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# Constraints on alpine speleogenesis from cave morphology — A case study from the eastern Totes Gebirge (Northern Calcareous Alps, Austria)

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ABSTRACT

The Totes Gebirge is the largest karst massif in the Northern Calcareous Alps (NCA). This paper focuses on the eastern part, where two major multiphase alpine cave systems (Burgunderschacht Cave System and DÖF–Sonnenleiter Cave System) are described with respect to morphology, hydrology, and sediments. The caves consist of Upper Miocene galleries of (epi)phreatic genesis and younger vadose canyon-shaft systems. Morphometrical analyses were used to determine the relevance of (1) cave levels (horizontal accumulations of galleries), (2) slightly inclined palaeo water tables of speleogenetic phases, (3) initial fissures, and (4) inception horizons on the development of the cave systems. (Epi)phreatic cave conduits developed preferentially along vertical faults and along only a restricted number of bedding planes, which conforms to the inception horizon hypothesis. For at least one of the systems, a development under epiphreatic conditions is certain and a hydrological behaviour in the "filling overflow manner" is likely.

Observations in further major cave systems in the Totes Gebirge identify palaeo water tables of speleogenetic phases that show inclinations of 1.5°±1°. Analyses of cave levels reveal distinct peaks for each cave but it is hardly possible to correlate these elevation levels between caves of different parts of the karst massif. Therefore, we conclude that cave levels (strictly horizontal) indicate speleogenetic phases or palaeo water tables respectively, but they cannot be correlated with palaeo base levels or on regional scale. An exact correlation between cave development and palaeo base levels at the surface is only possible with inclined palaeo water tables of speleogenetic phases.

For the Totes Gebirge, the inclination directions of the speleogenetic phases imply that palaeo drainage was radial and recharge was autogenic, which is in contrast to observations from other plateaus in the NCA. Differences in fracture properties seem to be the reason for the development of divergent types, according to the Four State Model. A simplified model for cave genesis and surface development in this area since the Upper Miocene is presented.

## 1. Introduction

The study of solutional cave systems provides many insights into the evolution of karst massifs and the surrounding landscape (e.g. Kuffner, 1998; Klimchouk and Ford, 2000; Frisch et al., 2002; Audra et al., 2006; Häuselmann et al., 2007). A frequently used link between subsurface karstification and surface morphology is the concept of "cave levels". In 1909, Sawicki noticed that cave passages concentrate at certain altitudes and introduced the term *evolution level* ("Evolutionsniveau"; Sawicki, 1909). However, cave levels and their correlation with base levels were highly controversial for a long time. A review of the topic was given by Bögli (1980). Today, however, it is widely accepted that the concentration of solutional cave conduits at certain elevations can be used to study cave genesis in relation to landscape evolution, as fluvial base levels control subsurface cave development (Palmer, 1987). The case study presented here focuses on the largest karst massif in the Eastern Alps of Austria. In the Totes Gebirge area (Fig. 1), several cave levels were already identified in the middle of the last century (Lechner, 1949; Schauberger, 1956). Later works by Haseke-Knapczyk (1989) and Fischer (1990) distinguish three major, distinctive levels in the central Northern Calcareous Alps (NCA) that share similar morphological characteristics. Each of them comprises a few hundred metres of altitude, although the absolute elevations differ between the massifs. These were incorporated into a speleogenetic model for the Tennengebirge (Fig. 1) by Audra et al. (2002). The latest comprehensive work was

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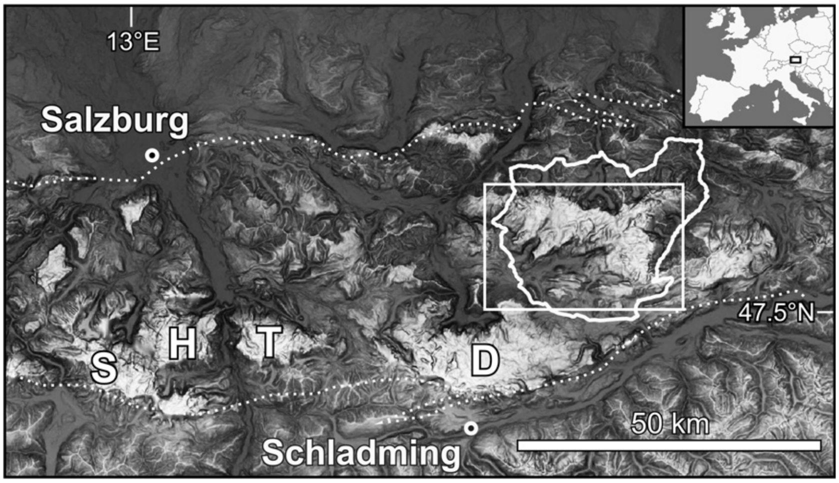

**Fig. 1.** The Totes Gebirge (white polygon: outline; white rectangle: site of Fig. 2) is located within the central NCA. Greyscale of the background map depicts elevation and slope gradient highlighting elevated plateaus (data base: SRTM); the dotted lines delimit the NCA; other karst massifs: S — Steinernes Meer, H — Hagengebirge, T — Tennengebirge, D — Dachstein. Inlet shows the location within Central and Western Europe.

performed by Frisch et al. (2002) who utilise geological correlations, including morphology, tectonics and sedimentology, to specify the ages of the formation of the three levels. The highest, the Ruin Cave Level (~2200 ± 300 m a.s.l.) developed between the middle Eocene and Early Oligocene, the Giant Cave Level (~1600 ± 500 m) in the Upper Miocene, after the onset of the major uplift of the NCA, and the low lying and often hydrologically active Spring Cave Level (~800 ± 300 m) in the Pliocene and Quaternary.

Here, we focus on two major multiphase (Ford, 2000) cave systems in the eastern Totes Gebirge. Apart from field observations, statistical analyses are used to investigate tectonic fissures as well as inception horizons (Lowe, 1992). Further, horizontal cave levels and slightly inclined water tables of speleogenetic phases are determined; it turns out that a strict differentiation of these phenomena is crucial for the interpretation and correlation with base levels. The paper demonstrates how morphological observations and morphometrical

