Austrian Journal of Earth Sciences | Vienna | 2024 | Volume 117 | 163–175 | DOI: 10.17738/ajes.2024.0010

Cave Levels in the Totes Gebirge (Eastern Alps)

Lina Rummler[1], Lukas Plan[1*] and Xenia Hauser[1]
[1)] Natural History Museum Vienna, Karst and Cave Group, Museumsplatz 1/10, 1070 Wien, Austria
[*)] Corresponding author: lukas.plan@univie.ac.at

Keywords: Cave level, speleogenesis, landscape evolution, Northern Calcareous Alps, Totes Gebirge

Abstract

The Totes Gebirge is not only the largest karst massif in the Northern Calcareous Alps, it also contains the most cave passages. In this area we are investigating the vertical distribution of phreatic cave passages to determine cave levels. These are vertical zones with clusters of cave passages that can be correlated with former valley floors. Since only phreatic cave passages (i.e. caves that were permanently or episodically filled with water during their formation) are to be analysed, a genetic classification is made on the basis of field observations, cave maps, 3D surveys and descriptions.

As of Sept. 2023, the Totes Gebirge range, including the adjacent Warscheneck and the Hohe Schrott, contains 3172 known caves with a total length of 821 km, including the two longest cave systems in Austria, the Schönberg- (156 km) and the Schwarzmooskogel-Höhlensystem (137 km). As small caves do not contribute significantly to these statistics, only caves ≥50 m were included. The remaining 754 caves have a total length of 790 km. Only 46 % of these caves are at least partially of phreatic origin, but they contain 92 % of the total passage length. After subtracting the caves from which no data were available and cave sections that are not phreatic in origin (i.e. vadose or those created by weathering and erosion), 641 km of cave sections remained, which were analysed for their vertical distribution in 25 m increments.

The histogram of cave length distribution vs. elevation for the Totes Gebirge range shows only a single significant cluster of phreatic cave sections between 1300 and 1850 m above see level (a.s.l.), with a clear maximum at 1500 m. The massif was divided into four sub-regions and all of them show this main interval, which is why it was interpreted as a cave level. It correlates well with the Giant Cave Level known from all other karst massifs in the Northern Calcareous Alps analysed so far. However, it is peculiar that in the other massifs at least three cave levels are present. Other reasons, such as the lack of known caves and the large size of the massif, which could lead to overlapping of cave levels, are unlikely. Therefore, it seems possible that the palaeo surface drainage pattern around the Totes Gebirge or its uplift history was different from the other karst massifs in the Northern Calcareous Alps and that low-lying cave levels (Spring and Berger Cave Level) or an elevated one (Ruin Cave Level) did not develop. For each of the 21 largest cave systems (≥5 km in length), the peak of the vertical distribution of the phreatic passages was determined. Vectors were calculated in order to test whether palaeo-flow directions could be inferred from their distribution. These phreatic maxima indicate a general dip from ESE to WNW, which could be interpreted either as a palaeo-drainage direction or as a tectonic tilting of the whole massif after the formation of the passages.

1. Introduction

The largest karst massif in the Northern Calcareous Alps (NCA) of Austria, which also has the highest cumulative cave length, is the Totes Gebirge range (Fig. 1; Spötl and Plan, 2016). To learn more about the landscape and drainage evolution of the area, this study examines the massif and investigates the vertical distribution of (sub) horizontal cave passages. Vertical ranges in which the abundance of cave passages is higher than in the surrounding elevations are termed cave levels (e.g. Audra and Palmer, 2011).

The first studies on this topic in the NCA analysed the

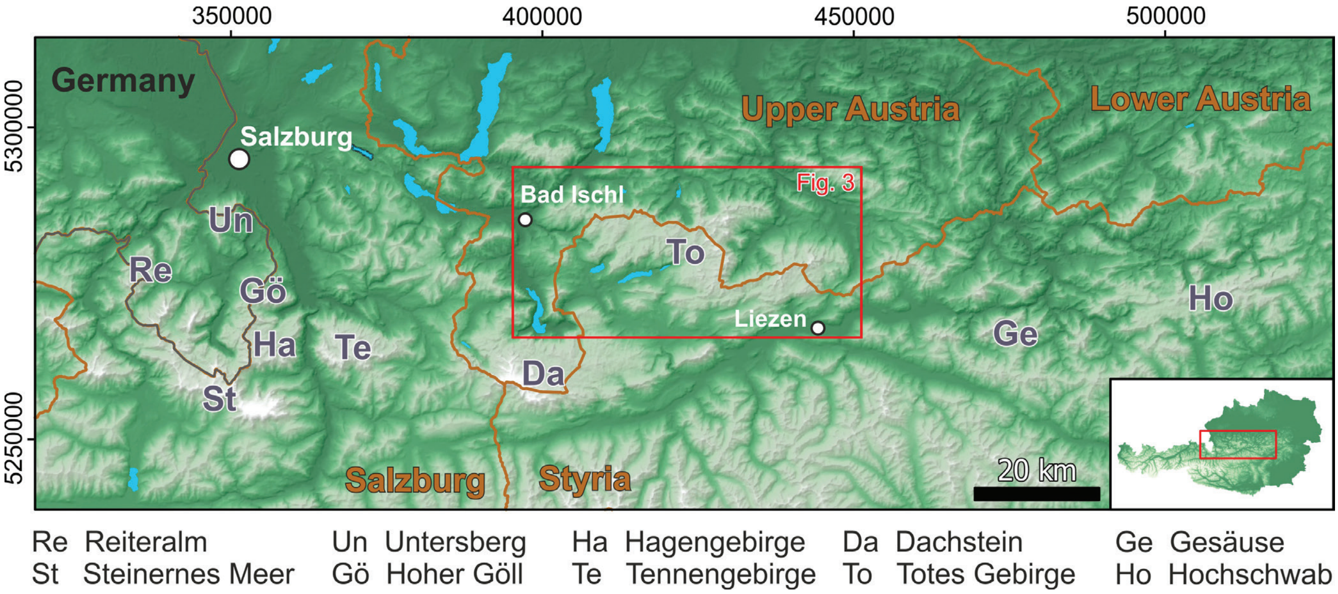

Figure 1: Overview of previously analysed karst massifs in NCA and the location of the Totes Gebirge range. Coordinates: UTM 33N. The insert shows the location within Austria.

vertical distribution of cave entrances in the Tennengebirge (Hell, 1926), Totes Gebirge (Lechner, 1949), and Dachstein (Schauberger, 1955). However, the vertical distribution of cave entrances and cave passages can vary significantly (Rummler and Plan, 2023). In later studies, the vertical distribution of cave passages was analysed using histograms (Klappacher and Knapczyk, 1977, p. 157, 1979, p. 91; Klappacher and Haseke-Knapczyk, 1985, p. 101; Haseke-Knapczyk, 1989; summarised in Fischer, 1990; Kuffner, 1998; Frisch et al. 2002). They identified three or partly four cave levels in the central NCA that also share similar morphologic and sedimentological characteristics. From top to bottom, they were referred to as the Ruin Cave Level (in German: "Höhlenruinen-Niveau"), the Giant Cave Level ("Riesenhöhlen-Niveau"), the only partially developed Berger Cave Level ("Bergerhöhlen-Niveau"), and the Spring Cave Level ("Quellhöhlen-Niveau"). Rummler and Plan (2023) analysed cave levels in the Dachstein massif and postulated a fifth cave level, the Voodoo Cave Level above the Ruin Cave Level. Most of the caves in the NCA are karst caves. In general, these caves form along initial fissures in the vadose zone above the karst water table or in the phreatic zone below the water table (e.g. De Waele and Gutiérrez, 2022). The so-called epiphreatic zone marks the fluctuation of the water table and is only episodically water-filled during flooding. As the characteristics of the phreatic and epiphreatic zones are similar, we will hereafter talk about the phreatic but include the epiphreatic one. Unless disturbed by aquiclude strata, the water table within a karst massif correlates with the elevation of the springs at the base level. And since caves form mainly at or slightly below the karst water table, the distribution of cave levels is related to the former base levels (Audra and Palmer, 2011).

