HYPOGENE LIMESTONE CAVES IN GERMANY: GEOCHEMICAL BACKGROUND AND REGIONALITY

Stephan Kempe1

Germany exhibits a very diverse geological history. Thus, a large number of stratigraphically, petrographically and tectonically different carbonate and sulfate rocks exist that have been subject to karstification. Here, I discuss first the possible “agents” (sensu Klimchouk) of hypogene karstification. Three principally different processes are identified: water rising because of buoyancy (either thermally or concentration induced), in-situ oxidation of siderite, or rising gases (CO2, CH4 or H2S). Next, a rough overview of German caves and karst is presented. If applying the most pertinent epigene versus hypogene morphological characteristics, it becomes evident that hypogene caves occur in many different areas, often side-by-side with clearly epigene caves. For many areas, the agents of hypogene speleogenesis must remain unclear. This applies for most caves in the Paleozoic limestones of the Rhenish Schist Massif. Only the Iberg/Harz caves seem to be a clear case, with the world-wide highest concentrations of siderite weathering-induced caves occur. The large cavities discovered recently in the Blauehöhlen System and some of the deep pit caves in the Swabian Alb may have their explanation in volcanic CO2, having emanated from some of the 355 pipes of the Swabian volcanic field. Most striking is the high concentration of hypogene caves in the Franconian Alb. Many of them occur in a small area while other areas are devoid of larger caves. Here the tectonic situation suggests that fractures could have taped reservoirs of either sulfide or methane from below. The finding of goethitic crusts in the Bismarckgrotte may indicate that rising anaerobic gases could have been involved.

INTRODUCTION

Hypogene karstification is a more common karstification process than anticipated even 20 years ago. It also appears to be a much more complicated process, involving a geochemistry far beyond that of the “simple” reaction of carbonic acid with carbonate rocks. Hypogene karstification is defined as upward movement “of the cave-forming agent” (sensu Klimchouk, 2007, 2012). This “agent” may be either the water itself rising or a compound available in situ at depth or rising from the depth of the crust. Water can rise either by thermal convection or by natural convection driven by dissolution of an easily dissolvable compound. This latter case is illustrated by some of the German gypsum caves as reported by Kempe (this volume). On the other hand a number of chemical reactions are discussed that give rise to hypogene karstification cause by in situ processes or advection of certain compounds.

In 1971, the author showed that siderite weathering can produce appreciable caves far below the water level (Kempe, 1971, 1975, 1998, 2008, 2009; Svensson and Kempe, 1989).

According to:

\[ 4 \text{FeCO}_3 + \text{O}_2 + 6 \text{H}_2\text{O} \rightarrow 4 \text{FeO(OH)} + 4 \text{HCO}_3^- + 4 \text{H}^+ \]

\[ 4 \text{FeO(OH)} + 4 \text{H}_2\text{O} + 4 \text{CO}_2 \]

The ferrous carbonate, the mineral siderite, is oxidized to the ferric oxy-hydroxide, the mineral goethite, thereby liberating protons and/or free CO2. These can in turn attack surrounding carbonate rocks, forming hypogene cavities around and near the oxidizing iron ore lode.

The simplest case involving a rising gaseous agent would be CO2 derived from either volcanic vents or dikes or from other sources at depth. In such a scenario, the caves should be largest very near to the base of the karstified limestone stratum.

In the early 1980s, another process was identified producing hypogene cavities, i.e. oxidation of rising H2S (e.g., Palmer and Hill, 2012):

\[ \text{H}_2\text{S} + 2 \text{O}_2 \rightarrow 2 \text{H}^+ + \text{SO}_4^{2-} \leftrightarrow \text{H}^+ + \text{HSO}_4^- \]

This process appears to be capable of corroding very large cavities in the periphery of oilfields, such as in the Captain Reef complex at the Permian Basin, New Mexico and Texas. There some of the largest rooms and the largest caves of the world are found, such as Lechuguilla and Carlsbad Cavern among others (e.g., Kambesis, 2012). The process has been identified as in fact operative because in the process of limestone dissolution, gypsum is forced from solution. In spite of the high solubility of gypsum, it has survived attack by later seepage water in drier corners of the caves, thus forming “the smoking gun” of this important cave-forming process.

