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# Cave Levels in the Dachstein Massif (Eastern Alps)

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## Abstract

This paper investigates the vertical distribution of horizontal and subhorizontal cave passages in the Dachstein Massif of Austria. Cave passages that are confined to vertical ranges, so-called cave levels, can be correlated with former valley floors and thus reflect tectonically and climatically stable periods. Previous studies analyzed significant karst Massifs (or parts of them) in the Northern Calcareous Alps but have excluded the Dachstein massif so far. The Dachstein is the second largest massif in the area, contains many extensive caves, and plays a key role in reconstruction of landscape evolution ("Dachstein surface"). In contrast to some previous works, we aimed to analyze only passages that formed (or are forming) under phreatic or epiphreatic conditions (i.e. permanently or episodically water-filled). This genetic classification is based on field observations, cave maps, 3D survey shots and descriptions. For this study, 789 caves with a total length of 279 km were considered, but data were only available for 599 caves (276 km). Only 25% of all caves in the Dachstein Massif are at least partly of (epi)phreatic origin, but the total length of phreatic passages is 204 km. Altitudes of the phreatic sections of each cave were grouped in 25-m increments and plotted according to their phreatic passage length. It turned out that there are five vertical accumulations of caves in the Dachstein Massif. Despite some previous studies that also considered morphological, hydrological, and sedimentological characteristics, our correlation with the "classical" supra-regional cave levels in other karst massifs was based only on elevation. The following elevations for the cave levels were determined: Spring Cave Level: 475-775 m a.s.l., Berger Cave Level: 825-1075 m, Giant Cave Level (with the highest peak): 1125-1550 m, Ruin Cave Level: 1600-2050 m, and a formerly unknown level at 2525-2750 m, for which we propose the name Voodoo Cave Level. According to this study the two longest cave systems, the Hirlatzhöhle (114 km long and 1560 m deep) and the Dachstein-Mammuthöhle (68 km, 1207 m) are most relevant for the result. The local vertical distribution of caves within the Dachstein was compared with the regional northward tilt of cave levels in the Northern Calcareous Alps, however the heterogeneous distribution of the known cave obscures local effects in the Dachstein Massif.

## 1. Introduction

The vertical development of karst caves is closely related to the geomorphic evolution of the surrounding landscape, so their arrangement in different levels allows the reconstruction of valley incision and landscape evolution (e.g. Palmer, 1987; Audra and Palmer, 2011). So far, cave levels have been analyzed for most of the extensive karst massifs in the Northern Calcareous Alps (NCA), such as the Totes Gebirge, Tennengebirge or Hagengebirge (e.g. Klappacher and Knapczyk, 1979; Klappacher and Haseke-Knapczyk, 1985; Kuffner, 1998). However, the Dachstein, the second largest massif in the NCA, has not been studied in detail in this respect so far. This is surprising, because the Dachstein plays a key role in the landscape evolution of the Eastern Alps, where Frisch et al. (2001) defined the "Dachstein paleosurface" as a type locality for Eocene-Oligocene landscapes, which were only moderately modified due to a long-lasting sediment cover by the Augenstein Formation and due to the dominant subsurface drainage by karstification. In addition, the Dachstein caves, such as the Dachstein-Mammuthöhle (hereafter Mammuthöhle), were the first extensive cave systems to be explored in the NCA and subsequently played an important role in the development of speleogenetic models that were already linked to landscape evolution at that time (Bock, 1913; Plan and Herrmann, 2010).