It is generally assumed that cave levels are closely related to the geomorphic evolution of the surrounding landscape, particularly the evolution of karst and palaeo-groundwater levels (e.g. Audra and Palmer, 2011). The presence of distinct cave levels is interpreted as reflecting episodes of stable base level conditions, while the intervals between them indicate phases of tectonic and/or climatic change (e.g. Audra and Palmer, 2011). A similar but more precise concept identifies speleogenetic phases (Häuselmann et al., 2002). These are times when elevations (not ranges of elevation) of phreatic-vadose transitions mark the top of the fluctuating palaeo karst water table. During a speleogenetic phase, the surface of the karst water table tends to form a plane that dips by 1 to 2.5° during flood conditions. However, the definition of the palaeo karst water table is difficult and there are only a few cases in the NCA where speleogenetic phases have been identified (e.g. Schönberg-Höhlensystem [HS]; Plan et al., 2023).

In this study, phreatic passages are used to identify cave levels in the Totes Gebirge, including the adjacent Warscheneck and the Hohe Schrott (hereafter simply referred to as the Totes Gebirge range). Therefore, caves with a passage length ≥50 m were classified according to their model of formation. After that, the vertical distribution of sections of phreatic caves or the whole caves was examined. In addition, different methods for determining the phreatic parts of a cave were compared. In order to investigate the regional distribution, the study area was divided into four sub-areas, which were then compared with each other. The phreatic maxima (the height interval with the most phreatic passages) of 21 caves ≥5 km were also compared to investigate a possible gradient of the cave levels.

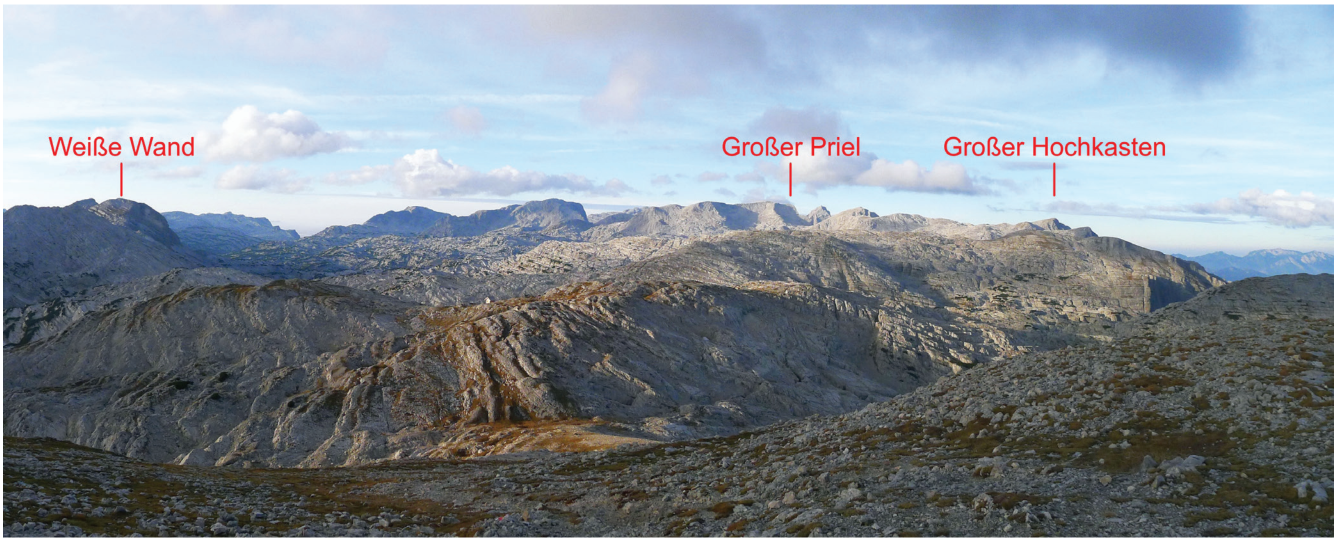

Figure 2: View from the area of Großes Tragl (northern end of DÖF-Sonnenleiter-HS) to the north respectively the northern part of Totes Gebirge. Photo: Robert Seebacher.

2. Study site

The Totes Gebirge range lies in the central part of the NCA. While the larger part lies in the federal state of Styria, the northern and western parts belong to Upper Austria. With an area of 1057 km^2, the Totes Gebirge range is the largest karst massif in the European Alps (Spötl and Plan, 2016; Tab. 1, Figs. 2, 3). The highest peak is the Großer Priel, reaching 2515 m a.s.l. The Warscheneck to the east (peak of the same name, 2388 m) can be considered as part of the Totes Gebirge, as it is only separated by a saddle (Salzsteigjoch) at 1733 m. The same is true for the Hohe Schrott (1939 m a.s.l.), which is also separated by an indistinct saddle. The massif is bordered by local streams and saddles in the north, the Steyr valley (493 m a.s.l. at Steyrbrücke) in the east, the Mitterndorf Basin (800 m a.s.l.) and Enns valley (at Liezen 635 m a.s.l.) in the south and the Traun valley (468 m a.s.l. at Bad Ischl) in the west. Some important rivers originate in the Totes Gebirge range, such as the Steyer and the Traun (Geyer et al., 2016).

Most of the Totes Gebirge range is formed by the Totes Gebirge Nappe (Mandl et al., 2012). In the northwest, it overthrusts the Stauffen-Höllengebirge Nappe and in the east, it is overthrusted by the Warscheneck Nappe. The base of these nappes are the Upper Permian Haselgebirge and the Lower Triassic Werfen beds. Both are impermeable, but may contain gypsum as well as rock salt and acted as a décollement for the nappes (Fernandez et al., 2024). In some parts of the Totes Gebirge, a thin layer of Gutenstein limestone and dolomite forms the base of the Middle Triassic carbonate platforms. To the east and north, Wetterstein dolomite is exposed, locally overlain by a thin layer of a few tens of metres of impermeable North Alpine Raibl beds (Upper Triassic; marls, sandstones and shales). The overlying Hauptdolomit rarely exceeds 100 m in thickness. The most prominent rock in the Totes Gebirge is the Upper Triassic Dachstein limestone, which is well bedded and over 1 km thick. In the westernmost parts of the Totes Gebirge, the Dachstein limestone may contain a thin layer of the marly Kössen Formation (Fm.). Above the Dachstein limestone, impermeable Jurassic rocks such as the Allgäu Fm. or the Ruhpolding radiolarite or partly well karstified Hierlatz limestone, Oberalm Fm. and Plassen limestone may occur locally (Mandl et al., 2012). The area is characterised by large plateaus and has been shaped by karstification

Area name	Area code	Area [km^2]	Number of caves	Number of caves ≥ 50m	Total length of caves ≥ 50m
Hohe Schrott	1616	60	470	71	67 km
Totes Gebirge	1621 to 1628	642	2219	572	677 km
Warscheneck	1631 to 1639	355	483	111	47 km
Total		*1057*	*3172*	*754*	*791 km*

Table 1: Subgroups and number of caves (as of Sept., 2023) in the Totes Gebirge range. Definition of subgroups and area code according to Stummer and Plan (2002).