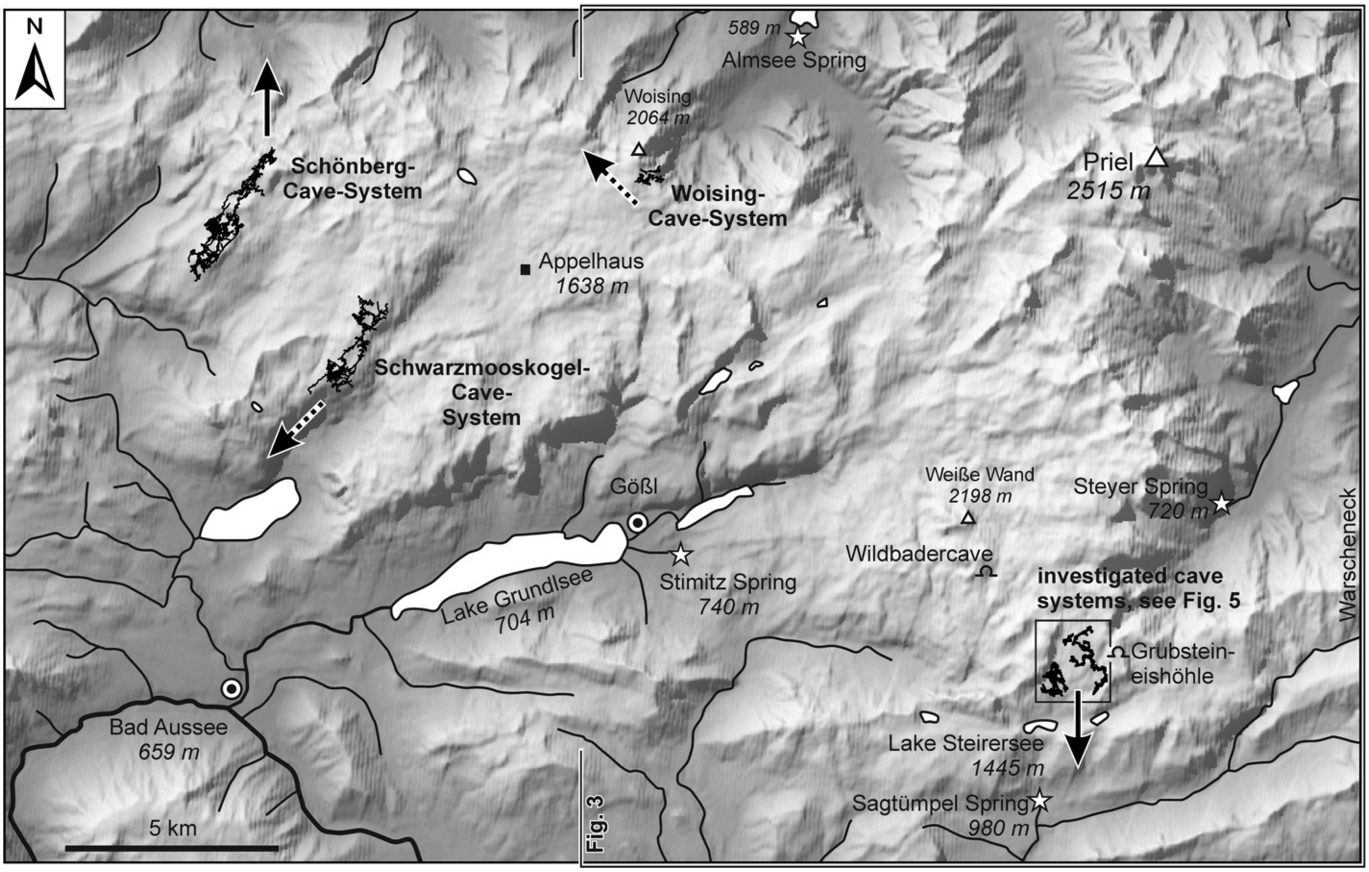

**Fig. 2.** Shaded digital elevation model of the Totes Gebirge including cave systems, springs, lakes (white areas). Location of the geological overview (Fig. 3) and the study area (Fig. 5) are marked by rectangles. Arrows indicate the dip direction of identified water tables of speleogenetic phases interpreted as palaeo-flow directions (cf. Section 4.5, 4.6; dotted arrows are uncertain).

analyses can be used as constraints for models of speleogenesis and subsequent implications for landscape evolution. Further, our analyses provide data that support the inception horizon hypothesis (Lowe, 1992). On a regional scale, we address in particular the question of drainage conditions in terms of allogenic recharge with a sinking river in the south, subsurface flow and reappearance in the north versus autogenic recharge and radial drainage of the karst massif. Finally, a simplified model for the evolution of cave systems of the Eastern Totes Gebirge since the Upper Miocene is presented.

In this paper, the following definitions are used, distinguishing between four types of planar features which are important for cave evolution: (1) *Initial fissures* (bedding planes, joints, and faults) are principal structural controls that enable subsurface karstification (e.g. Klimchouk and Ford, 2000); (2) *Inception horizons* (Lowe, 1992; 2000) are a limited number of stratigraphic horizons or bedding planes that favour cave evolution. Recently, statistical analyses (Filipponi and Jeannin 2006; Filipponi et al., 2009-this issue) found strong evidence to support the concept of inception horizons; (3) *Cave levels*, which we define as accumulation of phreatic galleries at strictly horizontal levels and have been described in many caves (e.g. Palmer, 1987); (4).

The *palaeo water table of a speleogenetic phase* is a slightly inclined plane that reflects the position of the top of the corresponding genetic phase. In turn, a speleogenetic phase, which is a temporal state, is defined by its springs and the height of the epiphreatic zone (Häuselmann et al., 2003). The minimum height is derived from the connection of the crests of phreatic loops of the corresponding galleries. In contrast, the floodwater table is inferred from canyon-tube-transitions. We avoid the terms tier and storey which have neither a geometric nor a genetic meaning.

There is an ongoing discussion if mature galleries actually form under *phreatic* (sensu stricto) or *epiphreatic* conditions (Audra, 1994; Häuselmann et al., 2003; Ford and Williams 2007). Since this difference does not affect our study, we use phreatic where the origin is unclear and epiphreatic only if there is clear morphological evidence for such a genesis.

## 2. Study area

### *2.1. Geography*

The Totes Gebirge (Dead Mountains) karst massif is located on the border between the Austrian provinces of Styria in the south and Upper Austria in the north. The whole mountain range, as defined in Stummer and Plan (2002), covers an area of 642 km$^2$ and is the largest karst massif in the NCA (Fig. 1). The stepped plateau reaches from an altitude of about 1500 m up to the summit (Priel) at 2515 m a.s.l. The massif is surrounded by deeply incised valleys at 400 to 850 m a.s.l. except in the southeast where a saddle separates it from the Warscheneck massif (Fig. 2). Our study focuses mainly on the south-eastern part of the plateau (Figs. 2, 5).

The alpine climate is chilly, with average temperatures around +7 ° C for the valleys and slightly below zero in the summit regions (Kuffner, 1998). Precipitation is in the order of 1200 mm/a in the valleys and 2500 mm/a in the elevated parts (Baumgartner et al., 1983). On the plateau, snow cover persists for more than 200 days per year.

### *2.2. Geology*

The study area belongs to the Totengebirgs Nappe, which is a part of the Tirolic unit of the NCA. The lithostratigraphy within this area is very homogenous, comprising almost entirely of Upper Triassic limestones of the Dachstein Formation (Fig. 3) in lagoonal facies that are well bedded in the order of few metres. According to Fischer (1964), an ideal bed consists of three layers: a few centimetres of greenish or reddish claystone, a few decimetres of intratidal dolomite, and finally a massive bed of micritic, very pure and fossil-rich limestone. Normally the lowest layer is absent or slickensides indicate tectonic movement along it. Although the Dachstein Formation has a sedimentary thickness of more than 1 km, this value can be significantly exceeded due to internal thrusting. In the area of investigation, the strata dip at 15 to 45° to the southeast. Unlike other parts of the Totes Gebirge, where Jurassic sediments (karstic and non karstic) cover significant areas, only Liassic limestone of the Hirlatz Formation has been preserved as unextended vein fillings (neptunian dikes) in the southeastern part.

Directly south of the study area, the Totengebirgs Nappe is delimited by the Warscheneck Nappe. Close to the thrust zone, Upper Triassic non-karstic rocks of the Karnian Stage crop out and lead to the development of small lakes (Figs. 2, 3, e.g. Steirersee, 1445 m a.s.l.).

The deformation history in the NCA comprises at least five phases of tectonic activity, spanning from the Cretaceous to the present (Linzer et al., 1995). Each period was characterised by a different set of normal, strike–slip and/or thrust faults that have resulted in a complex fault pattern.

In the Oligocene and early Miocene, fluviatile siliciclastic sediments of the Augenstein Formation were deposited over an Eocene hilly palaeo-karst landscape, ("Dachstein Palaeosurface", Frisch et al., 2000, 2002). These sediments, possibly up to more than 1 km thick, were removed in the Middle Miocene and only small accumulations of redeposited pebbles ("Augensteine") are found on the plateau today. However, weathering products of the Augenstein Formation are the main source for the clays that are common in the caves. Overall, the relatively simple and homogenous geological settings, favour studies on speleogenesis and the role of planar features in particular.

