Chapter II.5

GYPSUM KARST OF GERMANY

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1. Geological Situation

After the Variscan Orogeny, the larger section of Germany became part of the European continent. However, continued subsidence and rifting provided basins, which where occupied by epicontinental, i.e. relatively shallow marginal seas. Because of the low paleo-latitude of these basins, evaporation caused desiccation of these inland seas and the deposition of salt, gypsum and carbonates. Salt or gypsum were deposited in the Permian, Triassic and Jurassic (Richter-Bernburg, 1955a). Upon burial, the gypsum quickly was converted to anhydrite and is only converted back after having been exhumed almost completely so that often only the upper meters of a sulfate formation are gypsified.

The lower Permian (Rotliegend) salt and gypsum basin of the southern North Sea, which extends eastward toward Poland, is apparently not responsible for any specific karst development. The upper Permian (Zechstein) basin is much larger; it streches from England through the North Sea, across Northern and Eastern Germany far into Poland. A bay reached southward: the Hessian Depression. The geology and stratigraphy of the German Zechstein basin was extensively reviewed by Kulick & Paul (eds., 1987). In the north, up to eight salinar cycles can be differentiated, but only the lowest three (Werra Series, Staßfurt Series, Leine Series) can be traced at the surface (Richter-Bernburg, 1955b). The cycles typically start with a claystone, continue with a few meters of a limestone or dolomite, grade into massive anhydrite formations and finish with very thick halite and potash deposits. The gypsum formations are the Werra Anhydrite (A1), Basalanhydrite/Sangerhäuser Anhydrite (A2), and Hauptanhydrite (A3), which are the most important karst-bearing sulfate formations in Germany. Furthermore the upper Buntsandstein (lower Triassic; abbriviated So; 1 to 3 layers), the middle Muschelkalk (middle Triassic; abbrivated Mm; 1 layer), the middle Keuper (upper Triassic, abbrivated Km; Gipskeuper, 1 layer), and the upper Jurassic (Münder Mergel, 1 to 4 layers) occur near enough to the surface to give rise to karstic features (Herrmann, 1964).

Because of the wide extend of the Zechstein Basin (Fig. 1) and the enormous amount of salt deposited (the Staßfurt salt reaches 600 m), much of Northern Germany is underlain by salt domes. These provide the main tectonic structures in northern, north-central and eastern Germany, uplifting and tilting the sediments of the younger formations and punctuating even Pleistocene sediments. In Segeberg, Stade, Elmshorn and Lüneburg, for example, gypsum is found very near the surface or even rising in conspicuous hills above the moraines of the Last Glacial (in Segeberg).

To the south, mountain ranges consisting of folded Variscan rocks were uplifted as a reaction to the Tertiary Alpine Orogeny. These mountain ranges, Harz, Kyffhäuser, Rheinisches