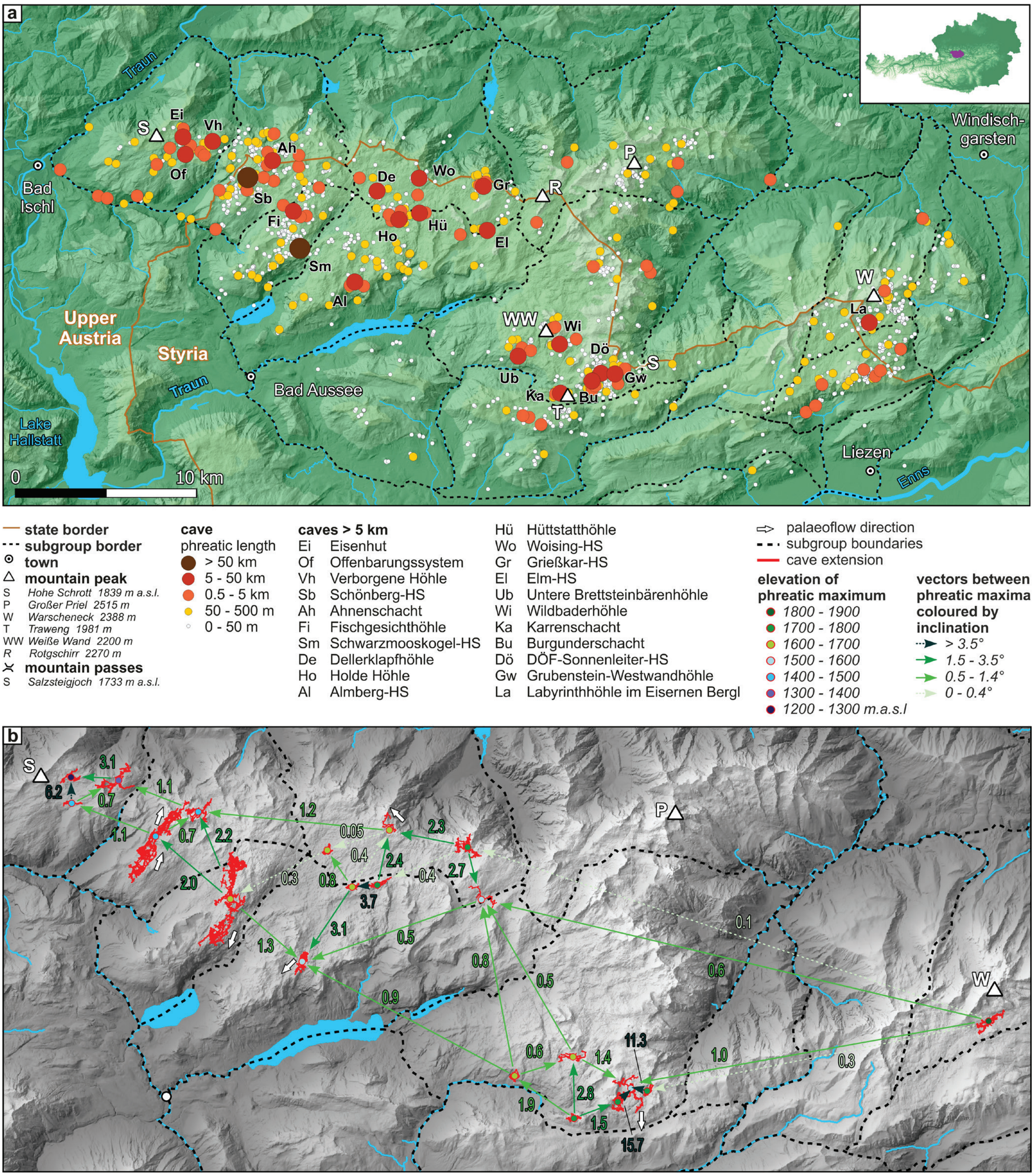

Figure 3: **(a)** Distribution of caves of the Totes Gebirge, colour-coded according to phreatic length. **(b)** Extension of caves ≥5 km and centre of the cave colour-coded by elevation of phreatic maximum. Vectors between nearby caves are colour-coded according to their inclination and the values of inclination are given in degrees.

and glacial processes (Fig. 2). In the western and eastern parts, the plateaus are often covered by vegetation. The central plateau is only sparsely vegetated and often Schichttreppenkarst has developed due to the well bedded Dachstein limestone and glaciation. In general, there are large karrenfields, as well as many dolines, grikes, and shafts. In the plateau area between 1440 and 1650 m a.s.l. there are several lakes. During the Pleistocene cold periods, the whole Totes Gebirge was covered and reshaped by glaciers of the Alpine ice stream network except some

Cave name	No.	Total length [km]	Phreatic length [km]	Elevation range [m a.s.l.]	Phreatic maximum [m a.s.l.]	Depth [m]	Lithology	F
Schönberg-HS	1626/300	156.2	143.9	871 – 1933	1500	1062	DK, (HD)	3
Schwarzmooskogel-HS	1623/40	137.4	121.8	756 – 1867	1625	1111	DK	2
Verborgene Höhle	1616/110	30.9	28.1	1112 – 1477	1400	365	DK	
Almberg-HS	1624/18	25.8	24.2	1375 – 1677	1525	302	PK	3
Ahnenschacht	1626/50	25.5	23.2	1266 – 1893	1475	627	DK, HD	
DÖF-Sonnenleiter-HS	1625/379	24.8	20.4	904 – 1996	1575	1092	DK	1
Labyrinthhöhle im E.B.	1636/77	23.9	22.5	1141 – 1912	1825 (1550)	771	DK	2
Burgunderschacht	1625/20	22.6	18.1	1023 – 1871	1725	848	DK	3
Woising-HS	1627/74	20.8	18.9	1152 – 1823	1650	669	DK, (HD)	3
Grießkar-HS	1627/126	19.2	17.9	1263 – 2015	1775	752	DK, (HD)	
Wildbaderhöhle	1625/150	12.5	9.2	911 – 2012	1650	1101	DK	
Karrenschacht	1625/49	10.6	7.2	1498 – 1904	1775	406	DK	
Grubstein-Westwandhöhle	1625/351	10.5	10.0	1610 – 2012	1750	402	DK	1
Hüttstatthöhle	1624/28	9.4	9.2	1591 – 1837	1750	246	OA, PK?	
Dellerklapfhöhle	1627/34	8.8	8.2	1237 – 1696	1650	459	DK	
Eisenhut	1616/422	7.3	5.5	1153 – 1570	1300	417	DK	
Holde Höhle	1624/160	7.1	5.9	1627 – 1845	1675	218	PK, OA?	
Offenbarungssystem	1616/80	6.6	5.9	1297 – 1519	1425	222	DK	
Fischgesicht-Höhle	1623/290	6.4	5.6	1239 – 1696	1450	457	DK	
Elm-HS	1624/38	5.5	4.0	1369 – 1723	1600	354	DK	
Untere Brettsteinbärenhöhle	1625/33	5.4	5.3	1446 – 1664	1675	218	DK	

Table 2: More than 5 km-long caves in the Totes Gebirge range (as of Sept., 2023) arranged according to length. HS - Höhlensystem / cave system; No. = Austrian cave register number; E.B. = Eisernen Bergl; lithologies: DK = Dachstein limestone, HD = Hauptdolomit, PK = Plassen limestone, OA = Oberalm Fm., F = own field observations: 1 = casual, 2 = moderate, 3 = comprehensive.

isolated peaks that stood out (Pleistocene Nunataks). The surrounding partly overdeepened valleys were shaped by the Traun- and the Enns glacier as well as smaller ones (Kuffner, 1998; Geyer et al., 2016; Mandl et al., 2012).

The study area comprises 3172 known caves with a cumulative length of 821 km as of September, 2023 (Fig. 3a). Most of them are formed in Dachstein limestone. The two largest caves, Schönberg-HS (157 km) and Schwarzmooskogel-HS (137 km), are also the two longest caves in the Eastern Alps. The deepest caves in the Totes Gebirge are the Schwarzmooskogel-HS (1111 m) and the Wildbaderhöhle (1101 m). Caves with a total length more than 5 km are listed in Table 2.

3. Methods

For the analysis of cave levels in the Totes Gebirge range, the subgroups of the Austrian cave register (as defined in Stummer and Plan, 2002) listed in Table 1 were investigated. Previous studies have shown that small caves have only a minor influence on defining cave levels (Plan et al., 2021; Rummler and Plan, 2023). To reduce the workload for this study, only caves with a length ≥50 m were analysed corresponding to 96 % of the known passage length in the Totes Gebirge range. In order to obtain a clearer picture of the cave levels, only phreatic caves or cave sections were considered for this study, ideally, those that formed in connection with a former base level. For this purpose, the genetic classification scheme of Oberender and Plan (2018) was applied. This classifies caves according to their main genetic processes. The relevant classes for the Totes Gebirge range were epigenetic corrosion caves (subdivided into phreatic and vadose) and weathering and erosion caves. In contrast to some former studies, no general morphological or sedimentological features of the cave levels are considered. Phreatic caves were permanently or periodically water-filled and their formation was influenced by the water pressure gradient and lithology. Phreatic caves are characterised by mostly horizontal or sub-horizontal passages and have tubes with lenticular, elliptical or nearly circular cross sections that can loop up and down. Vadose caves were formed above the water table and are only partly water bearing. Their formation is gravity-driven and they are characterised by a continuous downward trend of passages, mainly vertical shafts and in general high but narrow and meandering canyons (Audra and Palmer, 2011; Oberender and Plan, 2018).