During the Pleistocene glacial periods, the Totes Gebirge was part of the extensive Alpine ice stream network for at least the latest four

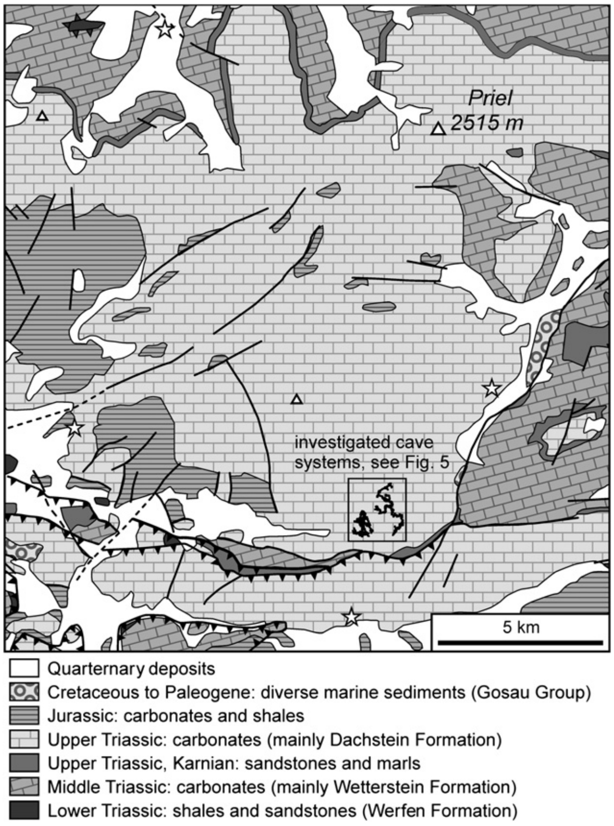

**Fig. 3.** Simplified geological map (modified after Krenmayr & Schnabel, 2006). For locations and names, see Fig. 2; Stars indicate mentioned springs.

major glaciations (Van Husen, 2000). The valleys were filled with up to 1 km thick ice and the glaciers extended up to 50 km to the north and much further to the south. Therefore, the settings can be classified as a "Canadian Type" of alpine karst (in contrast to the Pyrenean Type; Ford and Williams, 2007), in which both the input areas and the springs were occupied by glaciers during cold stages. On the plateau, glacial erosion stripped most of the area and developed staircase pavements (Schichttreppenkarst according to Bögli, 1980; Fig. 4) in the well-bedded Dachstein limestone.

### 2.3. Karst morphology and hydrology

The impressive karst landscape is characterised by extensive karren fields and truncated shafts that are mainly filled with debris. Only a few elevated areas stood above the massive ice, as nunataks, or just carried ice shields so that large, probably pre-Pleistocene dolines have been preserved. To date, about 1500 caves are registered and explored in the Totes Gebirge, but many areas are still unexplored.

The investigated area is highly karstified and drainage is entirely subsurface. Karst hydrology was studied by several authors, but the results of the tracer experiments by means of Lycopodium spores (Maurin and Zötl, 1964; Dincer et al., 1972) are not very reliable. Possible discharge areas of the investigated caves are the Steyer Springs in the east (720 m a.s.l.) or the Stimitz Springs in the west (740 m) which both show mean discharges in the order of several hundred litres per second, high discharge variations, and total dissolved carbonates between 75 and 90 mg/l (Zötl, 1961). Drainage to the north (e.g. Almsee 590 m) is unlikely, as aquitard strata (marls and sandstones of the Karnian stage) would have to be crossed. Drainage to the south is impossible as the spring (Sagtümpel spring ~980 m) lies higher than the deepest sump of the caves, at 904± 10 m.

## 3. Characterisation of the cave systems

We present observations and data from two cave systems (Fig. 5) with a total length of 42.3 km: the Burgunderschacht Cave System (in the following BUC) and the DÖF–Sonnenleiter Cave System (DÖC). At present, there is neither proof that they were part of a single hydrologic system nor that they were hydrologically separated, although obvious morphological differences suggest analysing them separately. Both cave systems consist of two caves, but the adjacency and morphology of the caves suggest strongly that in each case the two individual caves once formed one cave system. Apart from the host-rock, which is limestone of the Dachstein Formation in lagoonal facies, both cave systems share further similar characteristics which are described in the following sections.

### 3.1. Common features of BUC and DÖC

#### 3.1.1. Morphology

Most striking is the clear division into vadose shafts and epiphreatic, horizontal galleries. The shafts, of various depths (several meters to 191 m) and often 5 to 10 m or more in diameter, are bound to vertical faults. They are connected by partly narrow meanders that are generally less than few tens of metres long. Most of the meanders lack a phreatic profile on the top. Therefore, they are interpreted as invasion vadose canyons (Ford and Williams, 2007). With depth, the width of the meanders increases.

Most of the sub-horizontal galleries or mazes of phreatic origin are restricted to a small number of altitudinal levels. Their position, many hundred of metres above the present base-level, suggests an old age. The intersection of the shafts with the horizontal galleries seems incidental in almost all cases, except for using the same initial fault. Sometimes, the active vadose systems use the pre-existing phreatic galleries, where keyhole profiles with narrow entrenchments developed, but after a short distance, the vertical path is continued. Scallops, that allow the palaeoflow direction to be determined, are missing in the phreatic galleries, but paragenetic features are widespread (see Section 3.1.3).

#### 3.1.2. Hydrology

Nearly all cave entrances represent shafts that were truncated by glacial erosion. Therefore, they are not related to the present-day hydrological conditions. Nevertheless, many of the shafts and canyons are fed by streams from micro meanders that enter the vertical system when already some tens of metres below the surface. This behaviour is interpreted as drainage out of a postglacial epikarst. Only one side entrance of the BUC is related to the present hydrological conditions; this directly leads into a narrow canyon of probably postglacial age that is fed by a minor (~0.1–10 l/s) surface spring. After some tens of meters, this narrow meander cuts into a pre-existing series of major shafts.

Many of the vadose pits and interconnecting canyons are hydrologically active. As the surface above the caves mainly consists of bare karren fields, response to hydrological events is very rapid. During storm events, rapidly dripping water can turn into waterfalls with flow rates of several tens of litres per second. Generally, the streams unite at depth. In the lower parts of the caves, streams have minimum discharges of few litres per second in winter. Direct observations of the maximum discharge of these low lying streams are not possible, but it is estimated to be in the order of several tens or hundred of litres per second.

The karst water table is at least 1 km below the surface. Until now, only two low lying sumps were reached, but even for the lower one, at

**Fig. 4.** View over the eastern Totes Gebirge, where Schichttreppenkarst dominates the landscape.

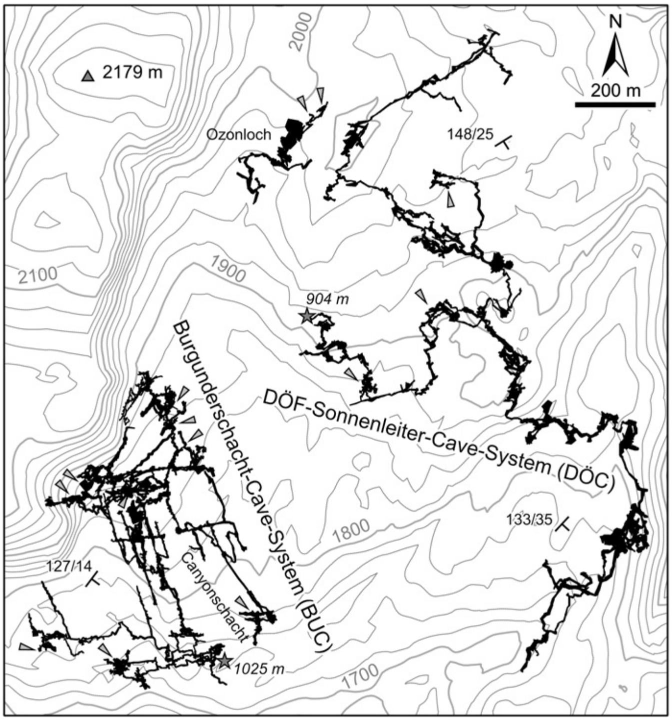

**Fig. 5.** Plan view of the studied cave systems and dip of the limestone. Arrows point at entrances; stars indicate low lying sumps.

904 m a.s.l., it is not sure if it represents the karst water table since it lies ~200 m above the springs that probably drain the area.

### 3.1.3. Sediments

Three main types of clastic sediments are present in the cave systems: (1) Autochthonous breakdown material is found in several parts of the caves, predominantly where frequent frost wedging occurs. (2) Glacial debris is found at the surface, in particular in depressions, and it completely fills most of the shafts that could represent potential additional entrances. It is a coarse, sub-rounded, and poorly sorted sediment consisting almost entirely of limestone clasts. In the caves, this sediment includes boulders up to 50 cm in diameter and it blocks many shafts and some horizontal passages. It can be observed down to depths of −300 m but is more frequent at shallower depths. Herrmann (1993, pp. 19–21) presents a simplified model for the small-scale reshaping of the postglacial surface and the transport and redeposition of glacial debris. (3) Fine grained sediments, mainly silts with a high proportion of calcite, are found in most hydrologically inactive parts down to the deepest explored sections. Many horizontal parts were previously completely filled with sediments and many galleries are still blocked. Sediment fill led to the development of paragenetic features like ceiling half tubes, ceiling meanders, and bypasses which are very common. In some sediment profiles, a lamination can be observed that could represent varve layering.

