpretation of this situation enables a correlation of the principle stress component 1 parallel to this stratigraphic boundary. Schematically, this reflection is demonstrated by fig. 11.

Interpreting the rose diagram of fig. 10 in this sense, again a typical orthogonal joint system is obvious.

Beginning with Malm B (MEYER, 1974) a facies boundary near Streitberg can be observed, which follows a direction of about 30° and is

Fig. 10: Number of passage traces per striking sector from the Schönstein - and Brunnsteinhöhle.
active until early cretaceous. Again an orientation of the principle stress component 1 parallel to this direction can be suspected - a fact already proven by the results of the interpretation of the data the Geisloch (fig. 8).

The evaluation of the "Fränkische Alb" data finally have elaborated two aspects:
- cave maps, respectively the traces of passage are suitable to describe the orientation of the orthogonal joint system;
- deviations can be explained, taking into account additional results of detailed geological investigations.

3.2. B-ORIENTED JOINT SYSTEM

3.2.1. SCHLÜSSELLOCH

The mouth of the cave system "Schlüsselloch" opens 1.274 m mean sealevel in the heavily karsted peneplain of the Laubenstein-Riesenberg area near Aschau/Chiemgau. Surveyes have outlined 1.400 m of passages with a depth of 150 m and a horizontale extend over 220 m, completely within the well corrosional Dogger limestone. This reddish formation
build up by numerous crinoids, is heavily bedded and shows enormous residual of undilatable clays.

The Laubenstein area is part of the so called Northern Synclinorium within the Lechtal-nappe (TOLLMANN, 1976). Triassic and jurassic sediments of different lithology have undergone a severe folding. Single folds are often displayed by B-parallel thrust faults and sinistral strike slip faults (FISCHER, 1962, LANGE, 1962; VOLK, 1982). The cave’s entrance is placed in the northern limb of a subordinate syncline of the synclinorium and its most distant parts run perpendicular to B into the hypothetical syncline core.

All passages show fracture bound origin and this allows a separation of the cave map’s structures into two different zones (CRAMER & TRILLER in TREIBS, 1962). Basing on detailed tectonic surveys, VOLK (1982) stated a specific superposition of folding phases for the main cave body, but a more regular pattern of surface near passages (phreatic created survey area west, fig. 12a). In this case, statistically insignificant distributions are caused by a superposition of orthogonal and B-oriented fracture patterns. In opposite, the most distant cavities show preferred directions, partly due to selective erosion (130°) and younger, big fault planes (170°), (fig. 12b). Specially their intersections were important for development of voluminous cavities, which are clearly bound to tectonically deranged rock. It seems that strong folding didn’t create many new joints and associate faults. Tectonic movements during a main phase of folding reactivated mostly the older, orthogonal system and subsequently rotated “tectonic blocks” within the carbonate body.

3.2.2. FRICKENHÖLE

The source “Kuhflucht” appears at 1.150 m mean sealevel near the western descent of the Estergebirge to the Loisach Valley. It drains nearly the entire alpine karst plain stretching eastwards to the small lake Wildsee. Only 100 m higher, the mouth of the Frickenhöle is situated at a steep slope. Cave length is more than 2.4 km with a vertical range of 57 m. All passages in the distant parts are hydrological active and mainly the “Styx” tributes most of its water to the Kuhflucht. The cave system is developed in well bedded uppertriassic limestone (Plattenkalk) between a dolomitic (Hauptdolomit) and a more shaly carbonate layer (Kössener Schichten). They are arranged in a syncline, B-striking 60° and dipping slowly to the SW (JASKOLLA, 1975). Different resistance to corrosion make the
Fig. 12: Number of passage-traces per striking sector from the Schlüssellochhöhle

Fig. 13: Statistics from the Frickenhöhle.
Plattenkalk-Hauptideolomit interface an acquicld. All water penetrating from the surface is gathered and flows towards the hydrological niveau of the Loisach. Drainage is completely controlled by the syncline structure and the dipping axis (WROBEL, 1970).

Due to the geological and hydrologica conditions cave genesis was heavily affected by intersections of the B-oriented fracture system and bedding planes. Erosion in the B-parallel drainage system widened the initial cavities and grew to the dominant factor in the cave’s history. So, nearly all passages show a convincing vadose shape; phreatic forms are rare and limited to a few places near the entrance.

Additionally recent landslips have created some so called ‘Urhohlräume’, initial cavities according to LEHMANN (1932). They are in a surface-near position and extended recently by vadose and corrosive forces.

Distributions of passage traces from the cave map identified clearly B and Loisach-fault-parallel fractures (fig. 13a). Number and length of mapped lineaments (fig. 13a and b) show two maxima in the 70° and 30° sector, pointing out the different importance of B- and Loisach parallel planes for cavity genesis. Minor accumulations are due to B associated shear joints, partly reactivated by the later Loisach faults. All significant tectonic directions obtainable in the field are discernible from this diagrams, demonstrating not only their qualitative distribution, but also nature in differentiation between long and short traces. An orthogonal joint pattern is not detectable; the selective and dominant features of erosion have superimposed them completely.

Summarizing, the cave map with its typical vadose erosive pattern is best suited to give an impression of young tectonic events but not to obtain sedimentary joint patterns.

3.3. JOINT SYSTEMS RELATED TO FAULTS

3.3.1. ANGERLLOCH

The “Angerlloch” is surveyed to only 600 m length at 40 m height in total and opens 2 km SSW of the Walchensee in the western slope of the Obernach Valley. A map was constructed in 1971 by TRILLER & VATER in DOBEN (1976, fig. 14). Situated at the eastern edge of the Estergebirge, this cave is a further witness of strong karst influence on Plattenkalk within the Bavarian Synclinorium. In opposite to Frickenhöhle it is domi-
nated by fault-oriented passage patterns. Sinistral, NE-striking strike slip faults, so called "Kesselbergstörungen" easily mappable on the surface, are a major factor.