Sub-horizontal cave passages form along fissures (faults or bedding planes) mainly at or slightly below the karst water table (Audra and Palmer, 2011). Here, at the base of the vadose zone (i.e. tubes are partially water filled allowing free surface flow), the movement changes from a sub-vertical one driven by gravity to a lateral one in the phreatic zone. In this hydrologic zone, tubes are completely water-filled and the water movement is controlled by pressure gradients towards the springs. Most of the passages are enlarged in the transitional epiphreatic zone, which is only filled with water during floods, when the flow velocities are high and the water, which is undersaturated with calcite, can penetrate deep into the karst massif without losing its aggressiveness (e.g. De Waele and Gutiérrez, 2022). Therefore, cave passages that form in the epiphreatic or phreatic zone correlate with the altitude of the springs and therefore with the base level of the valley floor. Hereafter, for simplicity, we will use “phreatic”, also including an epiphreatic genesis. If those cave passages are confined to a narrow vertical range they define a cave level. However, this is only the case if the karst rocks extend below this level and drainage is not controlled by impermeable layers that form the base of karstification. Therefore, the kilometer-thick Middle and Upper Triassic limestone and dolomite layers in the NCA are ideal for the development of base-level controlled cave passages.

For the NCA, already in the beginning of the last century clustering of cave entrances at certain elevations were noticed for the Tennengebirge (Hell, 1926) and later in the adjacent massifs Totes Gebirge (Lechner, 1949) and Dachstein (Schauberger, 1955; for location see Fig. 1). Later works by Klappacher and Knapczyk (1977 p. 157; 1979, p. 91), Klappacher and Haseke-Knapczyk (1985, p. 101), Haseke-Knapczyk (1989; summarized in Fischer, 1990), and Kuffner (1998) produced histograms of cave passages based on elevation. They distinguished and termed three or partly four major, distinctive levels in the central NCA that also share similar morphologic and sedimentological characteristics. From top to bottom, these are the so-called Ruin Cave Level (in German: “Höhlenruinen-Niveau”), the Giant Cave Level (“Riesenhöhlen-Niveau”), the only partly developed Berger Cave Level (“Bergerhöhlen-Niveau”), and the Spring Cave Level (“Quellhöhlen-Niveau”; Fig. 2). The general interpretation of these cave levels was that they are related to the base level, that they become subsequently older with increasing elevation, and they represent periods of stable base level conditions. Whereas the sections in between the cave levels (i.e. the minima in the histograms) indicate that cave development had no time to adjust to the base level showing phases of tectonic or climatic changes which is in accordance with well-accepted speleogenetic models (Audra and Palmer, 2011, De Waele and Gutiérrez, 2022).

So far, for the massifs in the NCA the vertical distribution of lengths of all cave passages (i.e. phreatic and vadose) have been used for the histogram analysis. As canyons and shafts that developed in the vadose zone are not related to the base level, later works only used phreatic passages (Wisshak & Jantschke, 2010; Herrmann and Fischer, 2013; Zagler, 2016; Plan et al., 2021; Fig. 2). Frisch et al. (2002) also correlated the three main cave levels with events in the evolution of the NCA and postulated that: the Ruin Cave Level developed during the formation of the Dachstein paleosurface in the Upper Oligocene to Lower Eocene, the Giant Cave Level after the uplift of the NCA in the Upper Miocene, and the Spring Cave Level in the Plio- and Pleistocene. Only in recent years burial age dating of Quartz pebbles in the Augenstein Formation was at least partly successful and numerical ages could be obtained for the Giant Cave Level. They suggest that it was formed 4 to 6 Ma ago (Häuselmann et al., 2020; Patscheider and Stüwe, 2023).

In this study, the Dachstein Massif is investigated for the existence and elevation of cave levels. Since cave levels just include those cave passages that were formed in connection with the base level, i.e. under phreatic conditions, initially all caves were classified according to their formation. Later, the phreatic caves and cave sections were examined for their vertical distribution.

## 2. Study site

The Dachstein Massif is part of the NCA and lies c. 50 km south-east of the city of Salzburg in Austria (Fig. 1). It covers an area of around 580 km$^2$ and is the second largest karst massif in the NCA after the Totes Gebirge. The highest peak, the Hoher Dachstein at the southern edge of the plateau, reaches 2995 m a.s.l. (Fig. 3). The massif contains a large hilly plateau around 2000 m altitude, which represents the remnants of a Late Eocene to Early Oligocene surface. Due to karst dissolution, this so-called Dachstein paleosurface has only been reshaped to a limited extent by later erosion processes and is thus well preserved (Frisch et al., 2001; 2002). The Dachstein slopes steeply in the north to Lake Hallstatt (508 m a.s.l.) and in the south to the Enns valley (c. 750 m a.s.l.), but is gentler on the east and west. From about 2300 m a.s.l., the area is partially glaciated.