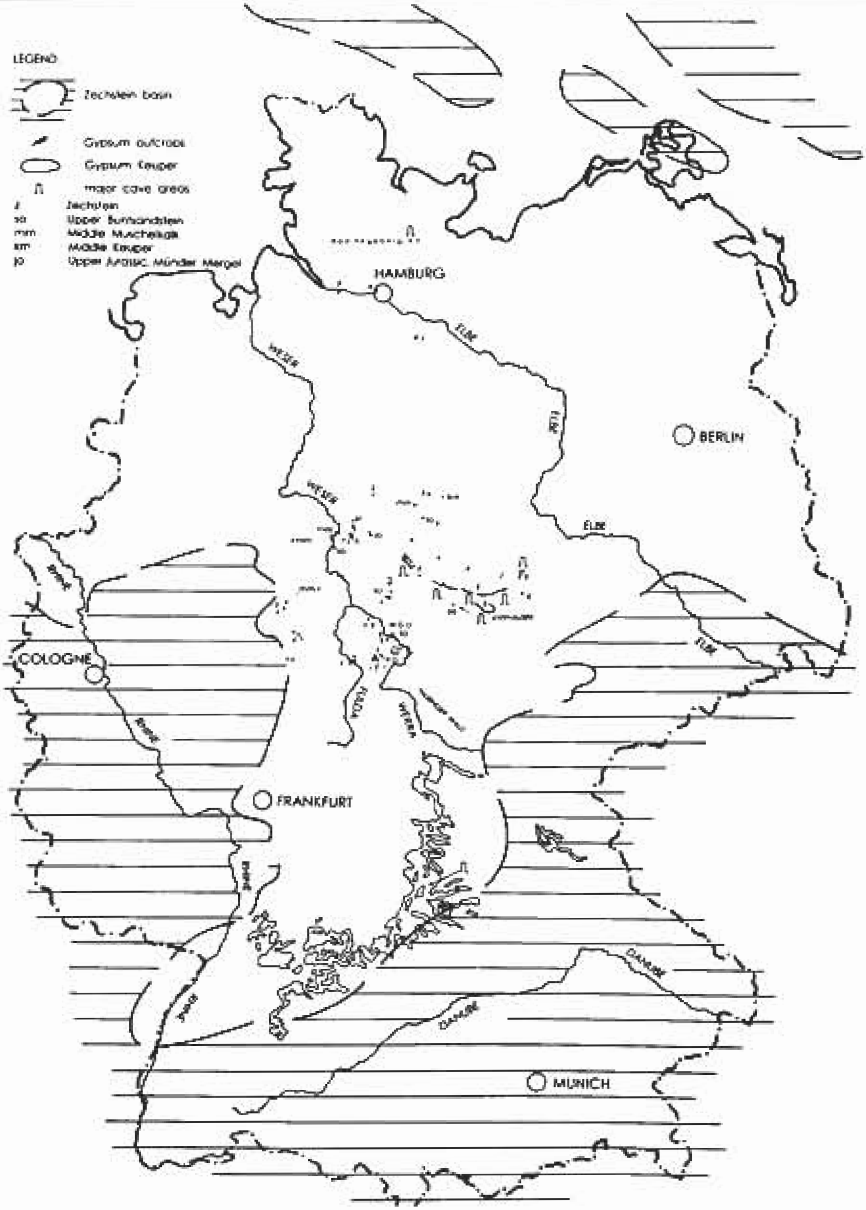

Fig. 1: Geological map of Germany with gypsum karst areas, compiled from various sources (e.g., Herrmann, 1964, 1976, and geological maps). RG = Richelsdorfer Gebirge; WGG = Werra Grauwacken Gebirge."

Schiefergebirge, Thüringer Wald, Richelsdorfer Gebirge and Werra-Grauwacken Gebirge, are fringed by Zechstein outcrops. The areas south of the Harz and Kyffhäuser are the largest continuous gypsum karst areas found in Germany. The outcrops actually belong to two different basins, separated by an old Variscan High, the Eichsfeldschwelle (part of the Hunsrück-Oberharz High), situated between Herzberg and Osterhagen (Herrmann, 1956; Jordan, 1979). On top of this NE-SW-striking High, evaporation of seawater was especially intense and large amounts of gypsum precipitated. It was transported into the adjacent basins. During the Werra Series the eastern basin was filled with more than 300 m and the western basin with more than 200 m of gypsum (the so-called "gypsum walls"). In the upper Staßfurt the Eichsfeld High become flooded and the relatively thin (up to 25 m) Basalanhydrite extends across it. In the eastern basin the Basalanhydrite is followed by the Sangerhäuser Anhydrite, itself ca. 40 m thick. The Leine Series gypsum (Hauptanhydrite) was deposited throughout the basins with a thickness of up to 50 m.

In between and to the south of theses mountain ranges isolated and very often tectonically disturbed outcrops of Zechstein, So, Mm and Km occur, most of them due to salt dome tectonics. Münder Mergel only occurs in a very local area, the Hils anticline. Only a few, very small caves have been described from these areas (Stolberg, 1934, in the So of the Hainleite range; Fischer, 1973, and Kasch, 1986, also in the So at Jena; Wrede, 1976, in the Zechstein of Othfresen, Salzgitter, caves mapped by Kempe; in the Mm of the Hopfenbergtunnel near Kreiensen, inaccessible now, cave mapped by Reinboth, unpublished). Towards southern Germany, in Bavaria and Baden Württemberg, the Mesozoic formations dip gently south towards the Tertiary Alpine Molasse Trough and an escarpment-dominated landscape formed, interrupted locally by minor tectonic horst and graben structures. Here the So, Mm and Km gypsum underlay large areas. The only cave area of note occurs near Markt Nordheim (Götz, 1979). Herrmann (pers. com.) reported of some caves in the gypsum mine (Km) near Seinsheim, the longest measured 150 m (map by Reinboth, unpublished). They are inaccessible now.

2. Gypsum Karst

$CaSO_4$ is highly soluble; about 14 mmol/l dissolve at 10°C (Wigley, 1973), i.e. 2.4 g of gypsum ($CaSO_4 * 2H_2O$; density 2.3g/cm^3) or 1.9 g of anhydrite ($CaSO_4$; density 3.1 g/cm^3) per liter. Brandt et al. (1976) and Kempe et al. (quoted in Kempe, 1982) measured gypsum karst springs in the Hainholz and found annual averages of 13.5 (Jettenquelle) and 14.0 (Schurfquelle) mmol/l $CaSO_4$ (2.3 and 2.4 g gypsum/l).

Weighting the specific discharges of Elbe, Weser and Rhine by their respective tributary areas (data compiled in Kempe et al., 1981) an average runoff (i.e. the difference between precipitation and evapotranspiration) of 323 mm/a can be assumed for Central Europe. This amount of water could dissolve gypsum at a rate of 0.036 cm/a (0.021 cm/a for anhydrite), consuming a 10 m thick layer of gypsum within 28,000 a (48,000 a for 10 m of anhydrite). For the Hainholz, a runoff of 450 mm/a was calculated resulting in a karstification rate of 0.044 cm/a (Brandt et al., 1976).