The cave map (fig. 14) shows up three main passage directions, all having typical joint — and fault-bound crosscuts. Most obvious are lineaments striking 30°, sometimes changing in 0°; they are connected by lineaments at 150°. Statistical evaluation (fig. 15) identifies Kesselberg parallel features as a major, fault originated fracture swarm in this area (30°-40°, 20 % of all measurements). An absolute maximum (0°, 18 %) seems to represent an asymmetric h(k0-cluster associated with the main faults and both together give a good example of a Loisach fault pattern (sinistral strike). At 150° some passages are conjugated to the "Ammer" lineaments (dextral strike).

Also this diagrams integrate all regional important tectonical lineaments as joint- and fault clusters.

Fig. 14: Cave plan of Angerloch (Kat. nr 1271/1, Verein f. Höhlenkunde München, Aufnahme TRILLER u. VATER, 1971). Typical pattern of a fault bound passage system.
3.4. HUGE CAVE SYSTEMS OF COMPLEX GENESIS (KOMPLEXE RIESENHÖHLEN)

3.4.1. LAMPRECHTSOFEN

All recently investigated parts of the Lamprechtsofen (LAO) and other hydrological connected caves as Wieserloch, Rothöhle, Riesenkogelschlacht are developed in the northern roof of the Leoganger Steinberge (Salzburger Land, Austria).

Nearly the entire surrounding mountains are subterraneously drained by a network of canyons and piezometric tubes, sometimes appearing in the LAO. Thick uppertriassic carbonate sequence (Dachsteinkalk and dolomit) build up a deeply corroded karstic terrain. Near the cave system they are arranged in a N-dipping anticline. Huge N-S- striking and steeply dipping fault planes displace the stratigraphical boundary dolomite/limestone. KLAPPACHER & KNAPZYK (1977) found other tectonic important directions: NW-SE, NE-SW, E-W. As much as 90% of passages and cavities are judged as bound to fractures, expressing the absence of bedding planes within the massive carbonates.

Basis of the research was a map of KLAPPACHER & KNAPZYK (1977). Summed up to more than 12.7 km length, LAO represents a type
Fig. 16: Passage-traces per striking direction from phreatic created upper levels of the Lamprechtsofen.

Fig. 17: Passage-traces per striking direction from vadose-erosive dominated lower levels of the Lamprechtsofen.
of alpine caves, characterized best as huge cave systems of complexe origin. From this follows, to be cautious in the discussion of their tectonics (ref. 2.3). In terms of statistics a separation is possible into two genetical groups by field observations:

— old and inactive upper levels, mostly phreatic, extending in several floors above the recently active hydrological niveau;

— relatively young vadose-phreatic and vadose-erosive parts, influenced by the recent karst water level.

Despite of some restrictions (ref. 2.3.), all vadose-erosive overprinted parts of this system were included in the investigations, because detailed additional field information from KLAPPACHER & KNAPZYK (1977) and own research was available. Two different patterns are to discriminate. Phreatic upper levels are characterized by a typical orthogonal joint system (50°/140°, fig. 16). In the length/sector diagram additional faults are to recognize at 160°. The recently active lower floors (fig. 17) don’t show a orthogonal pattern, but the dominance of the youngest, 10° striking faults.

Thanks to tectonic surveys in some northerly situated and similar structured carbonate masses (BODECHTEL et al., 1982a; BODECHTEL et al., 1982b; VOLK, 1982) the N-S linears can be identified as very young normal faults of an alpine dilatation phase. This is conform to fresh polished surfaces observed on the central fault in the cave. Maxima at 150°-160° obviously are used as drainage tunnels and perhaps over-represented. They outline the shortest passages for penetrating water from the anticlinal’s centre to the hydrological base, approximately parallel to B.

3.4.2. HÖLLOCH

Inside the helvetian nappes of the “Schwyzer Kalkalpen” (Vierwaldstättersee/Switzerland) spread one of the most dendritic and best investigated cave systems. About 110 km length (1971) and total height of 740 m make an integrating consideration of all tectonic phenomena problematic.

It develops in the heavily karsted cretaceous limestone of the “Axendecke”. The cave vertically cross “Drusbergschichten” at the bottom, “Schrattenkalk” and at its roof enters the “Seewerkalk”. Some passages to upper levels even cut a minor nappe of the Axendecke.

Here, BÖGLI started basic research about speleological processes and their karst-hydrological meaning. He also published a detailed monogra-
The tectonic framework is outlined and N-S striking faults are delineated. He found a different structure of upper and lower levels: an hydrological jointbound upper floors, phreatic and inactive (fig. 19).

Similar to LAO, statistics of passage traces from upper levels implicate the phreatic origin due to the primary, orthogonal joint pattern (fig. 28). 80° appart, two cluster stand for the genetically oldest planes. The length/sector diagram intensifies an absolute 0° -maximum meaning a
Fig. 20: Passage-traces per striking direction from the ancient, inactive upper levels of the Hölloch.

Fig. 21: Passage-traces per striking direction from the active lower levels of the Hölloch.
few but extended faults. Passages in lower floors show an extremely de-
veloped 0° -direction, representing a good correlation with BÖGLI's results.
Undoubtedly they are mostly vertical, big-scale faults with unknown ten-
sion parameters. All other directions are of minor importance.

The last two examples demonstrate the ability of cave maps even from
huge and complexe systems, to be used for tectonic surveys, if thematic
processed before a statistical treatment.

4. CONCLUSION

Our presentation intends to demonstrate the suitability of cave maps
to support tectonic investigations.

Fundamental requirements for this were:

— the availability of detailed and accurate cave maps; fortunately, this is
guaranteed by the important activities of many "hobby speleologists"
within large areas;

— the solution of many speleological problems by BÖGLI and TRIM-
MEL;

— increased understanding of the fundamentals of microtectonics and
their enlarged applicability;

— improved possibilities of statistical data processing and presentation;

— last not least, the extension on the genesis of caves as it is proposed with-
within this presentation, is of upmost importance. It was possible to de-
monstrate that joint sets or fault zones are also responsible for the ge-
nesis of passages. Therefore, elliptical shaped passages like those of
"network caverns" can be interpreted as bound to tectonic structures,
too, though directly no tectonic plane is evident.