The Dachstein Massif is built up by the Juvavic Dachstein Nappe. The stratigraphic sequence does not seem too complex compared to the surrounding areas (Mandl et al., 2012). The massif up to the summit is dominated by Upper Triassic Dachsteinkalk. This was deposited predominantly in lagoonal facies, with reef facies only appearing in the south. Underlying the Dachsteinkalk is the Wettersteindolomit and, more rarely, the Wettersteinkalk. The sandstones and shales of the Werfen-Formation follow below. Due to the northerly dip of the strata, this impermeable sequence is only exposed on the southern side of the massif. In addition to Jurassic rocks in fissures of the plateau area, remains of the Oligocene

Augenstein Formation can also be found here (Frisch et al., 2001). Today, the many areas of the Dachstein plateau show a strong glacial modification as well as the gentle forms and large dolines of the paleo-surfaces (Behm et al., 2016). About half of the area is drained through the subsurface. In order to investigate the underground waterways, several tracer tests have been carried out since the 1950s. The first experiments indicating a radial drainage were faulty, more recent measurements showed mainly north-directed and relatively fast waterways through the massif (Völkl and Eybl, 2018). In the Dachstein Massif 789 caves with a total length of 279 km are known (Fig. 3). Among them is the second deepest cave in Austria: the Hirlatzhöhle with a depth of 1560 m, as well as two of the four longest caves in Austria: again the Hirlatzhöhle with a length of 118 km and the Mammuthöhle with a length of 68 km.

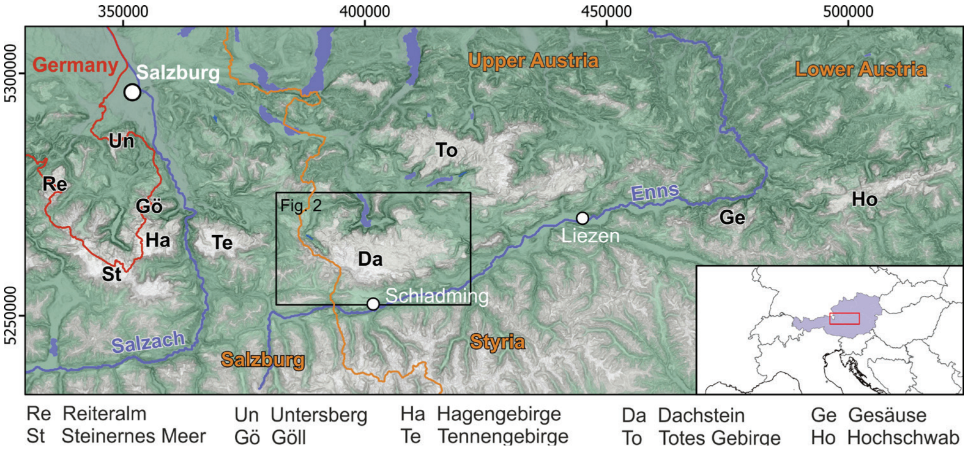

**Figure 1:** Karst massifs in the Northern Calcareous Alps and location of the Dachstein study area. Background: DEM colored by elevation in combination with slope gradient to highlight elevated karst massifs. Coordinates: UTM 33N.