The classification was made on the basis of the data available in September 2023. Data were provided by the non-public Austrian cave database Spelix (www.spelix.at) in addition to own field observations (Tab. 2, and many smaller caves) as well as information from other speleologists that provided data on cave morphology and origin. 3D data (especially *Compass* and *Survex* files) are available for many caves. Based on the assumption that (sub)vertical shafts are mostly of vadose origin, lengths of survey shots with more than 70° inclination were excluded (Plan et al., 2009). The results were checked by comparing it to maps (plan views and extended elevation), if available. If 3D files were not available, the vertical distribution had to be estimated from the plan view, and extended or projected elevation. After the classification, the (unprojected) phreatic passage lengths of each cave were assigned to a 25 m height interval according to their altitude and were plotted.

Finally, the Totes Gebirge range was divided into four subareas and these were compared with each other to investigate regional differences and whether the cave levels are inclined. Further, vectors between the peak of the height interval with the most phreatic passages of nearby caves, longer than 5 km, were calculated. The direction and inclination of these vectors were visualised to see if they may be assigned to a speleogenetic phase.

3.1. Comparison of classification methods

In order to estimate the errors that arise in the classification of corrosion caves based solely on the inclination of the passages, three methods were compared and visualised using the DÖF-Sonnenleiter-HS as an example (Fig. 4). (1) The vertical distribution based on the length of survey shots with inclinations <70° (in this case the software *Compass* was used). (2) The classification based on maps (plan view and extended elevation) to evaluate whether a section is of phreatic or vadose origin. The vertical distribution was based on survey shots classified as phreatic. (3) An estimation based mainly on the extended elevation but not on 3D survey data. As shown in Figure 4 the results are quite similar for the big horizontal system between 1400 and 1600 m a.s.l. and vary a bit for the shaft systems above and below. However, method 1 was significantly faster. To conclude, the most efficient approach was to use the inclination of the passage (method 1) and to verify the result using cave maps (method 2). This combined method was applied to all caves where 3D data and maps were available.

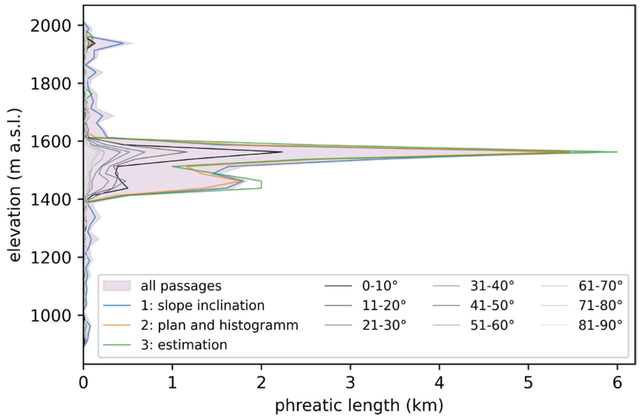

Figure 4: Comparison of classification methods at the example of DÖF-Sonnenleiter-HS. For details see text.

4. Results

4.1. Genetic classification

From 754 analysed caves, 26 % are phreatic or probably phreatic and 20 % are partially of phreatic origin. This is equivalent to 727 km or 94 % of the passage lengths with available data. 32 % of the caves or 6 % of the data-based passage length were vadose, probably vadose or non-corrosive caves. For 22 % of the caves no data are available (Fig. 5).

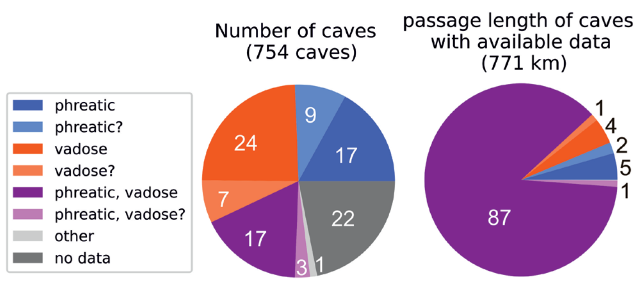

Figure 5: Classification of caves ≥50 m in the Totes Gebirge range according to their origin as of September, 2023. Values in %. “Others” are indeterminate or weathering and erosion caves.

4.2. Vertical distribution of cave passage length and entrances

The vertical distribution of phreatic cave passages is shown in height intervals of 25 m in Figure 6. The distribution shows one major range between 1300 and 1850 m a.s.l. It has a clear maximum at 1500 m and two smaller but distinct peaks at 1625 and 1725 m. Below this major range, there are several smaller and less distinct peaks between 450 and 1250 m a.s.l. To compare the current vertical distribution of caves to previous studies in the Totes Gebirge range (Lechner, 1949; Schauberger, 1955) also the distribution of cave entrances is shown in Figure 6. It is obvious that the vertical distribution of all cave entrances diverges from the one of the phreatic cave parts. The distribution is strongly influenced by the caves >5

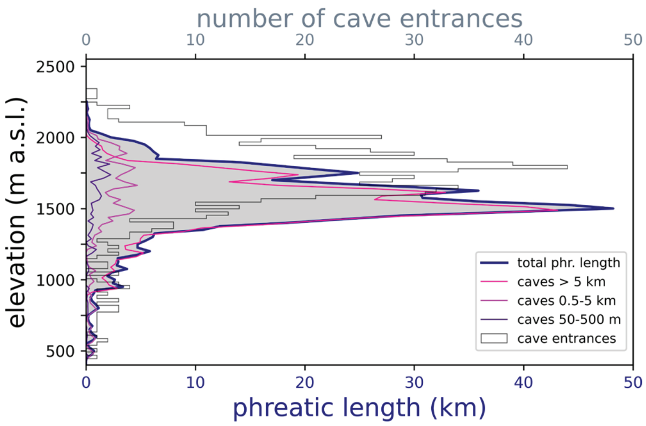

Figure 6: Vertical distribution of phreatic cave passages (blue) and cave entrances (grey) grouped in 25 m intervals at the Totes Gebirge range as well as the vertical distribution of phreatic cave passages of different cave length classes.

km, especially by the two largest caves which constitute 42 % of the phreatic length at the Totes Gebirge range. The Schönberg-HS forms the maximum at 1500 m a.s.l. as well as two smaller maxima around 1000 m a.s.l. The two local maxima at 1625 and 1750 m a.s.l. are dominated by the Schwarzmooskogel-HS and also influenced by the higher parts of Schönberg-HS and Almberg-HS. Shorter caves are distributed more homogeneously with respect to elevation, but they cluster also between 1250 and 2000 m a.s.l. and form the lowest parts between 450 and 900 m a.s.l.

4.3. Local distribution of caves and cave levels

The caves in the study area are not homogeneously distributed (Fig. 3, Tab. 1). The local distribution of the caves shows three clusters: one in the NW part from Hohe Schrott summit to Rotgschirr summit, one in the south-centre part between the south of the Weiße Wand and the Salzsteigjoch and the eastern cluster around the Warscheneck summit. The NW cluster was divided into two subregions. Comparing the cave levels of these clusters, it is noticeable that those in the south are at higher elevations than those in the north. Figure 7 compares the vertical distribution in four different subregions.

4.3.1. Northern region

In the northern region (for the extent see Fig. 7), the vertical distribution shows extensive phreatic cave passages between 450 and 2050 m a.s.l. with several maxima. The distribution above 900 m is dominated by long caves.

The Schönberg-HS resulted from the connection between Raucherkarhöhle, Feuertal-HS and some smaller caves (Geyer et al., 2016). The cluster of phreatic passages between 1300 and 1700 m with a clear maximum at 1500 m dominates the histogram of the whole massif. Below, there is a less significant accumulation of passages between 925 and 1175 m. In an NE-SW projected elevation, two well-developed speleogenetic phases are visible at around 1500 and 1600 m a.s.l. (Plan et al., 2009) dipping 1.7° to the northeast. This corresponds to the general palaeo-drainage derived from scallops. Only the modern drainage in the deepest and hydrologically active parts shows an additional overflow to the southwest during floods (Plan et al., 2023).