Nevertheless, the interpretation of cave maps has to take into account
the following aspects

— type of rock and stratification (e.g. dolomit - limestone, massive laye-
red);

— the genesis of a cave and its current stage (phreatic - vadose - erosive)
and

— secondary effects (e.g. sintering, incasion, cave deposits).
Although single examples stress out the significant influence of superposition of speleo-morphologic and tectonic features, it can be stated, that existing cave maps can support the selection of relevant fabric patterns and therefore tectonical investigations as a whole. Additional aspects can be obtained in transferring this conclusions to other disciplines as scientific speleology and especially hydrogeology. Since water supply is a difficult item in karstic areas, preferred joint-water bodies might be detectable by application of some ideas stated.

KURZFASSUNG

Die Ergebnisse nachstehender Untersuchungen zeigen, daß die Informationen aus Höhlenplänen tektonische Erhebungen nutzbringend unterstreichen können. 


Es ist somit eine Aussageverbesserung tektonischer Modelle zu erwarten, weshalb die zusätzliche Verwendung von Höhlenplänen in ähnlichen Untersuchungen an anderen Objekten empfehlenswert ist.

REFERENCE


THE SPELEOGENETIC ROLE OF AIR FLOW CAUSED BY CONVECTION. 1st CONTRIBUTION

Arrigo A. Cigna* & Paolo Forti**

ABSTRACT

In the past some authors described the speleogenetic role of convection in phreatic conditions. Similar effects exist also in the air-filled part of vadose passages of caves as a consequence of an air circulation due to a relevant temperature gradient; the effects can be enhanced by the presence of some acids as, e.g., H₂S, H₂SO₄, etc. In this paper the conditions matching convection and condensation which produce typical forms, very similar to those found under phreatic conditions, are discussed both for limestone and gypsum caves.

RIASSUNTO

In passato vari autori hanno descritto il ruolo speleogenetico di fenomeni convettivi in regime freatico. Effetti analoghi si verificano anche nelle zone emerse di livelli vadosi in conseguenza di una circolazione d’aria provocata dalla presenza di notevoli gradienti termici in atmosfera; questi effetti possono essere esaltati dalla presenza di acidi come, per esempio, H₂S, H₂SO₄, ecc. In questo lavoro vengono prese in considerazione, sia per grotte nel calcare che nel gesso, le condizioni che possono portare a convenzione e condensazione provocando così forme molto simili a quelle che si riscontrano in condizioni freatiche.

1. INTRODUCTION

This paper aims to describe the role of a new speleogenetic effect: the air flow caused by convection. Some typical shapes related to this type of air circulation can be found.

In the past the contribution of convection to speleogenesis was possi-
bly underestimated and, in any case, considered for the evolution of caves under phreatic conditions only (Bini & Cappa 1978; Muller, 1974; Muller & Sarvary, 1977; Rudnicki 1979). Some domes (not related to joints or small ducts) were considered to be caused by these phenomena. The presence of air bubbles was thought to increase the effect of water convection by the corrosion due to condensation (Bini & Cappa 1978; Muller & Sarvary, 1977).

Up to now air circulation due to convection was considered to have a negligible role in erosion processes and in a few cases only could produce some condensation followed by solution or corrosion (Pasquini, 1975). A more detailed knowledge of the speleologic mechanisms and the environments where they develop, particularly with reference to the karst and hyperkarst (Cigna, 1978; Forti & Perna 1986), emphasized the role of convection in cave atmosphere as a major factor in deep karst processes, even though cannot be the most important one.

In this paper, after a short theoretical description of air flow due to convection are given, then examples of caves, both in limestone or gypsum and in lava, where this effect was relevant, are reported. In the past these effects either were not studied or attributed to other causes.

2. AIR MOVEMENT DUE TO CONVECTION

This movement is due to the buoyancy of an air mass surrounded by air with a higher density. Air density is determined by its temperature, humidity and pressure, but in a limited environment pressure can be considered to be uniform and therefore it does not play a role in convection. Air density is given by the following formula:

\[ k = 3.484 \left( p - U_r \cdot p_w \right)/(273.15 + T) + U_r \cdot k_w \]

where:

- \( k \) = air density in kg/m\(^3\)
- \( p \) = atmospheric pressure reduced at 0°C, in kPa
- \( U_r \) = relative humidity (= for 100%)
- \( p_w \) = vapor partial pressure reduced at 0°C, in kPa
- \( T \) = air temperature in °C
- \( k_w \) = vapor density in kg/m\(^3\)
The $k$ values between 0 and 30°C when the relative humidity ranges between 100 and 60% are reported in Table 1. These data as well as the plots of Fig. 1, point out the greater influence of temperature to determine air density.

3. CONVECTION IN THERMAL CAVES

Some convection forms found in thermal phreatic caves were described by Rudnicki (1979). They are domes and spherical forms, sometimes overlapping each other, of different sizes.

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<td>1.1499</td>
<td>1.1506</td>
<td>1.1514</td>
<td>1.1528</td>
<td>1.1543</td>
<td>1.1558</td>
</tr>
<tr>
<td>27</td>
<td>3.57</td>
<td>0.0258</td>
<td>1.1451</td>
<td>1.1459</td>
<td>1.1467</td>
<td>1.1482</td>
<td>1.1498</td>
<td>1.1514</td>
</tr>
<tr>
<td>28</td>
<td>3.79</td>
<td>0.0273</td>
<td>1.1404</td>
<td>1.1412</td>
<td>1.1420</td>
<td>1.1437</td>
<td>1.1453</td>
<td>1.1470</td>
</tr>
<tr>
<td>29</td>
<td>4.01</td>
<td>0.0288</td>
<td>1.1356</td>
<td>1.1365</td>
<td>1.1374</td>
<td>1.1391</td>
<td>1.1409</td>
<td>1.1426</td>
</tr>
<tr>
<td>30</td>
<td>4.23</td>
<td>0.0303</td>
<td>1.1310</td>
<td>1.1319</td>
<td>1.1328</td>
<td>1.1346</td>
<td>1.1364</td>
<td>1.1383</td>
</tr>
</tbody>
</table>

Table 1 - Air density in function of temperature and relative humidity. Values are referred to a pressure of 100 kPa = 1 bar = 750 mm Hg.
Research carried out recently on the formations in Grotta Giusti (a thermal cave near Monsummano, Lucca, Italy) pointed out that the cave clouds were heavily corroded by a number of spherical domes also reaching and deepening into the limestone.