However, there may be yet a third process, i.e., methane oxidation (Kempe, 2008):

\[ \text{CH}_4 + \text{O}_2 \rightarrow 4 \text{H}^+ + \text{CO}_2 \]

Since methane is much more common than H2S in the subsurface, it may play a much larger role than the former in corroding large subterraneous cavities. There is one problem with methane; its oxidation does not leave a “smoking gun.” Thus it may be difficult to finally prove its importance. One possibility does, however, exist. If carbonates should be co-precipitated at sur-

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faces that allow degassing, then these carbonates should have a much lower δ¹³C signature. This is because crustal methane has a very low δ¹³C, i.e. up to 70 per-mil lower than the organic matter it has been derived from (Rosenfeld and Silverman, 1959). We all should look out for such cases.

HYPOGENE CAVES OF GERMANY

Germany has a complex geology featuring large tracts of Devonian, Carboniferous, Permian, Triassic, Jurassic and Cretaceous carbonates and sulfates. The Devonian and Carboniferous rocks have been subject to the Variscian orogeny with intensive folding. Permian and Mesozoic rocks have been subject to gradual uplift and fracturing and, in the south of Germany, to Alpine orogenic thrusting (Fig. 1). Thus, there is ample opportunity for karstification under various stratigraphic, tectonic, petrographical, morphological, and altitudinal setting. Moreover, these caves have been under severe permafrost conditions during glacial events. Accordingly, there are numerous different conditions under which caves are forming and have formed in the past.

In spite of the large limestone areas, Germany has only 15 caves longer than 5 km (VdHK, 2013). When looking at cave densities in Germany, we find large differences: Some of the Devonian rocks appear to be Swiss cheese with numerous caves in small areas, while some of the Triassic, Jurassic and Cretaceous rocks appear devoid of significant cavities over large regions. Even if this impression may be skewed because we have yet to find caves in those seemingly cave-less areas, it already suggests that cave formation is not a statistical process, such as one would expect if caves would form exclusively according to “Dreybrodt-type-epigene-cave-models” (e.g., Dreybrodt, 2008).

It is not entirely clear how to separate fossil epigene caves from those of hypogene origin, but Table 1 gives a rough matrix of criteria that may serve for the majority of cases.

According to these criteria, and in some cases without actually having visited the caves, one can try to differentiate German caves (Kempe and Rosendahl, 2008) into the two classes (obviously with leaving room for discussion).

The northern-most cave in Germany is the Segeberger Kalkbergöhle (Fig. 2), a typical, 2 km-long maze cave in the anhydrite/gypsum cap of a salt dome (for more data on sulfate caves, see Table 1 in Kempe, this volume; for data on limestone caves, see Müller and Wolf, 2013; VdHK, 2013). Most of Table 1 criteria above would put the cave into the hypogene category, i.e. the morphology is lacking epigene characteristic because the cave shows only elements of slow, convective dissolution (sloping side walls, solution ceiling, solution cups etc.). Nevertheless it is not clear if the water came from below, rather it seems to have infiltrated from the glacial sediments adjacent to the anhydrite and the altitude of this water exchange was not only near the groundwater level but also was restricted to a thickness of less than 2 to 3 m. Fresh water must have come in along the ceiling of the passages (where they are widened fastest) and left, after being saturated with gypsum, either through floor cracks or laterally back to the glacial sand or till body.

Further to the south, in the upper Jurassic (Korallenoolith) of the Weserbergland, we find a group of caves (Schillathöhle, Riesenbergsystem) that are linear in ground plan but lack other epigene morphological characteristics. Thus, the above table does not allow a clear grouping of these caves that at best are shallow phreatic caves with no real signs of an “agent coming from below.”

To the east of the Weserbergland the Harz Mountains rise, exposing two upper Devonian reef limestone complexes, the Iberg/Winterberg near Bad Grund and the Elbingeroder massif. The Iberg/Winterberg, roughly 2 km² in size is a prime example of high density of caves of both groups, hypogene and epigene. The Winterberg, a large limestone quarry, exposed a number of epigene caves: large, steep canyons such as the Mammut Höhle (1.04 km long). Most these are now destroyed, except for the Neue Winterberghöhle. In contrary to this, the neighboring Iberg is the world-wide most important example for hypogene cavities.