The Ahnenschacht is located close to the northeast of the Schönberg-HS and may soon be connected (Tenreiter, 2021). Phreatic passages cluster between 1425 and 1650 m a.s.l. with a maximum at 1475 m. Significant parts of the cave developed in Hauptdolomit. To the east, the Woising-HS shows a vertical distribution with maxima at 1625 and 1725 m a.s.l. The general palaeo-drainage was to the northwest (Kreuß et al., 2017). The deep parts reach into the Hauptdolomit below the Dachstein limestone. Further to the east, the Grießkar-HS shows a relatively homogeneous distribution between 1450 and 1800 m a.s.l. Again, the deep parts reach into the Hauptdolomit. In the Hohe Schrott (northwest part of the study area), the Verborgene Höhle is the longest cave (Tenreiter, 2016). The vertical distribution shows maxima at 1200 and 1400 m a.s.l., with the second being larger. Below 900 m a.s.l., in the northern region, smaller caves dominate the picture. These are the 1.4 km-long Kreidelucke (Austrian cave register number 1628/2), which forms the maximum at 600 m a.s.l, the Kühlloch (1616/5; 1.4 km long) and the Kogelgrabenhöhle (1616/75; 1.4 km long, forming the maximum at 500 m) which are active spring caves. The further east the caves are located in the area, the higher their known phreatic parts are.

4.3.2. Western region

In the western region (Fig. 7), the vertical distribution of phreatic passages is almost entirely dominated by the Schwarzmooskogel-HS. This cave system consists of Schwarzmooskogel-Eishöhle, Schnellzug-, Kaninchen-, Steinbrückenhöhle, and many smaller caves (Winkler and Day, 2013). The vertical distribution of phreatic lengths of the cave shows three maxima. The largest is at 1625 m, followed by smaller ones at 1550 and 1750 m a.s.l.

To the east, the Almberg-HS shows two distinct maxima at similar elevations as the two larger maxima in the Schwarzmooskogel-HS, at 1525 and 1625 m a.s.l. The Almberg-HS developed in the Plassen limestone (Upper Jurassic). The Hüttstatthöhle has one phreatic maximum at 1750 m a.s.l. This is at the same elevation as the smaller maximum of the Schwarzmooskogel-HS. The Holde Höhle is located at the same elevation as the upper parts of Schwarzmooskogel-HS and the Hüttstatthöhle, but has no distinct maximum. In the Fischgesichthöhle, which is close to Schwarzmooskogel-HS, the vertical distribution is homogeneous between 1550 and 1700 m with a maximum at 1450 m a.s.l.

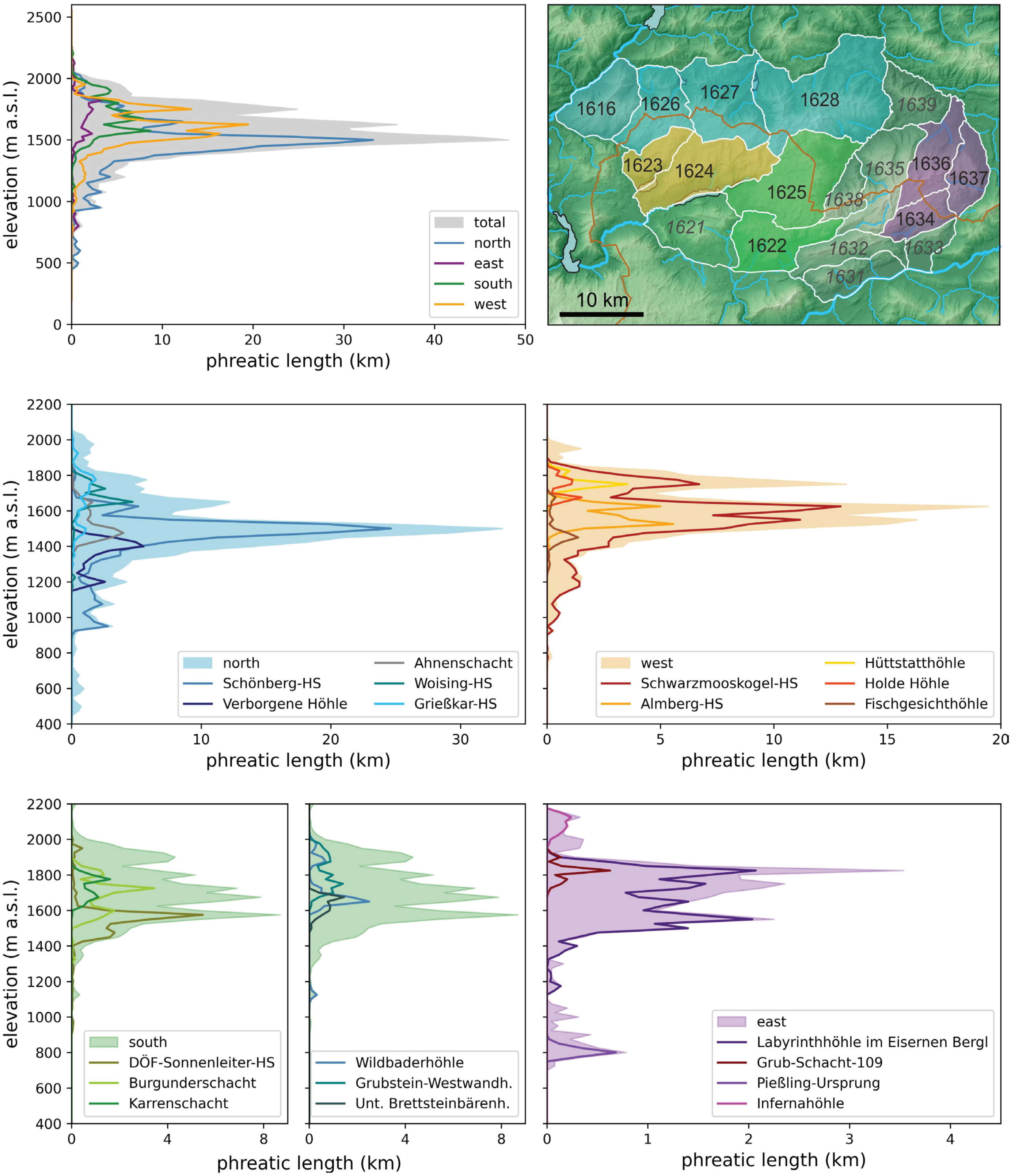

Figure 7: Vertical distribution of phreatic passages of caves ≥50 m grouped in 25 m intervals in four subgroups of the Totes Gebirge range. Map of the subgroups showing the separately analysed regions. Subgroups without significant phreatic caves (none or only one cave with less than 80 m phreatic length) are transparent.

4.3.3. Southern region

The southern region (Fig. 7) includes the Tauplitz-Schachtzone – a region with an extremely high density of shaft entrances (Herrmann, 1993). The vertical distribution of phreatic passages shows five maxima between 1400 and 2000 m a.s.l., without any dominant cave, and a small peak at 1125 m a.s.l., formed by the Wildbaderhöhle.

The longest cave system in this region, the DÖF-Sonnenleiter-HS, consists of four shaft systems intersecting a sub-horizontal system that forms during a speleogenetic phase dipping 1.6° to the south (Plan et al., 2009). This sub-horizontal system lies between 1400 and 1650 m with a maximum at 1575 m a.s.l. In the nearby Burgunderschacht, the vertical distribution shows two maxima, the smaller one more or less coinciding with the one in the DÖF-Sonnenleiter-HS and the larger one lying 150 m above the maximum in DÖF-Sonnenleiter-HS. The Grubstein-Westwandhöhle is also in the immediate vicinity of the DÖF-Sonnenleiter-HS, but its vertical distribution is more homogeneous with a single maximum at 1750 m a.s.l.

In the Wildbaderhöhle, the vertical distribution of phreatic parts has a maximum at 1650 m a.s.l. and 500 m below this is another small horizontal system. While in some parts of the horizontal system around 1650 m there are vadose streams, the lower parts around 1125 m are completely dry (Seebacher, 2021). The Untere Brettsteinbärenhöhle is the shallowest of the long caves in this region. The vertical distribution shows one clear peak at 1675 m a.s.l. The Karrenschacht has developed in the rather isolated Traweng mountain and is shallower than most of its prominent neighbours. The vertical distribution of phreatic parts shows two maxima, a larger one at 1775 and a smaller one at 1675 m a.s.l.

4.3.4. Eastern region (Warscheneck)

The eastern region corresponds to the Warscheneck area (Fig 7), where the vertical distribution is clearly dominated by the Labyrinthhöhle im Eisernen Bergl (in the following just Labyrinthhöhle; Steinmaßl, 2020). Its vertical distribution of phreatic passages has no clear maximum, but lies mostly between 1450 and 1900 m with two similar maxima at 1550 and 1825 m a.s.l. There is also a small local maximum at 1175 m. The 1.7 km-long Grub-Schacht-109 (1634/109; phreatic length 1.4 km; Geyer et al., 2021) lies in the same elevation range as the upper parts of Labyrinthhöhle and shares its upper maximum with that cave (i.e. 1825 m a.s.l.).