The corrosion of these formations are the consequence of a relevant air flow set up when the lowering of the water level started the air convection: air temperature gradient is rather high because the surface water temperature of the lake inside the cave is about 32-34°C while the rock wall at the upper levels is below 20°C. The corrosion is also enhanced by the high concentration of CO₂ in the water and, therefore, also in the air and in the water condensing on the cave walls.

The most common morphological feature due to convection in Grotta Giusti is a multitude of domes or hollow half-spheres in the roof and the walls in the higher series of the cave. The abundance of these forms, quite unrelated to joints or fractures, show that now the cave development is only due to convection processes (condensation and corrosion).

Due to the strong air flow, the condensation at the top of the domes is faster than the corrosion inside the domes and some furrows develop be-
low the domes. The edges of these furrows are decorated by coral-like formations.

To evaluate the actual importance of the corrosion due to convection, a simple calculation based on the parameters measured in Grotta Giusti was developed. In this cave the air temperature in the lower series is about 34°C and corresponds to that of a lake fed by thermal water. In the upper series the rock temperature is 20°C.

By assuming an atmospheric pressure of 100 kPa (750 mm Hg) and a relative humidity of 100% the absolute humidity at 34°C is 35.13 g of water per kg of air, while at 20°C it is only 14.95 g/kg: therefore the difference, 20.18 g/kg (corresponding to 24 g per m³ of air), is the condensed water. The air flow due to the rather high temperature gradient was measured to have an average velocity of 1 m/sec over a section of 4 m². Then it can be obtained by:

\[ 24 \text{ g/m}^3 \times 4 \text{ m/sec} = 96 \text{ g/sec} \]

i.e., nearly 100 g/sec of condensation water. In one day the total amount of condensation water is

\[ 100 \text{ g/sec} \times 86400 \text{ sec/day} = 8640 \text{ litres} \]

The concentration of CO₂ in air was determined to be about 1000 ppm corresponding to 0.038 mmoles/litre in water by applying the formula:

\[ K_c = \frac{[\text{CO}_2^\circ]}{p} \text{ (in moles/litre)} \]

The equilibrium constant \( K_c \) at 20°C is 0.0383 (Siedell, 1958; Picknett et al., 1976). A concentration of CO₂ of 0.038 mmoles/litre will dissolve about 73 mg/litre of CaCO₃ (Cigna, 1975, p. 400). Therefore in one day the total amount of CaCO₃ dissolved would be:

\[ 0.073 \text{ g/litre} \times 8640 \text{ litres} = 630 \text{ g} \]

Such a rather high amount is a clear indication of the importance of this phenomenon even if an equilibrium is unlikely to be attained and therefore the value must be considered as an upper limit.
4. CONVECTION IN PRESENCE OF STRONG ACIDS

In normal caves the thermal gradient is generally small and the convection can produce a slow air flow. But in particular conditions, e.g. in presence of H$_2$S, the effects can be enhanced by the corrosion due to H$_2$SO$_4$ formed by oxidation of the H$_2$S (Perna & Pozzi, 1959; Forti & Perna, 1986). The effect of H$_2$SO$_4$ on the development of karst phenomenon was extensively described also by Morehouse (1968). By assuming that the reaction of H$_2$SO$_4$ with the limestone will proceed with this formula:

$$H_2SO_4 + CaCO_3 + H_2O = CaSO_4 \cdot 2 H_2O + CO_2$$

and the condensed water has a measured pH = 3, it can be easily calculated that the reactants and the products will have the following concentrations:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Concentration (g/litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$SO$_4$</td>
<td>0.049</td>
</tr>
<tr>
<td>CaCO$_3$</td>
<td>0.050</td>
</tr>
<tr>
<td>CaSO$_4 \cdot 2$ H$_2$O</td>
<td>0.086</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Water with 22 mg/litre of CO$_2$ dissolves about 180 mg/litre of CaCO$_3$ (Cigna, 1975). On account of the common ion effect due to CaSO$_4$ (Picknett, 1977) a reduction of about 20% can be considered. But in such conditions the ionic strength of the solution is sufficient to lower the activity of the Ca$^{++}$ ions to a value of about 70% of its concentration. Therefore the final result of these two apposite effects causes a slight increase in the solubility of CaCO$_3$ which becomes something higher than 200 mg/l; therefore the total amount of CaCO$_3$ dissolved would be:

$$200 + 50 = 250 \text{ g/litre}$$

this value of about 250 g/litre corresponds to that of a rather aggressive water.

An example of an air flow (due to convection) with H$_2$SO$_4$ is found in the Grotta Grande del Vento (Ancona, Italy) in the area called “Fiabilandia”. Two potholes connect the lower series, where sulfide containing water flows, to the dry upper series of the cave. The roof of the latter series is characterized by many domes or huge ‘‘scallops’’ of different sizes and
partially overlapping each other. Their surface is covered by a thin layer of CaSO₄·2H₂O. The layer is thicker where the gypsum is not eluted by the condensation water.

The presence of the features here described suggests the possibility of the major role played also in the past by such a process in the development of large caverns. This hypothesis is supported by the existence of large gypsum deposits in many areas along the cave. A systematic research on this particular problem is expected to be carried out in the near future.

A similar hypothesis could also be made for Carlsbad Caverns where thick gypsum deposits are found in chambers whose roofs have many domes and hollow half-cavities. A speleogenetic process based on convection could be envisaged instead of a phreatic origin, which was considered valid up to now.