Massive, and most probably pre-Quaternary speleothems, which are known from many other elevated caves in the NCA (e.g. Frisch et al., 2002; Spötl et al., 2007, pp. 157), are missing. Small, apparently young calcite and aragonite dripstones, as well as hydromagnesite aggregates, have developed at several locations.

Permanent snow and ice fillings occur down to a depth of 250 m. As with glacial debris, many additional possible entrances to the cave systems are completely blocked with firn and ice.

## 3.2. Individual descriptions

### 3.2.1. Burgunderschacht Cave System (BUC)

Burgunderschacht (No. in Austrian cave cadastre: 1625/20, length: 20.2 km, depth: −848 m) and Canyonschacht (1625/382, 2.0 km, −287 m) are treated as one system as only few tens of meters of passages are missing to link them. The system ranges from 1025 to 1873 m a.s.l. Not less than 38 vertical entrances – many of them hosting massive ice and snow fillings – lead into several series of vadose canyon shafts that intersect with horizontal phreatic passages (Figs. 6, 7). Some single shafts have depths of about 100 m and the deepest has a 145 m vertical difference. The lowest point of the system is a sump, reached by French cavers in the 1980 s (Perrin et al., 1983), but surveying data for the deepest parts (below 1307 m a.s.l.) are missing.

Both direct observations in the cave as well as plan views and vertical sections indicate that the cave system has developed along a set of a few parallel directions of vertical faults (mainly strike–slip faults) as well as bedding planes that generally dip at 14° to the southeast (127°). Therefore, inclined (20°–70°) passages are rare (see also Herrmann, 1993, pp. 24). Three phreatic galleries, each showing

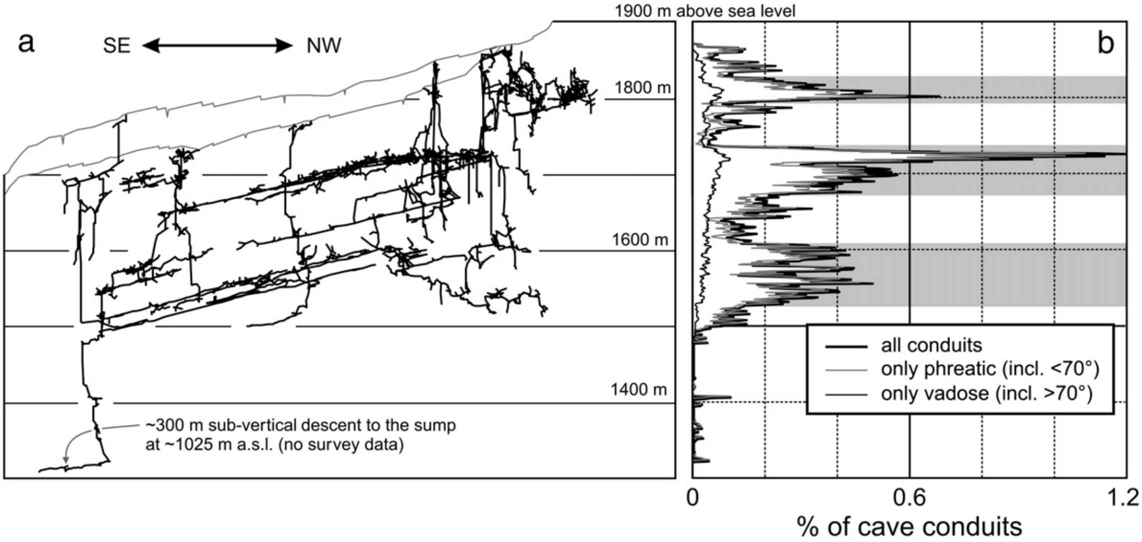

**Fig. 6.** a. Vertical southeast–northwest section of the Burgunderschacht Cave System (survey traverse only). The apparent tilt towards the southeast indicates the dip (14°) of the bedding (view is sub-parallel to the strike of the bedding). b. Frequency distribution of conduits with respect to elevation (cf. Section 4.1). Grey bars indicate interpreted cave levels.

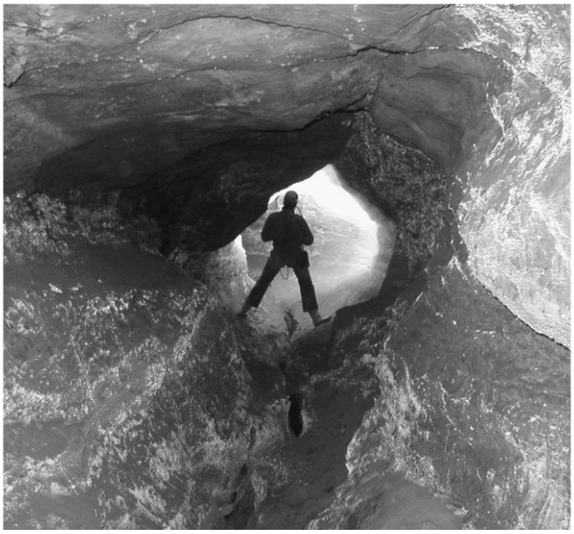

**Fig. 7.** Phreatic tube in Burgunderschacht Cave System that formed along the intersection of a bedding plane with a fault (~1540 m a.s.l.). The small canyon at the bottom is presently active and is not related to Upper Miocene phreatic development.

homogenous morphology throughout, follow the dip of the bedding for at least 100 m of elevational difference. Some parts of the phreatic galleries exhibit angular maze patterns in plan view whilst others represent branchworks. Major horizontal galleries have typical cross-sections of 5–15 m$^2$. Further descriptions are given by Herrmann (1993) and Behm et al. (2007).

### *3.2.2. DÖF–Sonnenleiter Cave System (DÖC)*

Again, the DÖF–Sonnenleiterschacht (1625/379, 18.2 km, −1054 m) and the adjacent Ozonloch (1625/406, 1.9 km, −591 m) are regarded a single cave system that ranges from 904 m to 1995 m a.s.l. Four inactive vadose shaft systems intersect with a major sub-horizontal gallery, which lies at 330 to 400 m below the surface (Fig. 8). Shafts are partly very voluminous and up to 191 m deep. Two of the many intersecting vadose canyon shafts were explored further down, whereas in one a final sump was reached at 904 m a.s.l.

The almost horizontal main gallery shows a rather homogenous morphology with elliptical cross-sections of roughly 30–50 m$^2$ for a long distance. Several textbook-like examples of vadose entrenchments into crests of upward phreatic profiles ("isolated vadose trenches" according to Ford and Williams, 2007, pp. 232) have developed that clearly indicate epiphreatic genesis. The resulting keyhole profiles are up to 15 m high and the canyons are 1–2 m wide. Several times the gallery loops down some tens of meters along bedding planes or faults and then immediately rises up along other initial fissures to the previous level again. At the bottoms of the loops, small phreatic tubes or mazes lead further down, which are interpreted as soutirages (as defined by Häuselmann et al., 2003; equivalent to undercaptures, Ford and Williams, 2007). The bedding of the limestone dips to the SE (148/25° in the north, 133/35° in the south). More detailed descriptions of the cave system are given by Jeutter and Seebacher (1997, 2001).

## 4. Morphometric analyses

We use a method (Filipponi and Jeannin, 2006, Filipponi et. al., 2009-this issue) that gives a quantitative relationship between the conduit network geometry, the geological settings and the hydrogeological context of a cave system. Based on the 3D geometry of the cave system and a geological model, the proposed method is aimed at identifying cave levels, initial fissures, and inception horizons. The geological model is set up by the orientation of the bedding planes, whereas the survey traverse of the entire cave is taken as a proxy for the geometry of the conduits. The frequency distribution of the conduits is calculated with respect to (1) the elevation a.s.l., (2) with respect to the angle between the dip of the conduits and the dip of the strata, and (3) with respect to the normal distance from a pre-defined stratigraphic layer.