Above 2000 m, the 1.4 km-long Infernahöhle (1636/9; 1.1 km classified as phreatic) dominates the histogram of the eastern region with a peak at 2125 m a.s.l. The lowest parts of the Warscheneck are formed by active spring caves such as the Brülloch (1634/2; 1.0 km) and the Pießling-Ursprung (1836/3; 1.8 km). The latter forms the maximum at 800 m a.s.l. This spring has one of the highest discharges in the Eastern Alps (Geyer et al., 2016). The outlet, which is also the entrance to the cave, is located at 755 m. This is relatively high above the base level which is the Teichel stream at ca. 580 m a.s.l. The permanently water-filled parts reach 84 m below the entrance and the dry parts 100 m above.

5. Interpretation and Discussion

After plotting all phreatic passages from caves ≥50 m in the Totes Gebirge range, only one broad vertical range between 1300 and 1850 m with a clear maximum at 1500 m a.s.l. and minor peaks at 1625 m and 1750 m a.s.l. dominates the distribution. Other local maxima are much less pronounced and rather insignificant. This is in contrast to the other nine major karst massifs of the NCA studied so far, where at least three distinct maxima can be distinguished which have been interpreted as cave levels (for a diagram comparing all the massifs, see Rummler and Plan, 2023). The reasons for this difference and whether or not cave levels exist in the Totes Gebirge range are discussed below.

5.1. Methods

This difference between the Totes Gebirge range and other karst plateaus in the NCA is unlikely related to the applied methods, as our approach is similar for seven other karst massifs and almost identical for two areas (Hochschwab: Plan et al., 2021; Dachstein: Rummler and Plan, 2023). One difference is that in earlier work the analysis was not restricted to phreatic sections (e.g. Klappacher and Knapczyk, 1977, 1979; Klappacher and Haseke-Knapczyk, 1985), but vadose passages were also considered for the histograms. However, considering only phreatic passages results in more pronounced minima, providing a clearer picture for the delineation of the cave levels.

The classification of caves and cave passages itself depends on the data available and also on the classification method. A comparison of the methods (see method section and Fig. 4) has shown that the differences are small and that a classification based on the inclination of the passages combined with a verification based on cave maps is a good compromise between accuracy and expenditure of time. The simplification of not considering caves ≤50 m for this study, which differs from Plan et al. (2021) and Rummler and Plan (2023), can be justified from Figure 6, which shows that even caves with 50 to 500 m length add background noise rather than contributing significantly to the overall picture. In general, geometric errors resulting from the cave survey (less than about 2 m per 100 m) and the elevation of entrances (for long and prominent systems <5 m, generally <20 m) can be neglected, especially for the overall picture. In contrast to some other studies, only the elevations of the phreatic passages were considered, but no general sedimentological (e.g. Ruin Caves often lack fine sediments), hydrological (e.g. Spring Caves are water active) or morphological (e.g. Ruin Caves are often intersected with the surface) characteristics of the caves (e.g. Haseke-Knapczyk, 1989), because these criteria can be just artefacts of elevation.

Another prerequisite for cave levels and their correlation with the former base level is that they are not controlled by aquiclude rocks. Aquiclude rocks such as the Werfen beds occur only at the base of the massif, and the aquiclude Raibl beds occur in the northern part of the Totes Gebirge and in the western part of the Warscheneck. In most areas of the Totes Gebirge and central Warscheneck, where most of the major cave systems are located, the Dachstein limestone dominates, with thicknesses of over 1 km. Non-karstic and karstic Jurassic rocks partly overly these limestones. The Elm-HS in the centre of the Totes Gebirge has streams that can be traced over long horizontal distances (pers. comm. R. Seebacher), which may indicate the presence of aquiclude rocks below. Similar long horizontal streams are known from Wildbaderhöhle, but in this cave shafts leading much further down have shown that the Dachstein limestone reaches below the present karst water table (Seebacher, 2021). Significant parts of the Ahnenschacht (pers. comm. C. Tenreiter) and small but spacious parts of the Schönberg-HS (Plan et al., 2023) developed in the Hauptdolomit, showing that this rock can also be karstified. In general, we conclude that aquiclude rocks can have a local influence on the occurrence of phreatic cave parts, but are negligible for the overall picture.

5.2. Cave levels in the Totes Gebirge range

If we accept that methodical errors are negligible, we can focus on the question whether the distribution of phreatic passages in the Totes Gebirge range represents cave levels. As mentioned above, there is one dominant interval between 1300 and 1850 m a.s.l. which could be interpreted as a cave level. This 550 m-wide range may seem a lot, but also in other massifs of the NCA like Hagengebirge and Hoher Göll the abundance of cave passages within a range of 450 and 525 m, respectively, was attributed to the Giant Cave Level. The interval interpreted as Ruin Cave Level in Steinernes Meer also comprises 550 m (Rummler and Plan, 2023). For the sake of clarity, it should be noted that a cave level such as this comprises more than one speleogenetic phase, which is clearly visible in Schönberg-HS with at least two phases at 1500 and 1600 m a.s.l. (see below). The main reason that speaks in favour of this interval being a cave level is that it is not only seen in the overall distribution of the Totes Gebirge range, but also that all subareas show similar peaks at similar altitude intervals. Only in the eastern region (Warscheneck) the level starts 100 m higher at 1450 m a.s.l. By correlation with other massifs in the NCA, the interval between 1300 and 1850 m a.s.l. can be clearly attributed to the Giant Cave Level (Fig. 6; Rummler and Plan, 2023).

Only in the southern region of the Totes Gebirge range there is an additional clear peak between 1850 and 2000 m a.s.l. (Fig. 7) which is mainly due to Grubsteineishöhle (1625/16), Schlazfresser-Schacht (1625/408) and several smaller caves. Since there is no clear delineation to the cave level below, it is not interpreted as a separate level, although it could be attributed to the Ruin Cave Level based on its altitude.

A possible reason as to why no clear minima which are important for the delineation of well-defined levels can be seen in the Totes Gebirge range may be its the large extension. Tectonic displacements or different local base levels could therefore have a larger influence and overlapping of the local levels could obscure the minima. However, this is contradicted by the fact that the analysis of the subareas did not show any clear cave levels either, but also a single large interval with few local maxima. Just a few of the local maxima of the subareas correlate with each other (Fig. 7). Exceptions are the maxima of the western region and the second maximum of the northern region. In general, it appears that the elevations of the maxima increase from west to east. Even within the subareas, the large caves correlate little with each other except for: The Hüttstatthöhle and the third maximum of the Schwarzmooskogel-HS, the maximum and the 2nd one of the Almberg-HS with the second and the first one of the Schwarzmooskogel-HS (both in the western region), the maxima of the Grub-Schacht and the Labyrinthhöhle (western region), and the Ahnenschacht and not so well the Verborgene Höhle correlate with the maximum of the Schönberg-HS (northern region). In the Schönberg-HS, the two maxima, which also form the first and second maximum in the overall image, correspond to the two planes dipping 1.7° to the NE, which were interpreted as speleogenetic phases and lie at approx. 1500 and 1600 m a.s.l., respectively (Plan et al., 2023). Also, the inclined plane in DÖF-Sonnenleiter-HS at 1550 m a.s.l. was interpreted as a speleogenetic phase (Plan et al., 2009) and is responsible for the maximum of the southern region.

Above 1850 m and below 1300 m a.s.l., the histogram of the Totes Gebirge range shows more of a noise (Fig. 7). Although there are numerous caves at the corresponding altitudes, some of which are large, they do not show any clear clusters. The fact that there are no clear levels here is not due to the Giant Cave Level's dominance. Above 1900 m a.s.l., which would correspond to the Ruin Cave Level, there are generally only a few extensive phreatic cave sections. It is also unlikely that the lack of extensive phreatic cave parts outside the Giant Cave Level are research artefacts: many entrances are also known above 1850 m to around 2150 m a.s.l. (Fig. 6) and the low-lying areas are generally easier to access than the remote plateau areas. It should be noted, however, that many low-lying flanks in the north of the Totes Gebirge are made up of dolomite and almost no caves are known there.