Fig. 2 - Solutional domes caused by condensation due to gas convection on the ceiling of a gypsum cave. An evidence of their genesis is that the evolution of the domes is still going on nowadays, while all the gallery is completely fossil (Photo by P. Forti).
5. CONVECTION IN CAVES DEVELOPED IN WATER SOLUBLE ROCKS

The air movement due to convection is a rather common feature and its speleogenetical role may be quite important in this kind of caves (Fig. 2). Nevertheless if the climate is too arid the condensation cannot occur and the convection has no consequences from the point of view of the cave development: this was the case of the halite caves of Mount Sedom (Israel) (Donini et al. 1985).

On the contrary, in regions with continental tempered climate the convection can produce large amount of condensation water. A typical example can be found in many gypsum caves near by Bologna (Italy). Caves with large exchanges between internal and external air (e.g. the cave system Grotta della Spipola - Grotta dell'Acquafrredda) develop many corrosion forms (domes, scallop-like cavities, hollow half-spheres, etc.) on the walls and the roof up to some tens of metres inside the entrance. In some instances these forms can be found further inside up to more than 100 metres.

In general these caves had a tectonic or a graviclastic origin but the corrosion features actually dominate the cave development in the vicinity of the entrances. The original features can be found in areas not influenced by convection.

Near the entrance of the Grotta dell'Acquafrredda on a typical summer day, the outside air temperature can be about 30°C with a relative humidity of 65% while the inside air temperature is 10°C. If the atmospheric pressure is assumed to be 100 kPa as in the other examples, the absolute humidity at saturation of the inside air is 7.76 g/kg. Therefore, on account of the outside air entering the cave, the condensation water will be 10.23 g/kg or 12.59 g of water per m² of air. The entrance has a section of 4 m² and the average air velocity is about 3 m/sec. In these conditions:

\[ 4 \text{ m}^2 \times 3 \text{ m/sec} \times 68400 \text{ sec} = 10^6 \text{m}^3 \text{ of air} \]

per day enter the cave; the condensation water will be:

\[ 12.59 \text{ g/m}^3 \times 10^6 \text{m}^3 = 13 \times 10^6 \text{ g of water per day.} \]

The solubility of CaSO₄ ·2H₂O being about 2.5 mg/litre, the total amount dissolved in one day might be:
of gypsum. Of course this figure is probably an upper limit of the actual amount because the solution of CaSO$_4$ *2H$_2$O will not reach a saturation condition. Also in this case the activity plays a noticeable role, due to the concentration degree of the solution. Therefore it can be assumed that the activity effect at least balances the lack of full saturation of the solution.

In the case of other water soluble rocks, as quartzites, the amount of material dissolved is smaller because at 10°C the solubility of quartz, which is the main constituent of quartzites, is about 8 mg/litre, i.e. about 300 times less than gypsum solubility. By way of comparison, in the same conditions of the previous example, the amount of quartzite dissolved would have been about 100 g/day, which are not negligible at all because of the very long time necessary for the cave.

Fig. 3 - Pendants generated by the melting of the ceiling in a lava tube. The melting is caused by local increase of roof temperature due to oxidations occurring in gas phase (Photo by P. Forti).
6. CONVECTION IN HYPOKARST CAVES

The lava caves are the natural caves where the gas flow due to convection has the most important role in the speleogenetic process as a whole. In

Fig. 4 - Large scallops developed via gas convection in an ice cave (Photo by M. Vianelli).
fact in these caves the forms produced by convection are not the domes (which, on the other hand, are often absent) and the scallop-like features but particularly the formations as the lava stalactites and stalagmites (Fig. 3).

Such formations are due to a local increase of the roof temperature on account of oxidation reactions which start when the lava tube is no longer completely filled with liquid lava (Wood, 1976). This effect is peculiar of the lava tubes and, of course, there is no equivalent effect in karst caves: therefore it can be concluded that the evolution of lava caves is greatly influenced by gas flow due to convection.

The speleogenesis of another type of hypokarst (Cigna, 1978; 1983; 1986) caves, the ice caves, is definitely influenced by the gas flow due to convection: many big "scallops" in the roof and the walls of potholes (Fig. 4) could be attributed to this cause. Some formations are also fed by the fusion water originated by the gas flow.

The mechanism of convection, therefore, seems to be particularly important for the speleogenesis of hypokarst caves in general.

7. CONCLUSIONS

Air flow (or, more generally, gas flow) due to convection plays a role, in the different phases of cave formation, which is more common and important than it was thought up to now. The effects are noticeable not only when a temperature gradient is high (as in thermal caves, rather often, it is) but also when the condensed water is very aggressive on account of strong acids (H₂S and H₂SO₄) or when the condensed water is more abundant as a consequence of a high relative humidity of the air entering the caves in summer time. For hypokarst caves (lava and ice caves) the effects are more important because they also influence the genesis of many formations.

The typical forms which can be attributed to the air flow due to convection are domes, hollow half-spheres, scallop-like features, etc. often rather shallow and overlapping each other, leading to large "scallops" in the roof. Sometimes coral-like formations grow along the edges of some domes. Stalactites and stalagmites are also formed in hypokarst caves.

The air flow due to convection is a fundamental speleogenetical mechanism which deserve much more interest. The knowledge of its effects is far from being exhausted and it is hoped that a great attention will be drawn on this particular topic under different particular conditions.
REFERENCES


ABSTRACT

The first german speleological expedition to the Himalaya went to the terrace-sediments of Pokhara, Nepal. New discoveries could be made in the longest cave of the Himalaya (Patalae Chhango or Harpan-River-Cave) and other caves were surveyed for the first time.

Due to the observations is the classification in the lump of conglomerate-caves as pseudokarst-appearances to be questioned.

ZUSAMMENFASSUNG

Die erste deutsche speleologische Himalaya-Expedition führte zu den Terrassensedimenten von Pokhara, Nepal. In der bisher grössten Höle des Himalaya (Patalae Chhango oder Harpan-River-Cave) konnte Neuland entdeckt werden und andere Objekte wurden zum erstenmal vermessen.