We discriminate between vadose and phreatic conduits. The separation is done automatically by classifying all conduits with an inclination of more than 70° as vadose conduits and all the flatter ones as phreatic conduits. In detail, this approach is not entirely accurate

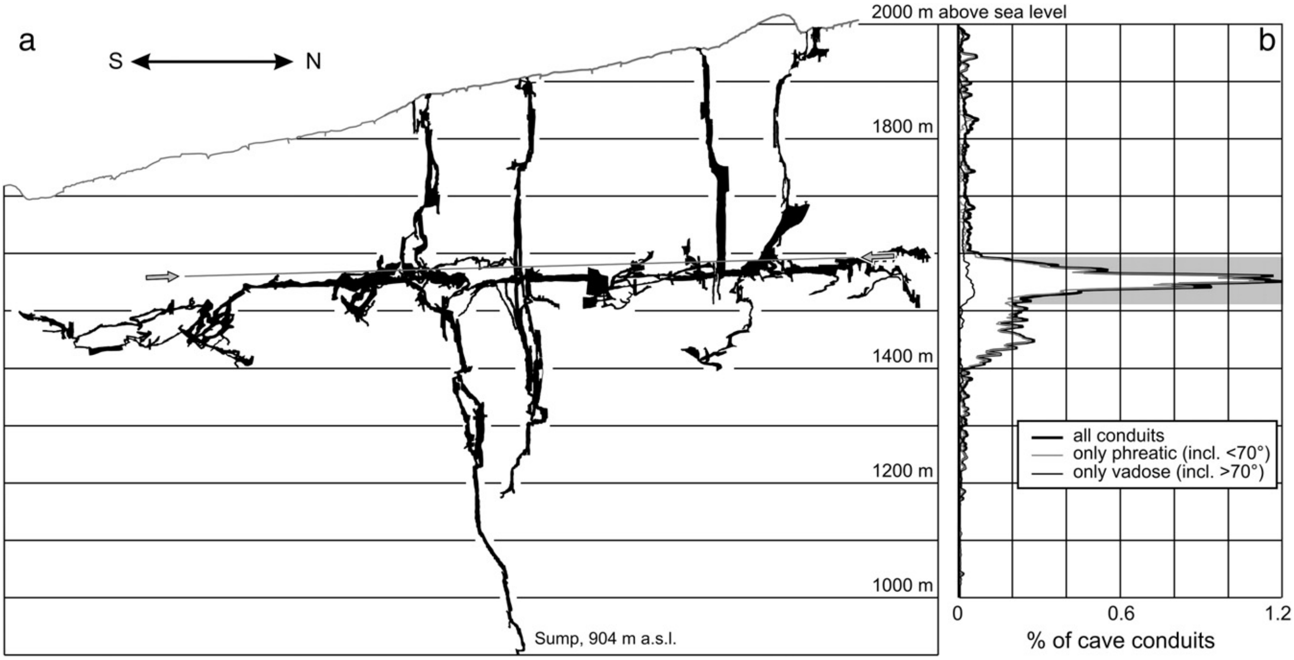

**Fig. 8.** a. Vertical south–north section of the DÖF–Sonnenleiter Cave System. Arrows and grey line indicate the watertable of a speleogenetic phase inclined with 1.6° to the south. b. Frequency distribution of conduits with respect to elevation (cf. Section 4.1). Grey bars indicate interpreted cave levels.

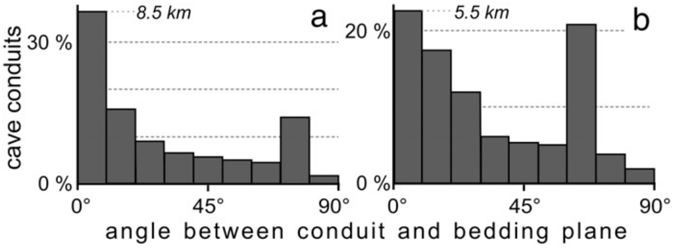

**Fig. 9.** Angle between conduit and bedding plane: (a) Burgunderschacht Cave System, (b) DÖF–Sonnenleiter Cave System (see text for details).

because there are also a few phreatic shafts as well as some sub-horizontal vadose passages (e.g. short meander passages between shafts). However, it is an adequate approximation for this case study, since the separation between vertical, vadose shafts and sub-horizontal, phreatic galleries is very pronounced in the investigated caves.

### *4.1. Cave levels*

Several cave levels are clearly visible in the vertical sections (Figs. 6a, 8a). To analyse them statistically, the complete survey traverse was subdivided into 1 m long segments and their frequency distribution for 1 m height intervals was calculated. A moving average over 5 m was used for smoothing the curves. For BUC, three distinct cave levels, centred at 1800, 1700, and 1560 m a.s.l. can be distinguished (Fig. 6b). In DÖC, major phreatic galleries range from 1400 m to 1600 m but a significant peak is centred at 1550 m a.s.l (Fig. 8b). Further, it is notable that, in both cave systems, vadose conduits are distributed nearly homogenously while only the phreatic conduits show a clear vertical zoning.

The current state of exploration of the caves gives no evidence of further extensive phreatic galleries between 1400 m and the present karst water table at or below ca. 900 m a.s.l. Only from the Wildbadercave (1625/150, 1.6 km, −874 m; Fig. 2) is a major horizontal system at ~1150 m a.s.l. assumed (Pfarr and Stummer, 1988).

### *4.2. Initial fissures*

For the interpretation of the dip of initial fissures, the frequency distribution of the survey traverse shots with respect to the angle between them and the bedding planes (see Sections 3.2.1 and 3.2.2) was calculated. Fig. 9 shows that in both cave systems a large number of conduits are sub-parallel to the dip of the bedding planes. The peaks are more distinct in BUC, which indicates that fewer sets of initial fissures were used. The second maxima represent the vadose shafts that predominantly developed along vertical faults; as bedding is generally steeper in DÖC, this peak is shifted towards a lower angle compared to the BUC.

Further, the frequency distribution of conduits with respect to their azimuth was calculated to check the influence of faults (Fig. 10). In order to eliminate steep survey traverse shots, where the direction may not be representative (e.g. nearly vertical shafts), the horizontally projected segment length serves as proxy. In BUC, we recognise two dominating directions corresponding to the main fault directions. In DÖC, the two recognisable maxima are less pronounced and differ from that of BUC. Overall, both analyses confirm the field observation that phreatic conduits developed preferentially at the intersection of the bedding planes with faults and vadose conduits (mainly shafts) are guided by vertical faults.

### *4.3. Inception horizons*

The inception horizon hypothesis (Lowe, 1992) is based on the assumption that within a homogenous carbonate mass, karst conduits develop preferentially along a limited number of stratigraphical horizons. Therefore, the spatial distribution of conduits should be neither uniform nor random, but should exhibit systematic 3D patterns. The distribution of cave conduits relative to the distance from a reference bedding plane are shown in Fig. 11. It is clear that phreatic conduits have developed only along a restricted number of stratigraphic horizons (i.e. bedding planes). Distinct peaks are interpreted as inception horizon. As stratigraphic markers are missing within the Dachstein Formation, it is not possible to establish a specific reference bed within the ~1 km thick sequence of limestone. Therefore, we choose a recognisable and distinctive bedding plane within each cave system, although it is not possible to identify the same reference horizon for both systems (BUC and DÖC) as a vertical shift along faults between the two caves is possible.

In BUC vadose shafts are homogenously distributed across the stratigraphic sequence whereas the phreatic conduits developed only along six clearly identifiable inception horizons. In DÖC the stratigraphic distribution of the conduits exhibits six less pronounced inception horizons. Again, vadose shafts are more or less homogenously distributed along the stratigraphic section. The evidence for inception horizons is clearer if only the phreatic conduits lying between 1520–1600 m a.s.l. (Fig. 11c) are analyzed. In this case, it is possible to distinguish five inception horizons.

### *4.4. Analyses of different cave levels in BUC*

In contrast to DÖC, the BUC shows three levels (Figs. 5, 6); these have been analysed separately, including histograms of the conduit direction for each level (Fig. 12).

- The level centred at 1800 m a.s.l. (2.7 km of phreatic conduits) developed at the intersection of one inception horizon with NNE–SSW orientated faults. However, the interpretation of only one inception horizon is possibly an artefact since the extension of the conduits is limited due to the intersection of the cave with the surface.
- Level 1700 m (7.0 km) developed at the intersection of two inception horizons with NNW–SSE as well as W–E orientated faults.
- Level 1560 m (5.3 km) developed at the intersection of three inception horizons with NNW–SSE as well as W–E orientated faults.