Between 1200 and 900 m a.s.l. there are quite extensive phreatic cave sections (the Unterwelt in the Schönberg-HS stands out here) but again without a clear peak and delineation between them. This altitude would correspond to the Berger Cave Level. Between 900 and 400 m a.s.l., which is classically attributed to the Spring Cave

Level, there are again only relatively few phreatic cave sections especially in the northern and eastern areas. Here in particular, the large size of the mountain range and divergent locations of the local base levels could play a role. The closest to the classic threefold division is the eastern region (Warscheneck) with a Spring Cave Level between 750 and 900 m, a Giant Cave Level from 1450 to 1850 m between and a Ruin Cave Level between 1950 and 2150 m a.s.l. (Fig. 7). Early analyses of the vertical distribution of caves in the Totes Gebirge by Lechner (1949), using entrance elevation, showed five clusters at 900, 1100, 1300–1400, 1500–1600, and 1800 m a.s.l. He compared cave entrances in the north and south of the Totes Gebirge and obtained a north-south gradient at some levels. Later Schauberger (1955) analysed the distribution of 187 known cave entrances and found six cave levels at: 450–700 m, 750–900 m, 1000–1150 m, 1200–1450 m, 1450–1900 m and 1950–2000 m a.s.l. Figure 6 shows that there are some similarities, but the comparison of the height distribution of entrances and phreatic cave parts clearly indicates that these do not correlate and that the cave entrances are not suitable for investigating cave levels.

The only major study that considered cave passages in the Totes Gebirge was done by Kuffner (1998) who analysed 385 caves known until 1992 in the western part of the Totes Gebirge range (subgroups 1616, 1623, and 1626) and described three cave levels: one weakly developed between 900 and 1120 m a.s.l., another well developed between 1220 and 1660 m a.s.l. with two maxima (related to the Giant Cave Level) and a third one between 1760 and 1920 m a.s.l. (related to the Ruin Cave level). However, a diagram (Kuffner, 1998, p. 139) shows that the distinctions between these levels are as unclear as those of our study (Fig. 6). Compared to Kuffner (1998) our study considered a much larger area and is based on more recent cave data (e.g. the cumulative length of the caves now united in Schönberg-HS has almost doubled and the one of Schwarzmooskogel-HS is 17 times longer than at the time of the Kuffner study). The histograms look similar but the significant increase of passages of the Giant Cave Level makes the few cave passages above and below to appear less prominent (Fig. 6).

As the review of previous studies on the Totes Gebirge range has shown, the results of this study also reflect the current state of research. However, it is impossible to solve the discrepancy between known and actual cave passages. Burial age dating has been attempted in the Totes Gebirge (Häuselmann et al., 2020), but has not yet been successful. Correlations with the Dachstein and Tennengebirge suggest an age of the Giant Cave Level of 4–6 Ma (Häuselmann et al., 2020; Patscheider and Stüwe, 2023), but there are indications that the Totes Gebirge had a different palaeo-drainage pattern than these other two massifs (Plan, 2023). Therefore, this correlation remains questionable.

5.3. Correlation with cave levels in other karst massifs in NCA

The Giant Cave Level of the Totes Gebirge agrees quite well with that of the other karst massifs in the NCA. Due to the large difference in altitude of 550 m most other intervals interpreted as Giant Cave Level fit the one of the Totes Gebirge. Only the top of this cave level in the Hagengebirge (1950 m a.s.l.; Klappacher and Knapczyk, 1977) is higher than that of the Totes Gebirge. The lower limits of Giant Cave Levels in the Dachstein (1125–1550 m a.s.l.; Rummler and Plan, 2023) and the Untersberg (1175–1575 m a.s.l.; Zagler, 2016) are significantly deeper (for a compilation see Rummler and Plan, 2023). The fact that the Giant Cave Level in the Dachstein (bordering the Totes Gebirge in the south to southwest) and, to a lesser extent, in the Gesäuse (about 40 km in the eastsoutheast) is lower than in the Totes Gebirge contrasts with observations in the area of the Steinernes Meer, Hagengebirge, Göll, Reiteralm and Untersberg, where a continuous gradient from south to north can be observed (Rummler and Plan, 2023).

5.4. Cave levels as an indicator for the palaeoflow

Furthermore, vectors were calculated between the phreatic maxima of the centres of the caves ≥5 km in length. The assumption behind this is that the known cave sections represent only a very small part of the former cave systems that traversed the entire massif - or at least large parts of it - and that the phreatic maxima of the individual caves represent the most significant cave level and were thus formed simultaneously. These vectors could therefore provide information about the palaeo-flow directions for the entire massif. Due to its large area and the reasonably even distribution of large cave systems, the Totes Gebirge range is suitable for this approach, which was tried here for the first time. Furthermore, most of the cave systems in the Totes Gebirge show a clear maximum. Only the Labyrinthhöhle has several similarly pronounced local maxima and the Almberg-HS has two similar maxima. At first glance, the picture is rather chaotic, but some patterns can be recognised (Fig. 3b). Most of the vectors are inclined at 0.5 to 3.5°, which appears to be a plausible angle of inclination for speleogenetic phases. Only in a few cave systems, such as Eisenhut, Burgunderschacht and Grubstein-Westwandhöhle, do the phreatic maxima not fit the overall picture.

The phreatic maxima of the individual caves generally decrease from ESE to WNW, which corresponds to the longitudinal axis of the massif, which could be interpreted as palaeo-drainage. A tectonic tilting of the Totes Gebirge by a few degrees also seems possible, although there is no geological evidence for this. However, no general trend can be recognised at right angles to the longitudinal axis of the massif. There is neither a gradient to the SSW or to the NNE, nor an outflow from the centre of the massif in either direction.

There are also observations of palaeo-flow directions from some caves at the corresponding level. Observations of scallops and other indicators of palaeo-flow direction are available from the Schönberg-HS (Plan et al., 2023), the Almberg-HS (Plan, 2023), the southern part of the Schwarzmooskogel-HS and the Woising-HS (both unpublished data by the authors). Furthermore, the inclination of the speleogenetic phase in the DÖF-Sonnenleiter-HS was interpreted as a palaeo-flow direction (Plan et al., 2009). The general palaeo-flow directions of the individual systems are shown in Fig. 3b. Although the comparatively few arrows do not show a good match, they do not represent any striking contradictions to the vectors calculated from the height of the phreatic maxima of the cave systems. In the Siebenhengste-Hohgant region of the Helvetic Units of the Swiss Alps, Häuselmann et al. (2002) were able to reconstruct a palaeo-flow reversal associated with base-level changes from detailed morphological mapping and delineation of 14 speleogenetic phases. In the NCA, unfortunately, the absence of certain morphological features (canyon-tube transitions) and the very few speleogenetic phases identified so far do not allow such detailed reconstructions as in the Siebenhengste-Hohgant region.

To summarise, it can be said that the directions from both phreatic maxima and field observations reflect a rather unsystematic palaeo-drainage pattern. It appears that there were some low-lying zones at the edges of the massif (Almberg-HS, Woising-HS, DÖF-Sonnenleiter-HS) as well as high-lying ones (Karrenschacht, Grießkar-HS). Whether the general dip towards the NNW reflects a palaeo-flow direction or is due to tectonics remains an open question.

6. Conclusion

The Totes Gebirge was examined for the existence and location of discrete cave levels. In order to obtain a clear result, only phreatic caves and cave sections were included. For this purpose, 754 caves longer than 50 m were examined in the area of Totes Gebirge, Warscheneck and Hohe Schrott. The phreatic sections of the caves were divided into 25 m height intervals and the vertical distribution of passage lengths was plotted. Contrary to expectations, there were not three or four distinct cave levels, but only one large cluster between 1300 and 1850 m a.s.l. with a clear maximum at 1500 m a.s.l. Although this cave level comprises 550 m of vertical extent, it can be correlated with the Giant Cave Level known in most other karst massifs in the NCA. It remains unclear why there is no distinct cave level above (Ruin Cave Level) or below (Berger and Spring Cave Levels) in the Totes Gebirge. The most likely explanation is that the palaeogeography and the corresponding drainage pattern around the massif and/or the uplift history were different from the other karst massifs in the NCA. Vectors calculated from the phreatic maxima of the caves ≥5 km show a WNW-directed dip, which could indicate a palaeo-drainage pattern or subsequent tectonic tilting of the whole massif.