Aufgrund der Beobachtungen muß die pauschale Einstufung von Konglomerathöhlen als Pseudokarsterscheinungen in Frage gestellt werden.

1. DAS HÖHLENBILDENDE KONGLOMERAT


* Marktplatz 32, D-7070 Schwäbisch Gmünd
Die obenliegende Konglomeratbank ist etwa 15 bis 20 m stark und differenziert modal. Sie besteht aus einem ungeschichteten Durcheinander zwischen automobilgroßen Findlingen bis hin zu staubfeinem Sand aus Phylliten, Granat, Gneisen, Basalt, Kalk und vielem anderen mehr. Die Matrix besteht aus etwa gleichen Teilen Kalzitkristallen und Quarzsand.

Darunter liegt eine mindestens 40 m starke Konglomeratbank aus feinem Sand mit wenigen größeren Einlagerungen. Sie ist häufig geschichtet in unterschiedlich widerstandsfähige Schichten, die im allgemeinen nur wenig lithifiziert, spröde und porös sind. Sie besteht aus 50 bis 80% Kalzitkristallen und -sand, der Rest sind gerundete Quarzsandkörner, ein wenig Gips und organische Rückstände. Manchmal sind auch tonige Schichten eingelagert, die extrem labil sind.

2. CHARAKTERISTIK DER KONGLOMERATHÖHLEN

Da die Höhlen in zwei unterschiedlichen Konglomeraten verlaufen wird das allgemeine Erscheinungsbild der Höhlen dem höhlenbildenden Gestein entsprechend unterschiedlich geprägt.

Klüfte streichen selten eindeutig in gerader Richtung, sondern schlängeln sich eher durch eine nach unten und oben beschränkte Anzahl von Schichten. Auch verlaufen sie gern entlang den Talabbruchkanten und fallen meist senkrecht.

Die widerstandsfähigere obere Konglomeratbank bildet in den Höhlen entweder waagrecht hängende Decken, die sich freitragend über viele Meter hinweg von Wand zu Wand ziehen oder statisch ideale Gewölbe, welche abgespannte Schuppen inkadieren oder sich Kiesel für Kiesel sphärisch weiten.

In der unteren Konglomeratbank sind die Decken allenfalls auf kurzer Spannweite waagrecht und meistens als "falsche Gewölbe" aus einander überkragenden Schichtplatten gebildet.

Es finden sich für Konglomerathöhlen unerwartet große Säle und Versturzhallen (chemiosklastische Versturzsäle) die manchmal bis knapp unter den Zenith der Kuppeln mit charakteristischen Versturzbergen erfüllt sind, deren Flanken sich konvex den Versturzhallenwänden annähern.

In der oberen Konglomeratbank sind Sinterbildungen, dem
PATALAE CHHANGO
DEVIS FALL
Tashilling, Pokhara, Nepal, Asien

SEEHÖHE: ca. 900 m u. NN
GESAMTLÄNGE: 2056,7 m
MW DIFFERENZ: -48,1 m
VERMESSUNG: 6.2.1990
BCRA - Grad 56
Vermessung, Kontrah., Berechnung
und Zeichnung: O. Gebauer

1. Wasserfall, Patalae Chhango
2. Canon unter dem Wasserfall
3. östlicher Nord-Sudgang
4. westlicher Nord-Sudgang
5. Klockenhalte
6. Gang zum Phusre-Khola
außerordentlich geringen Kalzitanteil entsprechend, selten jedoch in der unteren unerwartet häufig. In erster Linie treten Stalaktiten auf, die in Reihen das Kluftnetz nachzeichnen oder in zusammenhängenden Flächen wachsen, wenn das sinterbildende Wasser flächig aus dem porösen Konglomerat dringt.

Bodenzapfen kommen selten vor und erreichen aber trotz des geringen Kalzitangebots bemerkenswerte Größen. Auch deuten tonnenschwere, sich auflösende Sintermassen auf eine sinterbildendere Zeit hin.

3. GEDANKEN ZUR HÖHLENBILDUNG IM KONGLOMERATKARST

Auch die neuere speläologische Literatur hat sich in Bezug auf Konglomerathöhlen noch nicht aus der aristotelischen Einfalt gelöst, wenn sie unberücksichtigt der petrographischen Unterschiede zwischen verschiedenen Konglomeraten alle Konglomerathöhlen pauschal als Pseudokarsterscheinungen abtut und nicht selten so einfach wie Kyrle schreibt, der Konglomerate zur Bildung großer Höhlen nicht für möglich hält, „weil solcherartige Höhlenräume, die ein gewisses Raummaß überschreiten, wieder in sich zusammenbrechen“ (Theoretische Speläologie, S. 19).

Das von Kyrle gemeinte Raummaß ist in den Hallen des Patalae Chhango gewiß überschritten. Das verzweigte Höhlensystem bezeugt eine echte Karstentwässerung des Konglomerats und allein die Sinterbildungen beweisen die Echtheit des nepalesischen Konglomeratkarstes.

Dennoch verkarsteten die meisten Konglomerate nicht im eigentlichen Sinn. Es muß deshalb eine in die Konglomerate hineingeschobene Definitions- grenze gefunden werden.

EVIDENCE FOR KARSTIC MECHANISMS INVOLVED IN THE EVOLUTION OF MOROCCAN HAMADAS

Vittorio Castellani *, Walter Dragoni **

ABSTRACT

Underground tubular karst features, observed in an arid environment of southern Morocco, are described. On the basis of various evidences, it is suggested that such features were originated mainly by condensation water. A computation of the time necessary for their formation supports this hypothesis.

RIASSUNTO

Si descrivono delle forme carsiche ipogee tubolari osservate nel Marocco meridionale e, in base a varie evidenze, si avanza l’ipotesi che il loro sviluppo sia dovuto essenzialmente ad acqua di condensazione. Il calcolo sui tempi di formazione rende plausibile tale ipotesi.