### *4.5. Water tables of speleogenetic phases*

The 3D-orientation of the water tables of speleogenetic phases were inferred from survey data by analysing various vertical sections of the caves. If linear arrangements of tops of phreatic loops (giving the minimum height of the water table of the speleogenetic phase)

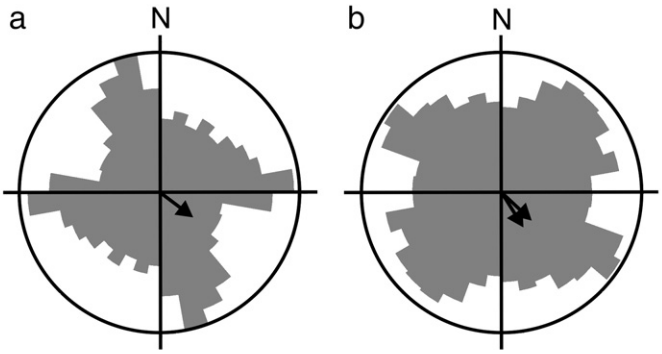

**Fig. 10.** Symmetrical bidirectional rose diagram of conduit length. Arrows indicates dip directions of the strata. (a) Burgunderschacht Cave System, cumulative length of peak maximum: 1550 m (b) DÖF–Sonnenleiter Cave System, maximum: 1330 m (see text for details).

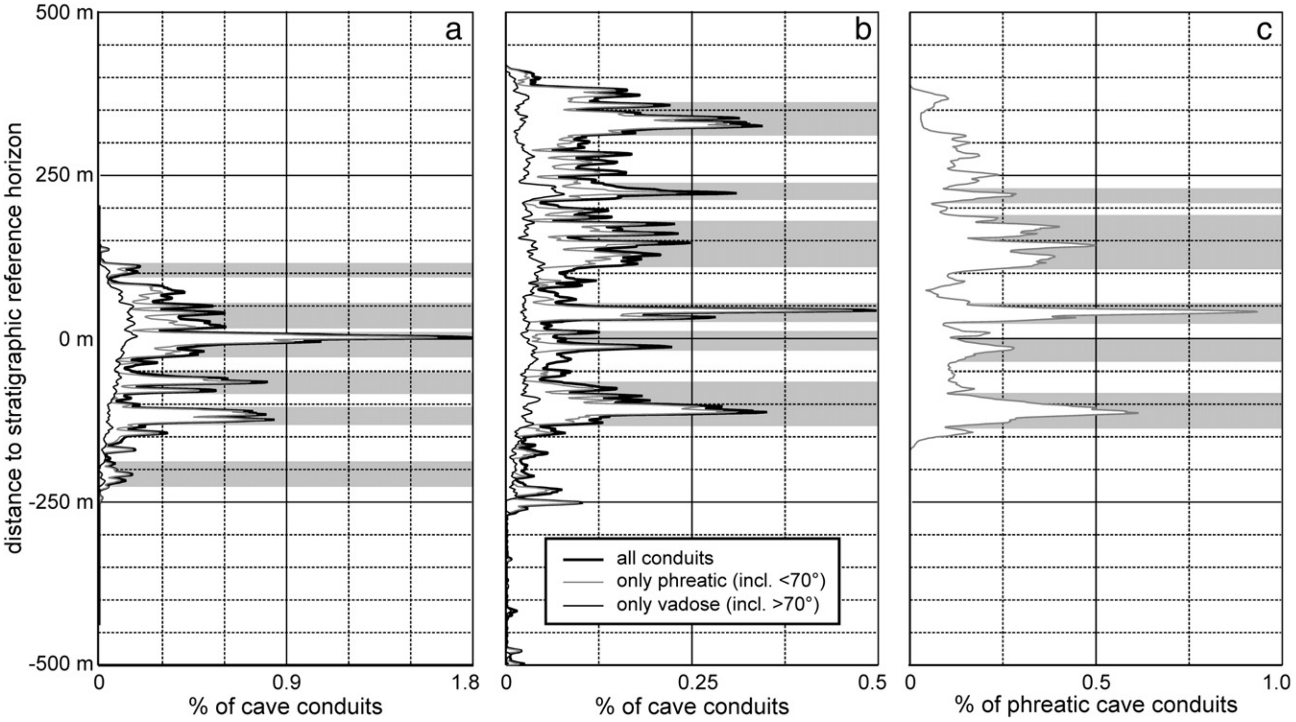

**Fig. 11.** Frequency distribution of conduits with respect to the normal distance from a reference bedding plane. Grey bars indicate interpreted inception horizons. (a) Burgunderschacht Cave System; (b) DÖF–Sonnenleiter Cave System, (c) Level 1520–1600 m in DÖF–Sonnenleiter Cave System (because of the inclination of the reference bedding plan the range becomes much wider than the 80 m of the analysed height interval).

were visible, the orientation of the projection plane which shows the steepest inclination of a line connecting the crests of phreatic loops was determined. The direction of the projection plan defines the approximate dip-direction of the palaeo water table and was interpreted as the palaeoflow direction. For BUC no morphologic features that define a watertable of a phase are visible (in contrast to clearly visible dip of the bedding planes; see Fig. 6.). For DÖC a very clear palaeo water table is visible (Fig. 8a) tilted at 1.6° to the south and extending over 1.1 km horizontally and from 1560 to 1590 m a.s.l. vertically.

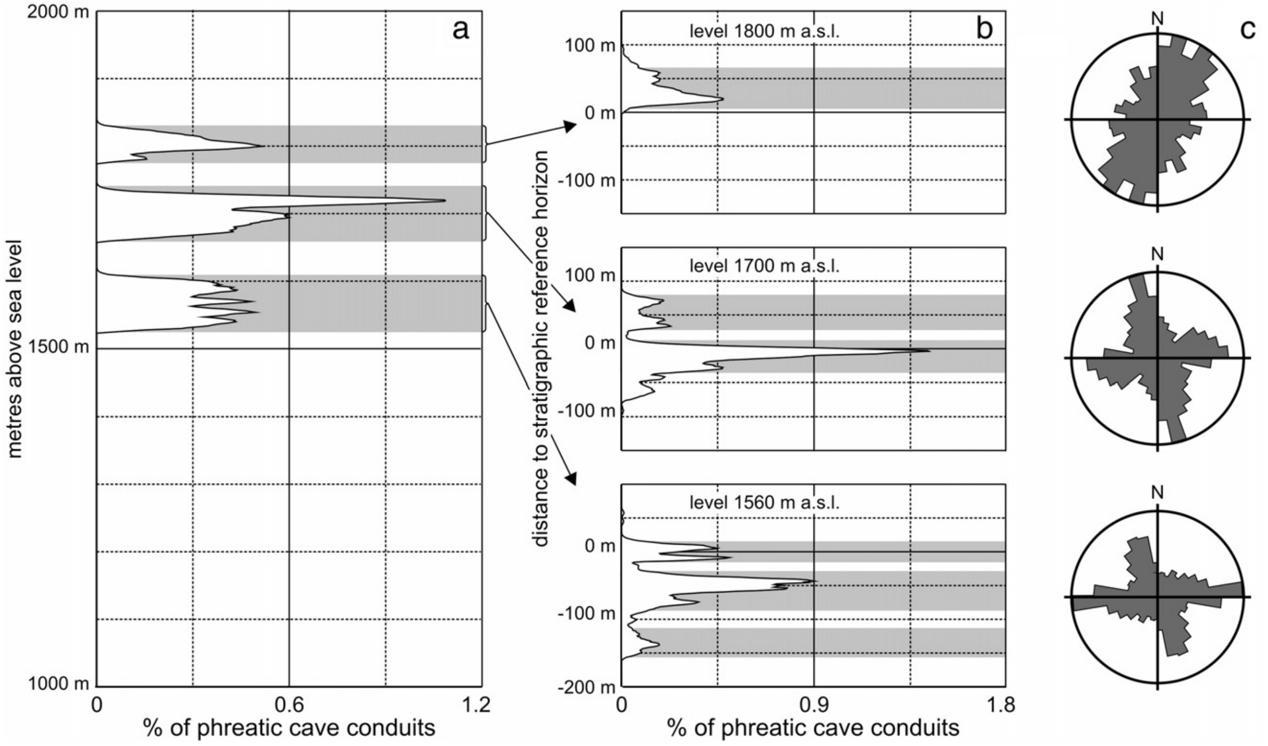

**Fig. 12.** Histograms of the three levels in Burgunderschacht Cave System. (a) Frequency distribution of the three phreatic conduits interpreted from Fig. 6b with respect to elevation. (b) Frequency distribution of phreatic conduits with respect to the normal distance from a reference bedding plane. Grey bars indicate interpreted inception horizons. (c) Analysis of preferred directions of conduits in each level; cumulative length at peak maximum: 255 m (at 1800 m), 691 (1700 m), 590 m (1560 m).