Under such conditions, it is actually astonishing that open gypsum karst exists at all in Central Europe. Several factors assist in the continued existence of these areas and determine their development. These are the Glacial-Interglacial climate cycles and the tectonic situation, which determines local hydrology and geomorphology.

In Glacial times, much of northern Germany was overridden by Scandinavian glaciers. The non-glaciated areas were subjected to harsh periglacial conditions. Permafrost effectively blocked groundwater formation and subsurface runoff for extended periods of time. This is well documented in limestone caves (Kempe, 1989). There, sinter grew only during the short Interglacials while it was mechanically destroyed by cave ice during the Glacials. Under permafrost dissolution of gypsum dropped to a minimum and its denudation was more by erosion than by corrosion. Evidence of periglacial erosion of gypsum is found all along the South-Harz where the gypsum karst is crossed by dry valleys. These valleys were once linked to Harz rivers which now either sink when they reach the gypsum or are deflected into subsequent depressions to join one of the few deep valleys funnelling Harz rivers through the Zechstein barrier. These consequent valleys, including the Söse, Sieber, Oder, Steina/Ichte, Uffe, Wieda, Salza, Thyra, Nasse, and Leine valleys (from W to E), mostly follow tectonic structures. But even these larger rivers seasonally loose part or all of their water, while crossing the Zechstein (Haase, 1936). This water reappears in some of the

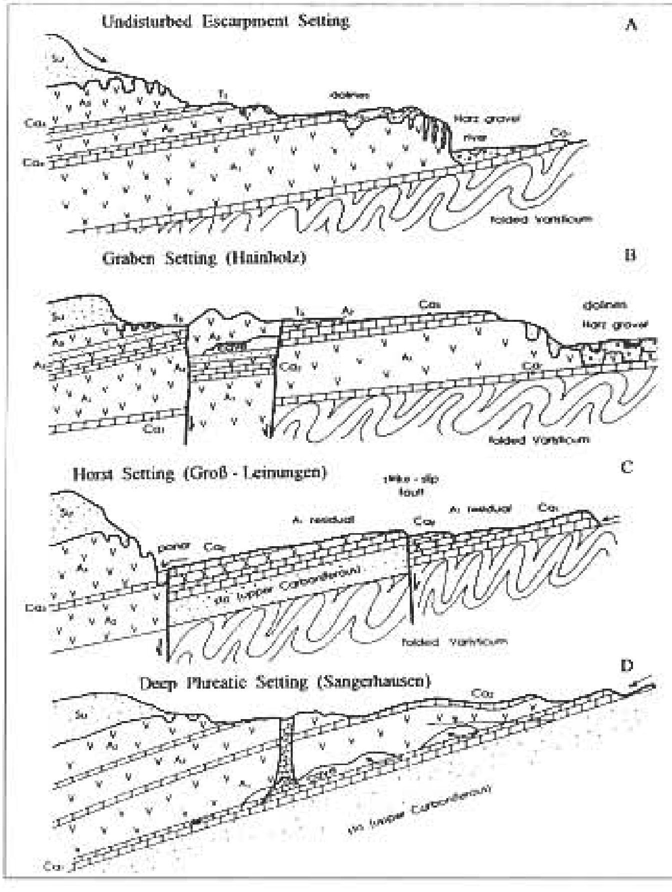

Fig. 2: Schematic cross-sections of the Zechstein karst of the S-Harz, a) tectonically undisturbed escarpment karst, b) karst area developing in a tectonic graben, example Hainholz, near Düna/Osterode, Niedersachsen, c) karst development along strike-slip faults causing a horst situation near Groß Leinungen, Sachsen-Anhalt, d) scheme of the deep phreatic karstification in the Sangerhausen and Mansfeld mining area, Sachsen-Anhalt.

most spectacular karstic springs of Germany, such as the Rhumequelle (Herrmann, 1969b), and the Salza Spring (Haase, 1936; Kupetz & Brust, 1994), kilometers below their points of infiltration. Along the Thyra near Uftrungen, sinking water undermining the western flank of the valley has created one of the largest gypsum cave systems in Germany, the Heimkehle (Völker, 1981).

It is interesting to note that most of the dry valleys have apparently been disconnected from their respective Harz rivers since well before the last Glacial. This is evident from the lack of Harz gravel in these valleys, which must have been removed under permafrost itself. Only pockets of Harz gravels remain (for example in the Marthahöhle, Hainholz), suggesting that these valleys date into the Elsterian Glacial (Brandt et al., 1975) and that the subsequent valleys have developed since, i.e. in the last three Interglacials. German gypsum karst therefore develops intermittently and experienced karstification stasis during Glacials and rapid development during Interglacials.