Figure 1. Geological map and show caves of Germany
Figure 2. 3D scan of a solutional passage of the Segeber Kalkberghöhle in anhydrite with typical sloping sidewalls and horizontal ceilings characteristic of a cave created by internal convection.

caused by siderite weathering. Within a square of 250 m, at least 8 km of cavities are recorded (Fig. 3). Iron ore mining has connected these originally isolated caves (Fig. 4) into one large 3D-maze, composed of large irregular halls and passages following former siderite veins (Reimer, 1990). In some ponds in the mine, siderite weathering is still progressing, forming small analogs of this sort of hypogene karstification (Svensson, 1989; Svensson and Kempe, 1989).

The Elbingeroder reef complex is also mined, but no large cave appears to have been discovered. Rather, the caves in Elbingerode concentrate on both flanks of the Bode valley, the Baumannshöhle (1.95 km long), the earliest regularly managed show cave, is located on the west and the longer Hermannshöhle (3.36 km long) on the east. The Baumannshöhle appears to be deep phreatic; none of the epigene characteristics are present. What sort of agent was responsible for its formation remains everybody’s guess. The Hermannshöhle on the other hand, is an epigene cave, linear in shape and with an active creek at its lower level. Other caves in the vicinity show solution ceilings and are also phreatic. They are not, however, associated with known iron ore veins.

The Harz and its smaller sister, the Kyffhäuser, are accompanied by upper Permian evaporative rocks along their southern borders containing a score of gypsum/anhydrite caves, many of those are hypogene (see Kempe, this volume). Only one larger dolomite cave is known, the Einhornhöhle (Unicorn Cave), famous for its cave bear bones (Paul and Vladi, 2001). Only part of the cavity is visible, most of its volume is buried by sediments, including thick layers of gravel. In spite of this and its general linear development, it is not clear at all what sort of development the cave took.

The Rhenish Schist Massif contains, similar to the Harz, many small limestone outcrops of middle to upper Devonian age that

Table 1. Criteria to differentiate between hypogene and epigene limestone caves according to own experience.

<table>
<thead>
<tr>
<th>Evidence for</th>
<th>Epigene</th>
<th>Hypogene</th>
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<tbody>
<tr>
<td>General layout of cave</td>
<td>Linear, tributary, cave of substantial longitudinal extent</td>
<td>Maze, isolated cavities, cave passages limited to a small area</td>
</tr>
<tr>
<td>Entrances</td>
<td>Former ponors or springs</td>
<td>No natural entrance, or cave opened accidentally by erosion</td>
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<tr>
<td>Shape of rooms</td>
<td>Canyons, waterfall pits, seepage shafts, or phreatic round or oval passages</td>
<td>Large chambers interconnected (if at all) by narrow passages, shafts, passages of rough cross-section</td>
</tr>
<tr>
<td>General wall morphology</td>
<td>Meandering passages, erosion pots, scallops</td>
<td>Ceiling cupolas, solutional ceilings, solution cups, sloping side walls</td>
</tr>
<tr>
<td>Wall roughness</td>
<td>Smoothed and polished walls</td>
<td>Walls irregular with pockets, harder seams protruding, fossils exposed</td>
</tr>
<tr>
<td>Sediments</td>
<td>Allochthonous or autochthonous gravel, sandy material</td>
<td>Fine grained, autochthonous sediments</td>
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show high degrees of karstification. Many of the caves are well-known show caves. Nevertheless, no overview exists about their genesis in general. Some of the caves are epigene, like the newly discovered and still active 6.2 km long Herbstlabyrinth near Herborn (Dorsten and Dorsten, 2012). Others, specifically those that are fossil, are difficult to judge. For example, the Kluterthöhle is a 5.7 km long maze cave (Koch, 1992), suggesting hypogene origin. However, it is also transgressed by epigene waters between a sink and a spring. This could be a secondary stream capture, thus complicating the interpretation. Other maze caves include the Aggertalhöhle and 6.7 km long Attahöhle. Linear caves are the Dechenhöhle and the Heinrichshöhle. At least one cave is clearly of hypogene origin, the Kubacher Kristallhöhle near Weilburg (Fig. 5). It features a nearly 200 m long, up to 23 m wide and 30 m high cavity created by deep phreatic corrosion. Since iron ores have been mined in the vicinity and siderite is a common ore in the Lahn-Dill district, the Kubacher Cave may also have been formed by siderite weathering even though there are no immediate remains of an ore vein in the cave. Also, the largest cave room yet discovered in Germany is situated in the Rhenish Massif and must have been hypogene: the at least 700 m long, 200 m wide and 20 m high cavity at the bottom of the limestone quarry Rhodenhaus-Süd near Wülfrath (Drozdzewski et al., 1998). The cave is entirely filled with quartz sand that contains layers of charred plant remains dating into the Lower Cretaceous. Thus, the cave is at least 100 million years old. Even more, at its center an impressive limonitic ore deposit at least 50 m wide and 10 m thick was unearthed. This suggests that the ascending “cave forming agent” was anaerobic, carrying ferrous iron into the cave and creating a speleogene iron ore deposit possibly similar to what is found in Jordan at Warda (Al-Malabeh et al., 2008) and, to a much smaller extent, in the Bismarckgrotte (see below).