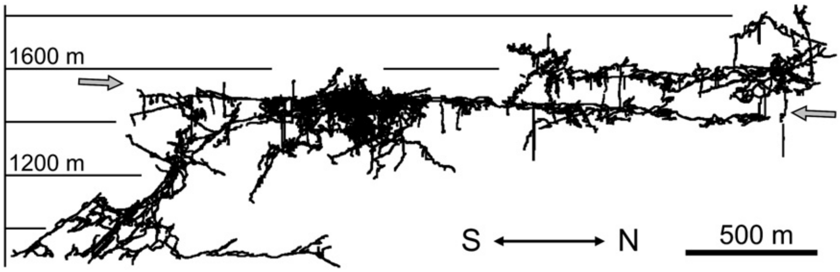

**Fig. 13.** Vertical S–N section of the Schönberg Cave System. Arrows indicate a speleogenetic phase that is inclined at 2.5° to the north.

### *4.6. Water tables of phases in other cave systems*

To compare the orientation of palaeo water tables within other parts of the Totes Gebirge (Fig. 1), further large cave systems were investigated. For Schönberg Cave System (former Raucherkar and Feuertal Cave System, 1626/55; 120.4 km; ±1060 m; Tenreiter, 2007) a major palaeo water table that extends over 2.4 km and dips at 2.5° to the north (Fig. 13) was detected. This is situated between 1430 and 1530 m a.s.l. A second, minor water table is also present ~100 m higher in the cave. Morphometric analyses reveal that Schönberg Cave System developed along four or five inception horizons.

In the Schwarzmooskogel Cave System (1623/40; 58.2 km; Winkler, 2004) large breakdown chambers partly obscure the original morphology. However, a potential water table of a phase seems to extend over 2.3 km and dips at 1.6° to the southwest. In this cave system, six inception horizons could be identified (Filipponi and Jeannin, 2006).

For the Woising cave area (1627/74; 10.6 km; Kalmbach and Spahlinger, 2001), a clear planar alignment of loop crests over a distance of 0.5 km is visible. As the inclination of the connecting line is very shallow (0.5°), its interpretation as a northwest-dipping phase at ~1650 m a.s.l. is uncertain.

Several caves (Harlacher at al., 2003; Frank, 2001) near Appelhaus refuge were analysed. Some 26 km of passages at Hüttstatt and Redender Stein developed in Jurassic limestone as well as 15 km of caves in Dachstein limestone (Dellerklapf Cave, 1627/34; Illegal Harem Cave, 1627/42; Klammkogelhöhle 1627/29) do not show significant water tables corresponding to speleogenetic phases. The 2.7 km long Grubsteineishöhle (1625/16; Seebacher, 2001), close to the DÖC, shows morphologic evidence of a phase at ~1900 m a.s.l., but due to its short horizontal extent (300 m), the dip-direction cannot be accurately estimated.

## 5. Discussion

In our study, we analysed cave levels (strictly horizontal accumulation of galleries) and palaeo water tables of speleogenetic phases (slightly inclined). Many former publications tried to correlate cave levels with surface morphology and palaeo base levels (e.g. Kuffner, 1998; Fischer, 1990). However, it was rarely possible to correlate the levels over regional scale or several cave systems respectively, even within a single karst massif. With the knowledge that phreatic cave passages develop below slightly inclined water tables corresponding to speleogenetic phases (e.g. Häuselmann et al., 2003), it is evident that an observed cave level may be mistaken for a water table of a phase, in particular if the observable horizontal extent is limited. Only detailed observations of cave systems that extend over long distances allow the determination of inclined water tables. Therefore, the term level for horizontal accumulations of galleries at certain altitudes should be used descriptively only. However, the observation of a cave level is an indication that there should be one or more speleogenetic phases within that height interval. Its observation may not be possible because the knowledge of the whole cave system is always limited (state of exploration, sediment fill etc.). This means that cave levels have some genetic relevance but they do not give the exact position of a palaeo water table nor can they be taken as indications for a flat palaeo water table. Therefore, the interpretation and correlation of cave levels is only feasible for large scale levels (in the order of a couple of hundred metres elevation) that may comprise many speleogenetic phases. In the NCA, three such major cave levels were defined (Haseke-Knapczyk, 1989) and the age of their development was determined by Frisch et al. (2002).

According to their morphology and their elevation between 1400 and 1870 m a.s.l., we identified three levels in the investigated area. The levels are centred at 1810, 1700, and 1560 m a.s.l and are regarded as expression for speleogenetic phases that are part of the Giant Cave Level of the NCA that developed in Upper Miocene times (6 to 10 Ma; Frisch et al., 2002).

Using the classical “Four State Model” (Ford, 1971) in a descriptive way, the BUC can be classified as a phreatic cave with multiple loops while the epiphreatic gallery in the nearby DÖC exhibits water table characteristics with few phreatic loops. Although there are current studies that support other factors responsible for the development of a certain “state” (e.g. discharge conditions; Häuselmann and Gabrovšek, pers. comm.) our studies suggest that the density of initial fissures still is an important factor, which is in accordance with the classical interpretation. For both the angles between conduit and bedding plane (Fig. 9) as well as the conduit directions (Fig. 10), the statistical analyses show more pronounced peaks for the conduits of BUC than of DÖC. This reveals that in BUC there are fewer sets of initial fissures, mainly six distinct inception horizons, which were used during solutional processes for a greater distance. On the other hand, at least for the cave levels at around 1560 m a.s.l., which can be observed in both cave systems, the conduits developed simultaneously, which does not favour the theory of different climate or discharge conditions to develop different states respectively. For BUC, the change of preferred conduit directions at different levels (Fig. 12) indicates that the flow direction or initial fissures have changed over time. This latter could be explained by a change of the stress fields due to the ongoing Alpine deformation, which influences initial fissure properties (aperture, fault rocks etc.). However, the exact reasons for the very local differences in fracture density and measurements of fracture density that are independent of the cave morphology are subject to further studies.

In contrast to the classical Four State Model, we attribute the genesis of the mature galleries, at least for the DÖC, to epiphreatic conditions, as previously suggested by Audra (1994) and Häuselmann et al. (2003). The main gallery of the DÖC is clearly epiphreatic. The soutirages imply that this part developed by the “filling-overflow manner” as it was observed by Häuselmann et al. (2003) in present-day water active caves. For the loops of the BUC, which have elevational differences of at least 100 m, there is no clear morphological evidence for epiphreatic flow. The relatively large elevational differences do not seem outstanding when compared to Audra (1994), who observed epiphreatic loops with a 250 m elevational difference in a cave system in the Tennengebirge (NCA, Cosa Nostra Bergerhöhle).

As small-scale morphological indicators for flow direction are missing, the tilting of the main gallery in the DÖC at 1.6° to the south allows for two interpretations of the palaeoflow direction. (1) Its location in the southern part of the massif, only 10 km north of the margin of the NCA, as well as the large cross-sections areas of the galleries could imply allogenic recharge and a north-directed flow. Similar conditions are very likely for the Dachstein Südwandhöhle at the southern cliffs of the neighbouring Dachstein massif (Seebacher, 2006). This cave is located directly at the southern margin of the NCA and shows north(west) directed palaeoflow. In the Tennengebirge massif, Audra et al. (2002) also suggested allogenic recharge from the south during the development of the Giant Cave Level. However, for the south-eastern Totes Gebirge a north-directed flow together with the observed south-dipping water table of a phase would imply a rotational component during tectonic uplift of more than 1.6°. (2) A south-directed flow according to the dip of the phase would imply autogenic recharge of a large area. The inclination of the palaeo karst watertable of ~1.6° matches data by Häuselmann et al. (2003) who observed inclinations of 1.3° to 2.1° in Bärenschacht (Thunersee, Switzerland). Analyses from other cave systems in the Totes Gebirge confirm the magnitude of these angles although Schönberg Cave Systems is slightly steeper (2.5°). Only the inclination of the water table of the phase in Nervensystem Cave seems to be exceptionally low (0.5°) but the horizontal extension of the system is limited. Considering these other cave systems, the dip-directions of the water tables (Fig. 2) are interpreted as palaeoflow directions and generally suggest a radial drainage pattern for the Totes Gebirge in the Upper Miocene. In turn, this implies autogenic recharge. The observations do not support a general north directed palaeoflow with allogenic recharge. Therefore, we reject the idea of north-directed flow and tectonic rotation for the investigated area.