The tectonic situation also plays an important role in determining the type of karst. Along the South Harz, the formations dip 10-15° to the SW (Jordan, 1979). Where they are tectonically undisturbed, the A1, A2 and A3 form a set of three escarpments topped by the escarpment of the lower Buntsandstein (Priesnitz, 1969, 1972; Herrmann, 1969a, 1981b; Fig. 2a). The A1-escarpment is the most prominent, not only because the A1 is the thickest formation but also because it is often undermined by rivers following subsequent courses (near Osterode, for example) or sinking streams (at the Trogstein near Bad Sachsa, for example).

Due to the relatively fast recession of the A1 face not many karst features can develop at the main escarpment. In quarries mostly deep circular karren are noticed, up to 30 m deep (termed geologische Orgeln or Schlotten in German) and filled with slumped clay and limestone from the overlaying Staßfurt Series. The Staßfurt carbonates also form a prominent plateau above the A1 face where shallow dolines occur. The A2 escarpment is missing in most places because of the low thickness of this formation while the A3 escarpment is often masked by slumped lower Buntsandstein (abbriviated Su). However, the Su provides runoff which causes the extensive formation of dolines and small ponors filled with red Buntsandstein mud. Several kilometers south, beyond the Su-escarpment, is a wide valley, this is the depression caused by the dissolution of the Zechstein salt more than a hundred meters below the surface.

In this sort of undisturbed tectonic setting, karst develops only along the very narrow bands of gypsum outcrops. Larger karst areas occur only where the gypsum is protected from erosion tectonically. This is, for example, the case in the Hainholz Nature Preserve near Osterode (Fig. 2b). Here the A3 was downfaulted and forms a graben, which protected the Hauptanhydrite from erosion under permafrost conditions. The Su was simply stripped off and a relatively large area of gypsum was uncovered. The park features 39 hectares of fully developed karst (Kempe et al., 1972; Brandt et al., 1976; Kempe et al., 1976; Herrmann, 1981a; Jordan, 1981; Vladi, 1981) including sinks, karstic springs and extensive active cave systems (over 30 objects listed) which led to a series of spectacular collapse holes (Erdfälle in German). Weinberg (1981) has documented the fast evolution of one of these sinkholes since the last Interglacial. In addition, countless circular karren are developed. They are filled with marl, which was partly excavated in the past in order to ameliorate nearby fields. In 1751, this marl exploitation yielded the first bones of the extinct wooly rhinoceros ever described (Vladi, 1979). Archeological excavations suggested that the natural pits

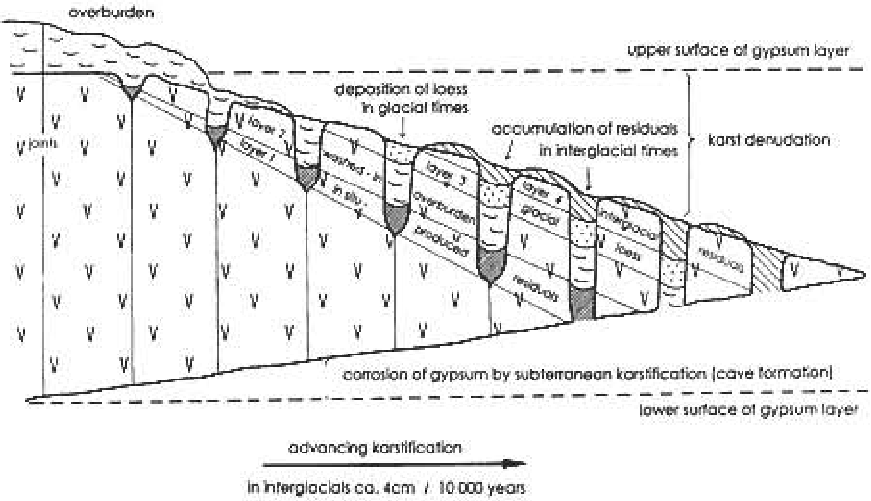

Fig. 3. Development of circular karren (Kempe & Emeis, 1979) according to sediment sampling conducted during archaeological excavations (Grote, 1979) in the Hainholz, Düna/Osterode, Lower Saxony.

may have been used by paleolithic hunters to trap animals (Grote, 1979). Fig. 3 shows how the sediment of these pits may have formed and how these pits keep ahead of the general lowering of the surface (Kempe & Emeis, 1979, 1981).

Several other areas have similar tectonic settings, like the Trogstein/Weißensee/Nuxei karst near Tettenborn and the Himmelreich near Walkenried, both also well known for their sinks, springs and caves (Priesnitz, 1969; Reinboth, 1963, 1969, 1970; Stolberg, 1928, 1932).

Further to the east, prominent E-W trending strike-slip faults with small amounts of uplift or downthrust have structured the area. Along these faults creek and groundwater flow is diverted into subsequent directions, creating an extensive, prominent strike valley (Auslaugungstal). Thereby, the escarpments of the higher Zechstein are protected from corrosion. The water infiltrates into the A1 as is the case at the Dinsterbachschwinde near Questenberg, but often the lower Zechstein is completely missing, only residual limestones remaining at the surface (Fig. 2c). In these cases Harz waters can collect and infiltrate the A3 directly such as is the case at the Bauerngraben, a spectacular episodic ponor-lake (Völker & Völker, 1983) and at the Ankenbergschwinde near Groß Leinungen, all in Sachsen-Anhalt.