1. INTRODUCTION

The saharian regions of northern Africa are characterized by the well known “Hamadas”: limestone plateaux emerging abruptly from the desertic plains with a nearly flat sub-horizontal surface. South of the Atlas mountains, the Moroccan Sahara presents many structures of this kind, scattered but impressive relics of the continuous sedimentary continental formations deposited in the area from the early Cretaceous till the end of the Tertiary era.

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From East to West, the Hamada du Meski, Hamada du Guir, Kem-Kem and Hamada du Dra form a nearly continuous belt which runs from the Algerian border to the Atlantic ocean, roughly following the line of the High Atlas and Anti-Atlas ranges, some 200 km to the South (fig. 1). The tableland of the Hamada du Guir lays between the rivers Ziz and Guir, East of the last inhabited area of Erfoud. The upper part of this hamada is made up of a lacustrine limestone with horizontal bedding of un-
certain recent age (Pliocene, lower Pleistocene). The edges are deep and often vertical, so that the "kreb" (the arab name for a hamada edge) looks like a natural section of the tableland. From aerial photos one can easily detect a network of drainage channels, which often abort (fig. 2) in one of the thousands of shallow depression ("dayas") which cover the hamada surface, and whose diameters range from about 1 m to 1-2 km with a maximum depth of 3-4 m.

Gautier (1951) first suggested that northern saharian dayas may originate from karstic phenomena, reporting evidences of a water absorption

Fig. 2 An aerial photo of a portion of the Hamada du Guir, showing the sinuous border of the hamada and drainage channels, which often abort in closed "dayas". North at top. Scales in km.
Fig. 3 A map of a portion of the Hamada du Guir corresponding to the aerial photo in fig. 2. The network of drainage channels is shown, connecting (black areas) or aborting in (white areas) soil covered depression.
up to 85% of the water collected during a heavy rainfall. This view was further strengthened by Mitchell (1970) on the basis of analogies with dolines or poljes, and later by Mitchell and Willimot (1974) who pointed out that a downward leaching of the daya floor is demonstrated by the lower salt and carbonate concentration with respect to the surroundings.

In fig. 3, derived from aerial photos, a large portion of the hamada surface is shown, where closed areas represent the soil covered central region of dayas. Though some dayas are connected to form a surface network eventually able to drain water across and out of the plateau, most of the area is made up of closed basins where rainfall water is collected and absorbed (Castellani 1977).

The surface of the hamada has been explored by means of a computerized image scanning device at the Institute of Geology of Rome University. It was found that the area covered by daya soil is about 5% of the total surface. Such a ratio does not vary considerably along the 80 km of hamada explored in such a way, which supports the idea that dayas are a constant characteristic of the hamada texture. Further suggestions for the efficiency of an underground waterflow can be found in some "edge effects", due to the lack of vegetation in the dayas near the hamada edge. This effect could be attributed to a more efficient drainage from these dayas (Castellani and Dragoni 1977) enhancing the soil aridity.

Such a situation suggests that also in an arid environment karst phenomena can play an important role in the evolution of a limestone hamada. This led us to investigate the way in which karst can develop in such an environment.

2. EVIDENCE FOR DEEP KARST

The Hamada of Guir, presently the border between Morocco and Algeria, is subject to special restrictions which greatly hinders the possibility of field investigations. Nonetheless, during a recent stay in the region we succeeded in reaching a butte, a detached part of the northern border of the hamada (fig. 4), near the small village of Ali, in the Boudenib district. The surface of the butte (about 1000 m above sea level) is a stony desert, with almost angular stones that show its residual origin. An inspection of this surface again revealed the occurrence of the daya phenomenon: the surface was scattered with depressions whose dimensions ranged from 1 to 5 m in diameter and were less than 0.5 m deep. The stony cover did not al-
low us to see the underlying rocky surface, so that the occurrence of a karstic sink (or a set of absorbing fractures) could be only hypothesized at this stage.

For more insight into this problem, we decided to submit the kreb to a careful inspection: if any underground karst features had been present, they would have been intersected by the surface of the eroded and fast retreating kreb.

Fig. 4 a) The location of the butte near the Ali village.
b) Geological sketch of the region referred to in the text.
Following this inspection, we soon found clear evidence of a well developed karstic hypogeal network, able to support a consistent ground water flow. Two different and well defined morphologies could be identified. The first one involved the upper portion of the butte, had a thickness of about 15-20 m and was formed by vertical conducts with regular and nearly circular cross-section, whose diameters were in the range of 0.5-1.0 m (fig. 5). As the kreb has been destroyed by the vertical fractures, in some areas examples could be found of cross sections of these tubesemer-

Fig. 5 The edge of the butte near Ab. One can notice that the upper portion of the limestone bank has a network of vertical tubes intersected by the edge of the butte.
Fig. 6 a) Orthogonal view of the tubes in fig. 5
b) Another orthogonal view of the tubes in fig. 5; the light through the tube is due to caving in of its upper portion.
ging on a rocky roof (fig. 6a, 6b), allowing one to view it orthogonally. In all cases, these tubes lay at the crossing of at least two families of vertical joints.

Another interesting feature was found at the contact between the limestone bank and a marl bed. For a thickness of about 1 m above the marl bed the limestone had strong karsification, consisting of small and tube-like cavities with a radius of up to 20-30 cm, with a horizontal general trend (fig. 7).

These findings, as schematized in fig. 8, support the above suggestions that the daya are the surface elements of a larger karstic system. The
occurrence of such a system and the morphology of the surface of the Hamada of Guir, can have strong implications regarding the relationship between karst and climate in general and the evolution of a calcareous plateau in arid environments in particular.

Let us refer to the two principal kinds of karst: those developing in a temperate climate and those developing in a humid tropical climate. Following the early ideas of Civijic, Grund and more recent ones [see, e.g., Smith and Atkinson (1976) and Jacus (1964)] in humid tropical areas the soil cover is extremely rich in CO₂, so that “typical karstic dissolution” is much faster at soil-limestone contact than deep in the limestone mass. In such an environment Cockpit or Tower Karst develops. Obviously, this is not the case of the Hamada of Guir.