Even though tracer tests by Maurin and Zötl (1964) indicated a radial drainage, we do not take this as support for our model, since the same methods resulted in the same radial pattern for the Dachstein massif (Zötl, 1974), which was subsequently disproved by further tests (Herlicska et al., 1995) that showed north-directed flow.

Nowadays, flow direction within the phreatic zone in the area of investigation is west- or east-directed and therefore perpendicular to that in Upper Miocene. Non-karstic rocks, which presently crop out at ~1450 m directly south of the caves, dam the karst close to the southern margin of the plateau. Therefore, the switch in the flow direction must have occurred relatively shortly after the development of the main phase in DÖC which, if extrapolated, intersects with the surface at ~1540 m. This, and the fact that the catchment area between the non karstic rock and the study area is very small, would be an explanation for the absence of extensive phreatic galleries below this level.

The fine-grained sediments, which were deposited during very slow flow velocities, are attributed to Pleistocene backflooding. This occurred when the valleys and the discharge points were filled with ice, which lead to several rises of the water table. These interpretations are in accordance with observations by Audra et al. (2002) from Tennengebirge. Also in our area, the slow current and the low chemical aggressiveness of the glacial meltwater that resulted from the suspended calcite rich sediments, restricted speleogenetic action.

Most probably, the widespread paragenetic features developed due to the backflooding, as they occur in many galleries that are filled with fine sediments. Further, old micromorphological structures like scallops were obscured during these periods.

## 6. Conclusion

Detailed observations of extensive alpine cave systems confirm that (epi)phreatic caves preferentially form below slightly inclined surfaces, the water tables of speleogenetic phases, and not at strictly horizontal levels. At least for alpine caves, inclinations in the order of 1.5° ± 1° seem to be typical for base level related speleogenetic phases that are not controlled by geological inhomogeneities. Therefore, cave levels (horizontal accumulations of galleries) indicate the presence of one or more speleogenetic phases, but they cannot be correlated over large distances or with surface morphology. The delineation of water tables of speleogenetic phases needs in-depth morphological observations and data from cave systems with major horizontal extents.

The two adjacent cave systems investigated show different morphological types with respect to length–depth-development, and to the Four State Model (Ford and Williams, 2007). The main

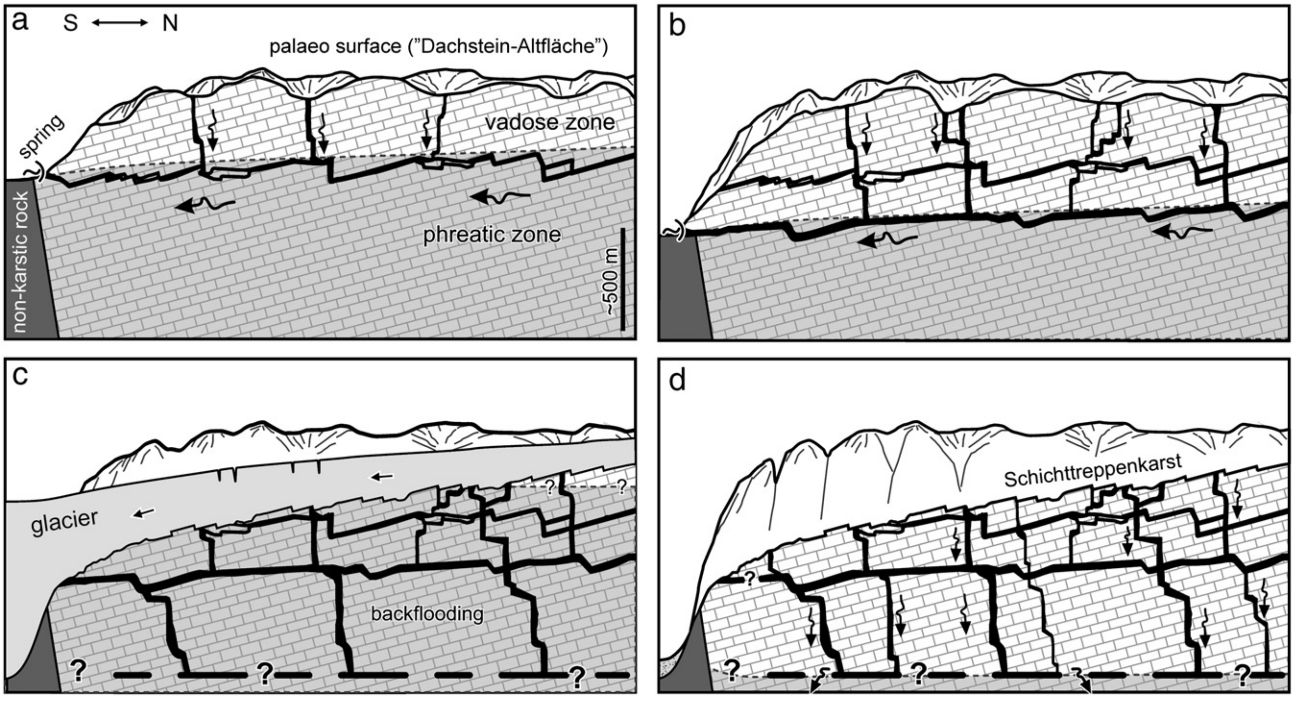

**Fig. 14.** Simplified genetical model of cave and surface development at the southern margin of the south-eastern Totes Gebirge. For explanation, see text.

gallery in the DÖF–Sonnenleiter Cave System (DÖC) is a watertable cave with only few loops whilst the three levels in the Burgunderschacht Cave System (BUC) show multiple looping. Statistical analyses of gallery inclination and direction indicate that the BUC formed along a few persistent initial fissures whereas the genesis of the DÖC was guided by less prominent initial fissures. This is in accordance with the explanation of the Four State Model. Further, the simultaneous developments of different states at the same level, which can be observed in both caves, suggest that discharge conditions or climatic factors have no influence on the state for the observed caves. In contrast to the Four State Model development conditions were clearly epiphreatic, at least in DÖC, and not phreatic (sensu stricto) and the loops developed in the filling-overflow manner (Häuselmann et al., 2003).

The Upper Miocene subsurface palaeoflow inferred from the inclinations of the water tables of phases indicate that the Totes Gebirge karst massif was drained radially and recharge was autogenic. This excludes a north-directed through flow of allogenic water as suggested for Tennengebirge and Dachstein.

From the observations above, a simplified genetical model for the caves in the south-eastern Totes Gebirge is deduced (Fig. 14): (a) Upper Miocene: The Dachstein–Surface is already significantly uplifted and speleogenetic phases fed by autogenic recharge develop corresponding to a base level in the south. The cave systems developed along a few inception horizons and faults — phreatic conduits often at the intersection of both. (b) Relative deepening of the base level causes the development of several phases. At least some of them were formed under epiphreatic conditions and behaved in the filling overflow manner. However, the phases differ in type according to the Four State Model as fracturing seems to vary locally. The galleries of both phases (a and b) are part of the Giant Cave Level (Frisch et al., 2002). (c) During Pleistocene glaciations, the Totes Gebirge was covered by massive glaciers of the Alpine ice stream network which eroded the valleys and most of the plateau area. On bedded Dachstein limestone, they formed staircase limestone pavements (Schichttreppenkarst). Back-flooding due to the ice filling of the valleys caused sediment fill and paragenesis in the caves. (d) Pleistocene interglacial (e.g. present conditions): vadose waters enter the old phreatic galleries through the shafts and partly remove the sediment fill. Several cycles of glacial (c) and interglacial periods (d) occur. Galleries of the actual epiphreatic zone, which drain to the east or west, are unknown.

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