In southern Germany the gypsum layers of the So, Mm and Km are less steeply inclined, their bedding lies almost horizontally (Herrmann, 1976). They are less thick and their fronts have been deeply corroded. Therefore they do not form prominent escarpments and rarely break the surface. Exceptions occur near Markt Nordheim, Franken/Bavaria, where also caves have developed in the Km, which occurs near the surface (Götz, 1979).

3. Gypsum Caves

German gypsum caves have been a subject of study since several centuries. The earliest account of a gypsum cave is that of the Kelle, near Ellrich, which was described by H. Eckstorm in 1597 (Reinboth, 1989, 1996). Georg Henning Behrens (1703) mentioned, in the first review about Harz caves, entitled "Hercynia Curiosa", already seven gypsum caves (among them the Heimkehle and the Kelle). At the same time caves were encountered incidentally or on purpose in the eastern Harz in the mining districts of Sangerhausen and Mansfeld during the early days of modern mining. The mined vein is the Kupferschiefer, the 10 to 60 cm thick claystone forming the base of the Werra (A1) Series. It is impregnated with several percent of copper and other metal sulfides. As the miners followed the formation deeper and deeper underneath the A1-escarpment they encountered severe water problems. They soon learned that water could be piped into so-called "Schlotten" (Kupetz & Brust, 1991) (not to be confused with the circular pits at the karst surface), enormous underground cavities formed along the paths of sinking water (Fig. 2d). The vaults were also handy when it came to deposit mine wastes. The ownership of such a cave could decide about success or failure of the mine venture. Thousands of pages dealing with these caves and the law suites about their ownership still exist (Korte et al., 1982; Völker & Völker, 1983). Around 1799, the largest of these caves, the Wimmelburger Schlotten, were discovered (Fig. 4) (Völker & Völker, 1986). Freiesleben (1809) published the first scientitific paper about these caves, including maps, in which he already suggested that they form in standing water. Altogether he mentioned almost 30 Schlotten and other caves in gypsum.

It then took over a hundred years before somebody else addressed the question of how these caves were formed and where the water eventually ended up (Fulda, 1912, unpublished). In 1913, when in Segeberg, Schleswig-Holstein, a large cave system was found by quarrying (see Table 1), Karl Gripp (1913) started the modern scientific gypsum cave research. The cave has a maze-like pattern, rather flat ceilings and peculiarly inward sloping side walls (Fig. 5). Gripp concluded that the cave has been formed by very slow solution in a more or less standing water body. He also postulated that the side walls would start vertically and then tilt outward as solution continued. In 1926, Friedrich Stolberg published a review of all the accessible gypsum caves in the Harz and included newly surveyed maps. With Stolberg's maps and Gripp's theories at hand Walter Biese (1931) reviewed the gypsum cave development and firmly established the concept of the solution cave (Laughöhle), which is characterized by flat ceilings and sloping side walls (for which he introduced the terms "Laugdecke" and "Facette", respectively). He also showed that the Schlotten-type caves are solution caves as well.

In West Germany Fritz Reinboth (1968, 1971b, 1974, 1992) and the author (Kempe, 1969, 1970, 1972a,b, 1975; Kempe et al., 1975, Kempe & Seeger, 1972; Brandt et al., 1976) developed the theory of gypsum cave evolution further, while in East Germany the practical exploration of caves was the main thrust, until in the 1980ies Völker & Völker began their publication series on gypsum karst, caves and schlotten. After the reunification of Germany the first field guide, covering both sides of the South Harz karst, appeared (Kupetz & Brust, eds., 1994) and now a hiking path leads along the entire expansion of the South Harz karst landscape (Völker & Völker, 1996).