Acknowledgements

Maps, survey data and descriptions were provided by the Landesverein für Höhlenkunde in Oberösterreich and the one in Wien und Niederösterreich as well as the Verein für Höhlenkunde in Obersteier, and were taken from the Spelix database. Special thanks to Richard Frank, Ernest Geyer, Sebastian Heiland, Robert Seebacher, Clemens Tenreiter, Franz Rührlinger, and Wookey. Two reviewers, Philipp Häuselmann and Christoph Spötl, provided valuable input to improve the manuscript.

References

Audra P., Palmer A.N., 2011. The pattern of caves: controls of epigenic speleogenesis. Géomorphologie: relief, processes, environnement, 4, 359–378. https://doi.org/10.4000/geomorphologie.9571

De Waele J., Gutiérrez F., 2022. Karst hydrogeology, geomorphology and caves. Wiley, Chichester, 888 pp. https://doi.org/10.1002/9781119605379

Fernandez O., Ortner H., Sanders D., Grasemann B., Leitner T., 2024. Salt-rich versus salt-poor structural scenarios in the central Northern Calcareous Alps: implications for the Hallstatt facies and early Alpine tectonic evolution (Eastern Alps, Austria). International Journal of Earth Sciences, 113, 245–283. https://doi.org/10.1007/s00531-023-02377-4

Fischer K., 1990. Höhlenniveaus und Altreliefgenerationen in den Berchtesgadener Alpen. Mitteilungen der Geographischen Gesellschaft München, 75, 47–59.

Frisch W., Kuhlemann J., Dunkl I., Székely B., Vennemann T., Rettenbacher A., 2002. Dachstein-Altflächen, Augenstein-Formation und Höhlenentwicklung. Die Geschichte der letzten 35 Millionen Jahre in den zentralen Nördlichen Kalkalpen. Die Höhle, 53, 1–36.

Geyer E., Seebacher R., Tenreiter C., Knobloch G., 2016. Totes Gebirge. In: Spötl C., Plan L., Christian E. (eds.), Höhlen und Karst in Österreich. Oberösterreichisches Landesmuseum, Linz, 541–552.

Geyer E., Benischke R., Hasitschka J., 2021. Höhlen und Karst - steirischer Warscheneckstock: das Weißenbach-Höhlenprojekt mit kulturhistorischen Betrachtungen. Die Höhle, Beiheft 66, 1–636.

Häuselmann P., Jeannin P.Y., Monbaron M., Lauritzen S.E, 2002. Reconstruction of Alpine Cenozoic paleorelief through the analysis of caves at Siebenhengste (BE, Switzerland). Geodinamica Acta, 15, 261–276. https://doi.org/10.1016/S0985-3111(02)01092-6

Häuselmann P., Plan L., Pointner P., Fiebig M., 2020. Cosmogenic nuclide dating of cave sediments in the Eastern Alps and implications for erosion rates. International Journal of Speleology, 49, 107–118. https://doi.org/10.5038/1827-806X.49.2.2303

Haseke-Knapczyk H., 1989. Der Untersberg bei Salzburg. Die ober- und unterirdische Karstentwicklung und ihre Zusammenhänge. Ein Beitrag zur Trinkwassererforschung. MaB-Reihe, 15, Österreichische Akademie der Wissenschaften, Wien, 1–223.

Hell M., 1926. Zusammenhang zwischen alten Landoberflächen und Höhlenbildung im salzburgischen Tennengebirge. Mitteilungen für Höhlen- und Karstforschung 1926, 1, 17–22.

Herrmann E., 1993. Die Tauplitz-Schachtzone im Toten Gebirge. Die Höhle, Beiheft 44, 1–230.

Klappacher W, Haseke-Knapczyk, H., 1985. Salzburger Höhlenbuch 4. Landesverein für Höhlenkunde in Salzburg, Salzburg, 556 pp.

Klappacher W., Knapczyk H., 1977. Salzburger Höhlenbuch 2. Landesverein für Höhlenkunde in Salzburg, Salzburg, 348 pp.

Klappacher W., Knapczyk H., 1979. Salzburger Höhlenbuch 3. Landesverein für Höhlenkunde in Salzburg, Salzburg, 487 pp.

Kreuß M., Kalmbach U., Heiland S., 2017. Das Woising-Höhlensystem im Toten Gebirge, Stmk/OÖ. Die Höhle, 68, 3–13.

Kuffner D., 1998. Höhlenniveaus und Altflächen im westlichen Toten Gebirge. Die Höhle, Beiheft 53, 1–229.

Lechner J., 1949. Neue karst- und quellengeologische Forschungen im Toten Gebirge. Protokoll der 3. Vollversammlung der Bundeshöhlenkommission, Wien, 32–38.

Mandl G.W., van Husen D., Lobitzer H., 2012. Erläuterungen zu Blatt 96 Bad Ischl. Geologische Bundesanstalt, Wien, 215 pp.

Oberender P., Plan L., 2018. A genetic classification of caves and its application in eastern Austria. Geological Society, London, Special Publications, 466, 121–136. In: Parise M., Gabrovsek F., Kaufmann G., Ravbar N. (eds.), Advances in Karst Research: Theory, Fieldwork and Applications. Special Publication 466. Geological Society, London, pp. 329–362. https://doi.org/10.1144/sp466.21

Patscheider L., Stüwe K., 2023. Entwässerungssystem der Ostalpen im Miozän: Eine Provenienz-Studie an Höhlensedimenten. Die Höhle, 74, 30–49.

Plan L., 2023. Geowissenschaftliche Untersuchungen im Almberg-Höhlensystem – Hinweise auf eine radiale Paläoentwässerung des Toten Gebirges. Die Höhle, 74, 50–64.

Plan L., Filipponi M., Behm M., Seebacher R., Jeutter P., 2009. Constraints on alpine speleogenesis from cave morphology – a case study from the eastern Totes Gebirge (Northern Calcareous Alps, Austria). Geomorphology, 106, 118–129. https://dx.doi.org/10.1016/j.geomorph.2008.09.011

Plan L., Neuhuber S., Kaminsky E., Oberender P., 2021. Höhlenniveaus in der Hochschwabgruppe. Die Höhle, 72, 139–159.

Plan L., Kaminsky E., Oberender P., Tenreiter C., Wimmer M., 2023. 4D flow pattern of the longest cave in the Eastern Alps (Schönberg-Höhlensystem, Totes Gebirge). International Journal of Speleology, 52, 45–56. https://doi.org/10.5038/1827-806X.52.1.2471

Rummler L., Plan L., 2023. Cave Levels in the Dachstein Massif (Eastern Alps). Austrian Journal of Earth Sciences, 116, 151–163. https://doi.org/10.17738/ajes.2023.0009

Schauberger O., 1955. Über die vertikale Verteilung der nordalpinen Karsthöhlen. Mitteilung der Höhlenkommission, 1955, 21–28.

Seebacher R., 2021. Die Wildbaderhöhle, eine weitere über 1000 m tiefe Höhle im Toten Gebirge. Die Höhle, 72, 45–65.

Spötl C., Plan L., 2016. Karst und Höhlen. In: Spötl C., Plan L., Christian E. (eds.), Höhlen und Karst in Österreich. Oberöstereichisches Landesmuseum, Linz, 1–10.

Steinmaßl H., 2020. Die Labyrinthhöhle im Eisernen Bergl (Warscheneckstock, OÖ). Die Höhle, 71, 31–44.

Stummer G., Plan L., 2002. Speldok-Austria – Handbuch zum Österreichischen Höhlenverzeichnis. Speldok 10, Verband Österreichischer Höhlenforscher, Wien, 132 p.

Tenreiter C., 2021. Der Ahnenschacht im westlichen Toten Gebirge. Die Höhle, 72, 3–21.

Tenreiter C., 2016. Die Verborgene Höhle auf der Hohen Schrott, OÖ. Die Höhle, 67, 14–24.

Winkler R., Day A., 2013. Das Schwarzmooskogel-Höhlensystem – jetzt drittlängste Höhle Österreichs. Die Höhle, 64, 62–71.

Zagler G., 2016. Untersberg. In: Spötl C., Plan L., Christian E. (eds.), Höhlen und Karst in Österreich. Oberöstereichisches Landesmuseum, Linz, 541–552.

Received: 5.4.2024
Accepted: 14.7.2024
Editorial Handling: Hugo Ortner