By area, the middle Triassic Muschelkalk formation is one of the largest limestone areas in Germany, occupying much of the center of the country. Nevertheless, it is the limestone formation with the lowest number of caves. The Eberstadter Tropfsteinhöhle, one of the few Muschelkalk show caves, and the parallel, over 3 km-long Hohler Stein are clearly epigenic, however, also of strange character. These caves appear to have been formed by erosion of back-cutting waterfalls and not so much by turbulent dissolution. Other caves in the (upper) Muschelkalk are large maze caves such as the Fuchslabyrinth (9.4 km in length) and the associated Schandtauberhöhle (3.7 km), both today with an epigene hydrology but most likely hypogene in origin (Klimchouk, 2007).

The upper Jurassic (Malm) limestone forms the largest continuous karst area in Germany. It consists of the Franconian Alb in...
Hypogene Cave Morphologies

S. KEMPE

Figure 5. View into the Kubacher Kristallhöhle, a large cavity formed by convective dissolution as illustrated by the cupolas in the background and the sloping sidewalls (facets) in the foreground.

The east and southeast and the Swabian Alb in the west, divided by the Nördlinger and Steinhemer impact craters in the center (Fig. 1). The south-dipping strata are terminated in the North by an imposing escarpment. Several thousand caves are known in the Malm, however, km-long caves are rare.

In the Swabian Alb, recent exploration by diving and digging down more than 100 m in sinkholes has discovered a large cave system, the 10 km long Blauhöhle (Hinderer and Kücha, 2012). It discharges its water through the Blautopf, one of the largest karst springs in Germany. In spite of the fact that the system is largely linear and active, its tremendously large halls do not fit the small tributary area of the present cave nor its missing aggressivity (Kempe et al., 2002). Therefore, doubt remains about what “agent” was responsible in forming this voluminous system.

Figure 6. The deep vertical caves such as the Laichinger Tiefenhöhle (1.35 km long) and the Laierhöhle (2.43 km long) may be of interest as well. These are not former sinks of surface waters but may also represent hypogene features (Fig. 6). The Swabian Alb holds many more epigene caves, including the Wulfbachquellhöhle (6.5 km), the Mordloch (4.4 km), the Falkensteiner Höhle (4.0 km) and the Wimsener Höhle, not to mention the large caves system that currently disverts the water of the upper Danube towards the Achtropf and the Rhine. There are also many fossil epigene caves, like the Nebelhöhle and the Charlottenhöhle. Thus overall the character of the larger caves in the Swabian Alb is more epigene than hypogene.

In the Franconian Alb, the general picture seems to be the other way around. Here, clearly hypogene caves dominate. Until the Mühlbachquellhöhle (7.7 km) near the southern border of Franconian Alb was discovered, not many sizeable, epigene caves were known in the area, among them the fossil, linear Bing Höhle and the Fellner Doline, an active, vertical sinkhole. All of the other larger caves (e.g., Kaulich and Schaaf, 1980; FHKF, NHG, 2002) seem to be hypogene. Most of them are formed in the dolomitic stromatolitic sponge “reefs” (Massenkalk), showing irregular large halls which are connected by small passages or pits forming three dimensional mazes. These include the famous Zoolithenhöhle to which William Buckland paid a visit in search of the Deluge (Fig. 7), as well as the show caves Maximiliansgrotte (Fig. 8), Sophienhöhle and Teufelshöhle (1.5 km long). Internationally less well-known is the Geisloch, the northernmost caves of this type with its well-preserved glacially damaged speleothems. Some of these caves are labyrinthic and attain respectable lengths on small areas, such as the Windloch at Kauerheim where 2.2 km of cave fit into 200×100 m of area, or the Moggaster Höhle featuring 2 km of passages within an area of 150×100 m and the Bismarckgrotte where we find 1.2 km of passages within an area of 110×100 m. Clearly, hypogene are also the typical maze caves Schönstein-Brunnstein (0.6 km) and Stein-am-Wasser and a score of smaller caves such as the Windloch at Kürmeuth. Some of the caves essentially consist of one large cavity only, such as the Riesenburg and the Rosenmüllerhöhle, named after the scientist who established the cave bear as the first extinct mammal in 1794 and the Oswald-/Witzen-/Wunders- cave system. Others are larger rooms opening below a pit or doline such as the Esper-Höhle, the Breitensteinbäuerin or the Windloch at Großmeinfeld. Many of the even smaller caves (there are about 3000 caves listed with less than 50 m in length) are most likely hypogene but often impacted in their morphology by frost shattering, obliterating their original morphology.