Table 1

List of German gypsum caves longer than 200 m

1. Wimmelburger Schlotte**	Wimmelburg, E-Harz, Sachsen-Anhalt; large, deep phreatic solution cave system (Biese, 1931; Stolberg, 1943; Völker & Völker, 1986)	2550 m
2. Segeberger Kalkhöhle*	Bad Segeberg, Schleswig-Holstein; maze type, drained, shallow phreatic solution cave with some breakdown halls (Gripp, 1913; new survey, including all side passages, Fricke, 1989)	1985 m
3. Heimkehle*	Uftrungen, S-Harz, Sachsen-Anhalt; shallow phreatic solution cave with breakdown-dominated large halls (Stolberg, 1926; Biese, 1931; Völker, 1981)	1780 m
4. Numburg-höhle***	Kelbra, Kyffhäuser, Sachsen-Anhalt very large, shallow phreatic solution cave with enourmous breakdown halls (Stolberg, 1926; Völker, 1989; Völker & Völker, 1991)	1750 m
5. Schlotte am Ottilaeschacht****	Ahlsdorf, Sachsen-Anhalt; large, deep phreatic solution cave (Stolberg, 1943)	1710 m
6. Höllern**	Markt Nordheim, Franken, Bavaria; maze type, active, low, shallow phreatic solution cave (Cramer & Heller, 1933; Götz, 1979)	1040 m
7. Jettenhöhle	Hainholz, S-Harz, Niedersachsen; active, shallow phreatic solution cave with large breakdown halls (increased by 130 m since 1990), (Stolberg, 1926; Kempe et al., 1972)	748 m
8. Schlotte am Schacht E****	Mansfeld, E-Harz, Sachsen-Anhalt; large, deep phreatic cave (Stolberg, 1943)	725 m
9. Barbarossahöhle*	Rottleben, Kyffhäuser, Thüringen; shallow phreatic solution cave in anhydrite, dominated by vaulted halls(Biese, 1923; Kupetz & Mucke, 1989; Kupetz & Brust, eds., 1994)	670 m
10. Himmelreich-höhle**	Walkenried, S-Harz, Niedersachsen; possibly formed by creek down-cutting, one very large hall with stream passages (Biese, 1931; Reinboth, 1970)	580 m
11. Niedersachsen	Fitzmühlen Quellhöhle Tettenborn, S-Harz; low, vadose stream cave (Haase, 1936; map by A. Hartwig, 1988, unpublished)	545 m
12. Brandschächter Schlotte****	Sangerhausen, S-Harz, Sachsen-Anhalt; deep phreatic solution cave (Stolberg, 1943; Völker, R., 1983)	530 m
13. Marthahöhle**	Hainholz, S-Harz, Niedersachsen; shallow phreatic solution cave (Stolberg, 1936; Kempe et al., 1972)	450 m
14. Großes Trogstein System***	Tettenborn, S-Harz, Niedersachsen; system of low, meandering vadose stream passages (Stolberg, 1928, 1932; Biese, 1931; Reinboth, 1963, 1969)	435 m
15. Schusterhöhle**	Tilleda, Kyffhäuser, Sachsen-Anhalt; shallow phreatic solution cave	434 m
16. Schlotte am Eduardschacht****	Mansfeld, E-Harz, Sachsen-Anhalt; deep phreatic solution cave (Kupetz & Brust, 1991)	400 m
17. Elisabeth-schächter Schlotte**	Sangerhausen, S-Harz, Sachsen-Anhalt; large, deep phreatic solution cave (Stolberg, 1943; Völker & Völker, 1982)	357 m
18. Höhle im Grundgips der Kläranlage****	Bad Windsheim, Franken, Bavaria; shallow phreatic solution cave	250 m
19. Segen Gottes Schlotte**	Sangerhausen, S-Harz, Sachsen-Anhalt; deep phreatic solution cave (Stolberg, 1943; Völker & Völker, 1982)	240 m

Notes: * = show cave; ** = accessible only by permission making them essentially inaccessible; *** = major parts no longer accessible; **** = not accessible at all

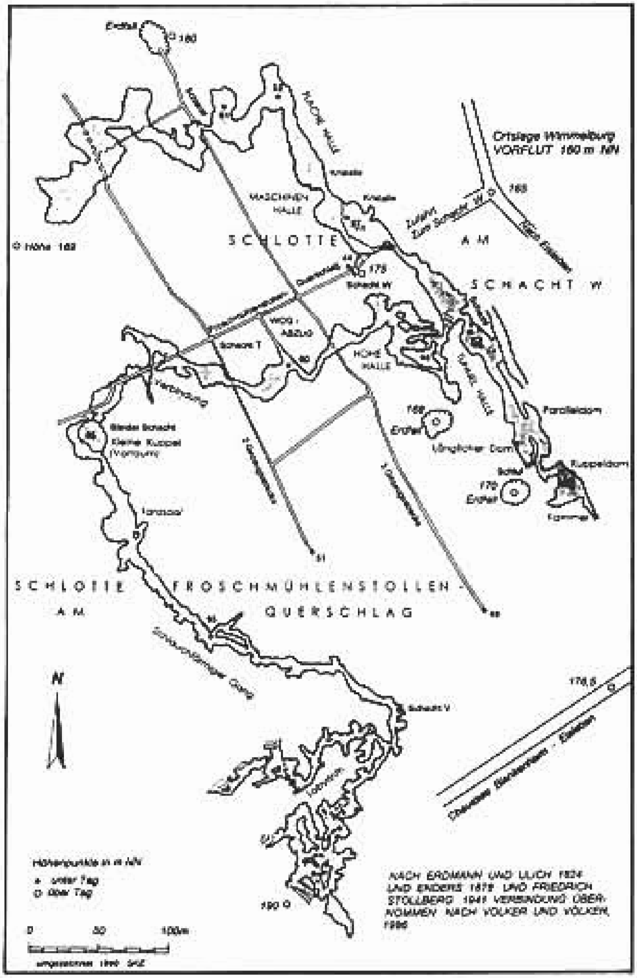

Fig. 4: Map of the Wimmelburger Schlotten, redrawn after various sources.