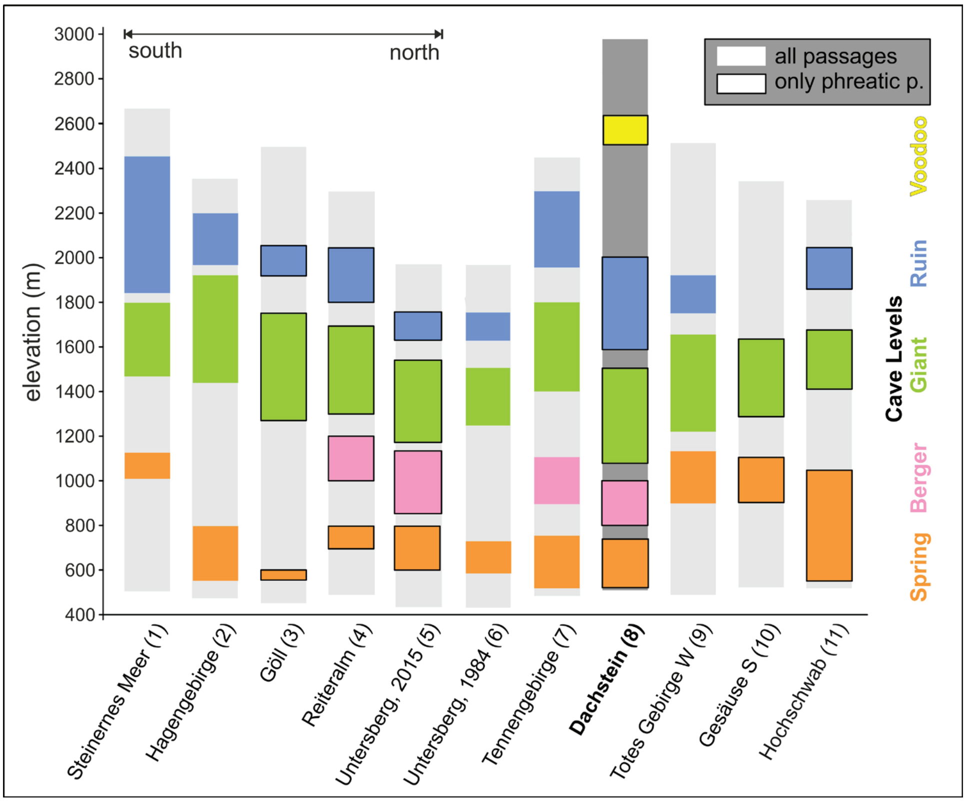

**Figure 2:** Overview of cave levels (variegated boxes) in the NCA. Upper and lower limits of gray bars indicate the present summit and the base level elevations of the massif. Data sources: (1) Klappacher and Knapczyk (1977, p. 157), (2) Klappacher and Knapczyk (1979 p. 91), (3) Szczgiel pers. comm., (4) Wisshak and Jantschke (2010), (5) Zagler (2016), (6) Haseke-Knapczyk (1989), (7) Klappacher and Haseke-Knapczyk (1985 p. 101), (8) this work, (9) Kuffner (1998), (10) Herrmann and Fischer (2013), (11) Plan et al. (2021).

## 3. Methods

For the analysis of cave levels in the Dachstein Massif, the subgroups (Stummer and Plan, 2002) of the Austrian cave register No. 1541 to 1549 were investigated. In contrast to many older studies (e.g. Haseke-Knapczyk, 1989) this study focuses only at phreatic caves or cave sections, ideally, just those that formed in connection with a former base level. Therefore, an attempt was first made to classify all caves according to their origin. 28 % of the caves did not have maps, survey data or descriptions that could be used for classification. The genetic classification scheme of Oberender and Plan (2018) was applied. This divides caves into genetic classes. The relevant classes for the Dachstein massif were epigenetic corrosion caves (subdivided into phreatic and vadose origin) and weathering and erosional caves. Caves that developed under vadose conditions (i.e. above the water table and only partly water bearing) are characterized by a continuous downward trend of passages, mainly vertical shafts and in general high but narrow and meandering canyons. Phreatic caves were permanently or periodically water filled during their formation. They are characterized by mostly horizontal or subhorizontal passages and have tubes with lenticular, elliptical or nearly circular cross sections that can loop up and down (Audra and Palmer, 2011).