Two clues exist as to their common origin: most of these caves seem to fall into a very narrow NW-SE striking corridor (Fig. 9) and in the Bismarckgrotte fragments of goethite crusts were found (Fig. 10).

The map (Fig. 9) shows that many of these caves are grouped in the center of the Alb at around Muggendorf on the flanks of the Wiesent valley. The valleys in the northern Franconian Alb are striking mostly NW-SE, a direction called “Hercynian” in Central Europe. Other directions are NNE-SSW (“Rhenish”)...
and NE-SW ("Erzgebirgisch" or "Variscian"). The tectonic domination of the Alb valleys have long been noticed (for an overview see Baier, 2008). Thus, it appears that the site of hypogene caves is controlled tectonically. The Franconian Alb has been compressed and forms a shallow bowl-shaped basin (Streit, 1974, 1977), visible in the direction of the river network that focuses towards the center of the bowl. Thus, it is conceivable that deep-reaching fractures formed that opened migration paths for crustal fluids and gases. Below the Malm, we find a thick package of middle and lower Jurassic pyrite-rich clays. Thus, sulfide-rich fluids could have been mobilized from below causing the observed hypogene karstification. Further down a thick suite of Triassic rocks occurs, including the middle Muschelkalk evaporites that could have functioned as methane trap that were tapped by the fractures. The methane could have evolved from the lower Muschelkalk, a marine marly limestone. Thus, several options exist, to obtain reducing gases. That CO2 is not an option can be concluded from the fact that the discussed caves are not found at the base of the Malm but in its upper layers. Also they are more horizontal than vertical in shape suggesting control by the oxygen front in the former groundwater body. This scenario is substantiated by the finding of a substantial goethite crust in the Bismarckgrotte by the author (Fig. 10). These may even have had the form of chimneys, such as if they represented "black smokers." Unfortunately, these crusts have been much destroyed by the traffic through the cave. If such crusts appeared at the bot-
Figure 9. Google Earth view with some of the larger hypogene caves in the Franconian Alb pinned. Blue: Outline of the Malm escarpment; yellow: Hercynian lineaments; green: other lineaments.

Figure 10. Piece of goethite/limonite with a vertical texture from the bottom of the Bismarckgrotte. It could suggest that anaerobic waters (high in ferrous iron solutions) entered the cave to be oxygenated, thereby producing acidic byproducts that corroded the cave and precipitated the goethite in situ.
tom of other caves as well cannot be ascertained. This is because German caves are generally filled by glacial solifluction loams. In case of the Bismarckgrotte, the site where these crusts occur is away from the entrance pits, so that it was not covered by later sediments.

The cave at Stein-am-Wasser (actually called “Höhle ohne Namen”), a large maze cave, may be a different case. Here we measured a CO₂ concentration of up to 1% in the passages furthest away from the entrance, a value much higher than normally found in our caves (Kempe et al., 1998). Since the water table is intersecting the cave, it appears as if it is the source of this high CO₂-value.

The southern-most karst areas of Germany are represented by the few Alpine carbonate mountain massifs along the border with Austria. These areas seem to have a rather high cave density. Here the longest and deepest caves in Germany (Riesendtopf in der Blauhöhle 2011/2012. Mitteilungen des Verbandes der deutschen Höhlen- und Karstforscher e.V., Herborn, 41 p.

REFERENCES


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