Many questions concerning the hydrodynamics of solution caves and the formation of facets and solution ceilings are still open to debate (see Reinboth, 1992). Nevertheless, we can now paint the following general picture of gypsum cave development: At places where water, not saturated with gypsum, can enter gypsum or anhydrite, it will quickly saturate with $CaSO_4$. This water can enter from two directions: from the sides or from below. Seepage water running into the cave through joints from above cannot aid in cave formation: it is already saturated with $CaSO_4$ after a few meters of percolation. This is shown by measurements made in the Jettenhöhle (Kempe et al., 1976; Kempe, 1982). Water entering sideways can be derived from sinking creeks (Marthahöhle, Hainholz, for example) or can be derived from groundwater percolating through a gravel-filled valley adjacent to the gypsum rock (examples: Heimkehle, Segeberger Höhle and Numburg-höhle). But water can also enter the gypsum rock from below because of the nature of the Zechstein salinar cycles: below each of the gypsum beds, a limestone or dolomite bed occurs. These beds, the

Zechsteinkalk for the Werra Series, the Stinkschiefer/Hauptdolomit for the Staßfurt Series and the Plattendolomit for the Leine Series, are subject to karstification themselves. They can conduct water far underneath the anhydrite bodies and cause attack of the anhydrite/gypsum bed from below. The water in the limestones is less dense and rises up into the gypsum because of buoyancy. Once saturated with gypsum, it becomes heavier and returns into the carbonate layer setting up a system of natural convection and continues its way downdip in the carbonate karst. This explains, where the water for the gigantic Schlotten-type caves came from and it was also shown to be the water-delivering mechanisms for the caves of the Hainholz (Kempe et al., 1976) (compare Fig. 2, B). There, rising groundwater can be seen in cave pools containing water of low gypsum saturation.

Once inside the gypsum rock, the water starts to attack the gypsum, forming dense solutions. At the ceiling of the developing caves a pattern of convecting "saltfingers" evolves, leaving small circular solution cups (Laugnäpfe), the size of finger tips (Kempe, 1969). At the cave walls a dense film of solution forms, sliding downward, smoothing the wall and forming the inclined smooth side walls so typical of solution caves (the facets) (Gripp, 1913; Kempe, 1975; Kempe et al., 1975). Thereby a convection is started involving the entire water body. Flat ceilings (solution ceilings) seem to develop if the solution is fast, i.e. if the water starts at a low saturation. The best example of a solution ceiling is found in the Marthahöhle where the level ceiling spans 20 m. If the water body operates near saturation, then the ceiling seems to attain more the shape of a cupola (like in the Schlotten-type caves) and the solutions cups are largely missing, indicative of large, and very slow convection cells (Kempe, 1996). At the same time the facets seem to recede in parallel to their starting position (Kempe, 1970). Solution experiments with salt models by Reinboth (1992) showed that the solution at the Laugdecke is about twice as fast as the solution at a vertical wall and about triple a fast as on a surface pointing upward. Solution from inclined surfaces seems to increase with the sinus of the inclination angle. It therefore remains a mystery, why the observed facets in nature seem to develop best at a slope of about 45°.

The general development of gypsum caves is given in Fig. 5. Caves formed by turbulent water flow are rather rare in Germany and the typical scallops caused by turbulent flow have been noticed in few caves as to date (Heimkehle, Kyffhäuser Caves for example). One of the few canyon-type gypsum caves is the very narrow Lichtenstein Cave (Kempe & Vladi, 1988). It must have formed very rapidly, possibly within a few years only, and then the water supply must have been cut off, otherwise the cave would not have been preserved. Another example of a gypsum cave formed by turbulent water flow is the Trogsteinsystem (Reinboth, 1963, 1968), where sinking creeks have formed meandering passages guided by a fault. The water reappears in the Fitzmühlenspring Cave on the other side of the ridge, a wide but extremely low cave passage following the joint pattern in large switchbacks.

In order to form solution caves (the most common type of gypsum cave in Germany) the water must percolate through the rock below a velocity causing turbulence. The solution cave development follows two branches (Fig. 5), one where the cave is developed at or near the water-table (shallow phreatic), the other where the cave development commences far below the water-table (deep phreatic).