The classification is based on data as of May 2022. In the following, the classification methods of the corrosion caves are briefly explained depending on the available data. Maps, 3D survey data, written descriptions, and photos from the Spelix database (www.spelix.at) were used to classify the caves. In addition, own field experience in the six longest and many other caves were useful as well as knowledge from other speleologists that provide data on cave morphology and genesis. Especially for larger cave systems like the Hirlatzhöhle and Mammuthöhle, 3D survey data were available at the Spelix database and were used in specific software tools that allow data manipulation, calculation and 3D visualization (such as Compass or Survex) as will be described in the following. After classification, the (unprojected) phreatic passage lengths of each cave were assigned to a 25 m height interval according to their altitude. According to available data sources of each cave, the following procedures were applied:

### 3.1 Compass-files or Survex files and maps

In the optimal case, a Compass .dat or .mak file as well as a plan view and projected elevation or extended elevation were available. In this case, the measurement data were exported from Compass and prepared for further processing with a Python script. Now the phreatic and vadose sections of the cave were distinguished according to the presented classification features (e.g. passage shape and slope) and added for each height interval. An example of such an approach is the Mammuthöhle. If Survex.3d files and cave maps were available, two procedures were applied depending on the structure of the cave. If the cave was phreatic except for vadose shafts, a Compass.plt file was exported and a histogram of the length per height interval was created in the Compass Viewer. Following the assumption that (sub)vertical shafts are mostly of vadose origin, lengths of steep survey shots with more than 70° inclination (in few cases 60°) were excluded in order to consider just the phreatic sections (Plan et al., 2009). This method was chosen e.g. for Schönberghöhle where all passages below 1150 m a.s.l. were classified as vadose and were excluded. If the cave is more complex, the survey shots of vadose sections were removed from the file. Afterwards, a histogram of the length distribution was created with Compass. This method was chosen for the Hirlatzhöhle.

### 3.2 Just maps or descriptions

For most of the smaller caves, classification was only done on the basis of the map. In the best case where both plan view and projected or extended elevation were available, often classification had to be done on the basis of one of these projections. The phreatic lengths per height interval were estimated from the map. This method was used, among others, for the Dachstein-Rieseneishöhle (hereafter Rieseneishöhle). In a few cases, especially for small caves, descriptions helped to classify caves where no data except for the elevation of the entrance were available.

## 4. Results

### 4.1 Genetic classification

Of the 789 caves studied, 25 % were classified as phreatic, probably phreatic or partially phreatic (Fig. 4). However, the total length of phreatic passage is 204 km, which is 73 % of the total lengths of all Dachstein caves. Most of these phreatic lengths are due to the extensive polygenetic (phreatic and vadose) cave systems. The caves of the Dachstein with a length of more than 1.5 km are responsible for 90 % of the phreatic lengths (Tab. 1). For 29 % mainly smaller caves (the largest is 445 m long) no data was available. Vadose and probably vadose caves make up 40 % of the caves. Vadose passage length accounts for 22 % of the total length of the Dachstein caves.

### 4.2 Cave levels

The vertical distribution of phreatic caves and cave sections is shown in height intervals of 25 m in Figure 5. The distribution shows numerous local maxima, but five clusters of maxima can be defined. In Zone A between 525 and 775 m a.s.l. there are two maxima of approximately equal size. The lower one is largely formed by the 4.6 km long Koppenbrüllerhöhle. The upper maximum around 725 m is largely due to the sections of Hirlatzhöhle. Zone B between 825 and 1075 m a.s.l. contains a much larger maximum around 1025 m. This zone is almost

| cave name | No. of cave register | total length [km] | phreatic length [km] | phreatic length [%] | elevation range [m a.s.l.] | depth [m] | lithology |
|---|---|---|---|---|---|---|---|
| Hirlatzhöhle | 1546/7 | **113.6** | **103.1** | 91 | 451 - 2011 | **1560** | DK, (WD) |
| Mammuthöhle | 1547/9 | 67.7 | 49.0 | 72 | 621 - 1828 | 1207 | DK |
| Südwandhöhle | 1543/28 | 10.9 | 10.1 | 92 | 1339 - 1848 | 509 | WD, (GK) |
| Schönberghöhle | 1547/70 | 9.3 | 8.8 | 95 | 1036 - 1311 | 275 | DK |
| Koppenbrüllerhöhle | 1549/1 | 4.7 | 4.7 | **100** | *541 - 687* | 146 | HD |
| Voodoo-Canyon | 1543/225 | 4.4 | 1.8 | 41 | 1974 - 2697 | 723 | DK |
| Mörkhöhle | 1547/12 | 4.2 | 3.3 | 77 | 1187 - 1399 | 212 | DK |
| Gowling Hale | 1543/130 | 2.8 | *0.0* | *0* | 1568 - 2152 | 582 | DK |
| Rieseneishöhle | 1547/17 | 2.7 | 2.7 | **100** | 1380 - 1470 | *90* | DK |
| Sammler | 1543/177 | 1.6 | 1.3 | 80 | 1866 - 2050 | 184 | DK |
| Orkanhöhle | 1546/35 | *1.6* | *0.0* | *0* | 1059 - 1813 | 754 | DK |