Also in a temperate humid climate (as it could be in the karst regions

Fig. 8 A sketch of the karstic system draining the hamada: 1: limestone, 2: marl, 3: stones.
of northern Italy and Jugoslavia), the karstic phenomena affect mainly the surface of the plateau, where, at an early stage, river channels, canyons and a complete surface drainage network are formed. Later, when the underground drainage and the surface sinks are well developed, the surface evolves towards the formation of closed basins and the water circulation is almost entirely subterranean. However, even in such an advanced stage of evolution, the ancient surface drainage network can still be recognized. As this is not the case of the Hamada of Guir, the suggestion can be made that the system outlined in fig. 8 is independent (or almost entirely independent) of the rainfall and surface runoff.

Such hypothesis is reinforced by the evidence that in areas where rainfall, runoff and surface corrosion are the predominant karst mechanisms, the size of the surface depression is generally much larger than that of the sink holes draining the depressions. Regarding the butte near Ali the tubes sizes are about as large as the surface depressions. This suggests that the tubes formed almost independently of the weak surface erosion, and that the hypogeal karst system of the Hamada was efficient from the start, stopping the weak "surface flow" and freezing the surface evolution early on. If this be true, it would be of great importance to understand whether or not this represent a common feature of carbonatic plateaux in arid environments.

3. ORIGIN AND EVOLUTION OF THE KARST

A detailed analysis of the speleogenetic mechanisms leading to the above karstic features is out of the limits of this report. Nonetheless it is worth discussing briefly the general framework, in the hope of obtaining suggestions for more advanced investigations.

First of all, one must keep in mind the aridity of the area: at present the average rainfall is between 50 and 60 mm/year and the average yearly temperature is 19.6°C. The erosion of the rivers Ziz and Guir has detached the lacustrine sediments from the Atlas to the North, so that at present one can exclude the flow of ground water from the Atlas to the Hamada.

The main problem is posed by the tube-like vertical shafts; a mechanism based on percolating water in a vadose environment, in our opinion, seems unlikely. The digging would be hardly cylindrical; indeed any cylindrical shape would be quickly destroyed (percolation would most likely
produce "channeled" surfaces, contrarily to what was observed in Ali butte tubes). One may consider the morphology as evidence, or at least as a suggestion, that the room where solution occurred was "permeated" by an aggressive agent. Following this line, one could imagine that the karst process occurred either below the water table or in an aggressive aerial ambient.

It is difficult to believe that the described morphology originated in a phreatic environment. The cylindrical shape of the tubes and their verticality would have required a vertical water flow, and it is hard to imagine a phreatic environment with such a permanent characteristic. Furthermore, the karstic tubes closely approach but never reach the hamada surface, suggesting a correlation between the present surface and karsification.

We suggest that dew condensation could have been an efficient mechanism for this purpose. It is well known that, due to the considerable temperature variations between night and day, in hot desert regions there is a large amount of water condensation on the rocky surfaces. It is also generally agreed that such water evaporates during the first hours of sunlight, causing the dissolved limestone to recrystallize.

Evidences for the efficiency of karstic erosion likely to be connected with dew can be found in the calcareous stones scattered on the desert surface. One can easily interpret the considerable erosion characterizing the bottom of such stones (fig. 9) as having been caused by dew condensed in the interspace between the stone and its desert resting place. This process progressively enlarges the interspace, leaving unaffected only the original points of contact with the surface.

We suggest that condensation of aggressive water should occur during the spring/summer at the crossing of two or more vertical fractures, if air is able to reach a depth of more than 2-3 m, the known limit for the daily thermal wave (Schoeller 1951). Indeed, below this limit rock temperature approaches more and more the average yearly temperature, so that below that limit the rock acts as a cold point where dew must form during hot days. This would quite naturally explain the lack of efficiency just near the surface.

Available data on condensation in deserts are uncertain and do not agree. Values range between 0.4 mm/night and 0.1 mm/night (Tonini 1974). In order to obtain indications regarding the efficiency of a similar mechanism, let us assume in a deep fracture a condensation of $c = 0.1$ mm/day and that the vertical crossing of two fractures can be assimilated to a thin vertical cylinder of radius $R$. 
Fig. 9 a) The bottoms of limestone stones covering the surface of the hamada show evidence of a substantial erosion to be connected with limestone solubility.

b) close up of the "vermiculation" covering the surface of the stone.
Thus, for a unit of length, the amount of condensed water is
\[ W = 2\pi R \times c, \]
which will dissolve a volume of CaCO₃ given by
\[ V = W \times S \]
where S is the solubility (by volume) of limestone in 1 cm³ of water. One has thus an increase of radius given by
\[ 2\pi R \times dR = W \times S \]

According to Roques (1975) and Smith (1977), water in equilibrium with atmospheric CO₂ (0.03% by volume) at 10°C has a solubility of about 0.07 gr/liter of CaCO₃. Since the density of limestone is about 2.7 gr/cm³, one can thus evaluate an increase in radius of about \(2 \times 10^{-6}\) cm/day. Therefore a radius of 0.5 m could form in about 500,000 years. The order of magnitude of this rough calculation indicates that there it was time enough in order that dew produced karstic tubes. Note that the process would be strongly accelerated if and when circulation of air is in some way facilitates through the fracture.

4. CONCLUSIONS

Tube karst is a peculiar karst form that is generally neglected in the literature. It is made up of vertical and almost cylindrical cavities, often unrelated to other karst phenomena such as cave systems or dolinas. We have reported evidences that tube karst in the saharian Hamada du Guir is an important feature governing the evolution of the Hamada and suggested that it originated from water condensation.

It would be of great interest to determinate whether a similar origin can also be ascribed to tube karst found in different climates (Castellani and Dragoni 1982), where the more efficient “usual” karst mechanisms could conceal the one here hypothized.

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