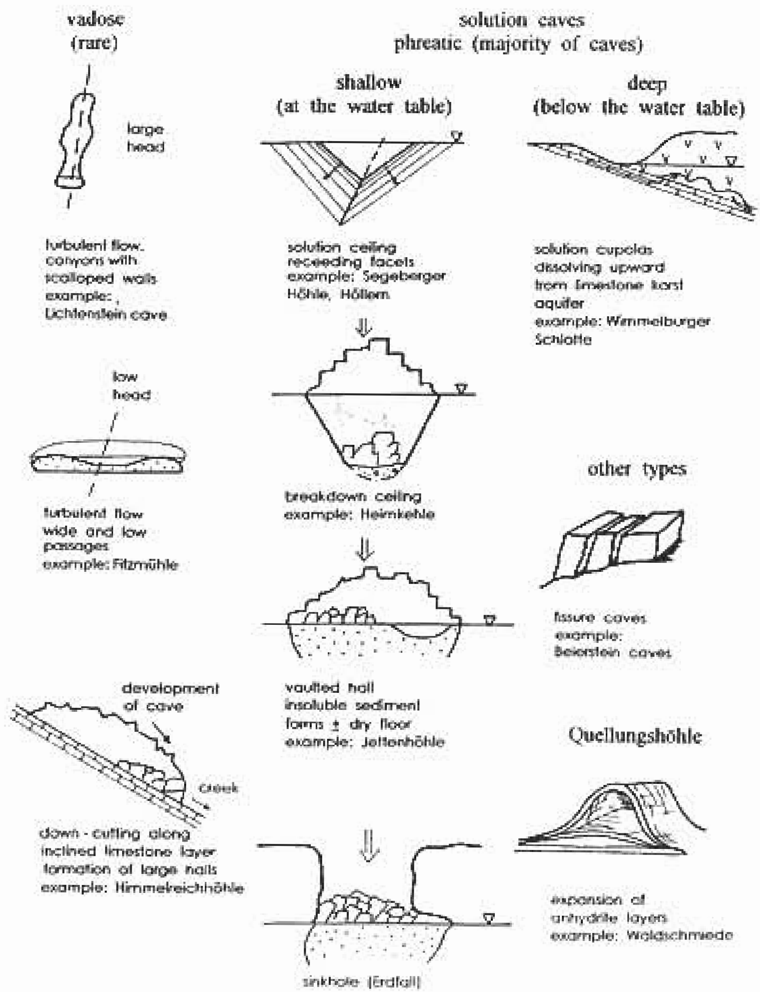

Fig. 5: Scheme of the general development of gypsum caves in Germany, explanation see text.

In the first line of development (center Fig. 5), the cave often starts as a maze of relatively narrow passages, as in the cases of the Segeberger Höhle, Marthahöhle and the Höllern, and is then more or less completely filled with water. It can grow above the watertable by breakdown once the solution cavity has undermined the walls far enough to cause instability. This breakdown can be dissolved completely or partially and insoluble sediments can fill the cave up to the watertable (Kempe, 1970). Typical examples for such caves are the Jettenhöhle, the Numburghöhle and the Heimkehle. Also the Barbarossa-höhle developed at a shallow phreatic level. It served as a path for the water collecting on the Kyffhäuser, sinking in the Zechsteinkalk and then dissolving its way through the steeply dipping A1 outward, at a level determined by the local watertable. Because the cave roofs are mostly rather thin, these caves very often end as a series of sinkholes (Erdfälle).

In the deep phreatic case (Fig. 5, right) cavities are formed far below the watertable (Kupetz & Brust, 1991). They tend to develop upward and not sideward. They follow the dip of the strata and can therefore be quite deep (vertical extent of the Wimmelburger Schlotten: 65 m). Normally they do not have any connection with the surface. However, breakdown can occur and can cause sinkholes at the surface (see map of the Wimmelburger Schlotten, Fig. 4). But this breakdown occurs underwater and the resulting vault will be smoothed by further solution causing the formation of large domes (Biese, 1931). One of the most famous of these domes is the Tanzsaal in the Wimmelburger Schlotte, where, in 1808, the famous geologist Johann Karl Freiesleben took his leave. Names inscribed during the party and the remains of a chandelier are still preserved (Völker & Völker, 1986). Stolberg (1943) counts 20 Schlotten and Völker (pers. com.) thinks that as many as 100 objects have been intersected by mining over the centuries. Two types can be discerned: The Wimmelburg Type (large, connected halls or low, wide, maze-like passages between 70 to 175 m below the surface) and the Ottoschächter Type (individual, pocket-like rooms up to 400 m below the surface) (Fulda, 1912; Kupetz & Brust, 1991). Due to the termination of the Kupferschiefer mining in the Mansfeld and Sangerhausen district, most of the Schlotten are now flooded and only a few remain, which still can be accessed providing proper permission by the mining administration.

Two more types of gypsum caves occur (Fig. 5, lower right): fissure caves and the so called "Quellungshöhlen". The fissure caves can be quite long. They occur at many places, specifically parallel to steep escarpments shedding off large blocks. Biese (1931) has reviewed this topic extensively. The "Quellungs" caves are a unique class of caves. They form due to the expansion (+26 vol. %) of the rock when anhydrite hydrates and recristallizes to form gypsum (Reimann, 1991). On the Sachsenstein, where most of these caves occur, anhydrite layers occur in parallel to the surface. When these layers increase in volume, they buckle upward and small blister-like cavities open up. Buckled layers of anhydrite changing into gypsum also hang from the anhydrite roofs of the Barbarossa- and Himmelreichhöhle.

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