**Table 1:** The caves of the Dachstein massif with more than 1.5 km length compared to the length of their phreatic sections as of May 2022. Elevation range is independent of the entrance(s). bold = highest values; *italics*: lowest values; lithology: DK = Dachsteinkalk, WD = Wettersteindolomit, HK = Hauptdolomit, GK = Gutensteiner Kalk.

exclusively due to sections of the Hirlatzhöhle. In Zone C between 1125 and 1550 m a.s.l., the phreatic lengths per interval again vary more strongly. The maximum of this zone is in the interval up to 1450 m a.s.l. This zone is strongly determined by Mammuthöhle, but up to about 1300 m a.s.l. the influences of sections of Hirlatzhöhle are also clear. Schönberghöhle and Mörkhöhle also produce two smaller maxima around 1250 m. Zone D itself is composed of three almost equal maxima at 1650, 1800, and 1950 m a.s.l. The zone lies between 1600 and 2050 m a.s.l. Up to 1850 m a.s.l. it is strongly characterized by the Südwandhöhle, but the overall picture is dominated by several large caves. The upper limit is formed by a cave called the Sammler. Between 2050 and 2525 m a.s.l. there are remarkably few caves with phreatic sections. However, the number of known cave entrances at this altitude is comparable to the number below 1000 m. The uppermost zone E between 2525 and 2725 m a.s.l. contains significantly fewer caves with phreatic sections than the lower altitudes. This zone is dominated by Voodoo-Canyon and Eiskristall-Canyon. A comparison of altitudes of cave passages in the north and south of the Dachstein indicates that some levels slope slightly to the north. They dip about as steeply as the rock layers of the massif in the profiles of Mandl et al. (2012). Due to the smaller number of levels south of the summit, no numerical value of the slope can be estimated. It is also not possible to determine whether all levels are equally inclined.

## 4.3 Local distribution

The known caves in the Dachstein are distributed unequally (Fig. 3). A north-south comparison shows that there are significantly more known caves in the north than in the south of the Dachstein region. Both in the east and in the west of the study area, significantly fewer caves are known than in the central area. Many of the (rather small) caves in the east and west could not be classified due to lack of data or were classified as vadose.

Based on the distribution of caves, the Dachstein Massif is subsequently divided into five regions, which are interpreted separately: (1) A central region from Lake Hallstatt to the Dachstein summit (Hoher Dachstein; subgroups 1543 and 1546, Fig. 3); (2) the Krippenstein region, eastern of it (subgroup 1547); (3) the Kopppengebirge (subgroup 1549), which contains a few larger caves somewhat east of Krippenstein; (4) East (subgroup 1544, 1545, and 1548) and (5) West Region (subgroup 1541 and 1542), each of which contains just a few caves with phreatic passages.

### *4.3.1 Central region*

The central region includes the subgroups 1546 and 1543 (Fig. 3) and extends from Lake Hallstatt in the north to the southern edge of the Dachstein Massif. Thus, this region includes the highest caves and many of the lowest caves of the Dachstein. The vertical distribution of the phreatic cave section shows many local maxima and no such clear zonation as in the whole Dachstein (Fig. 6). Roughly three areas can be distinguished. The lower one between 450 and 1500 m a.s.l. includes the Hirlatzhöhle as well as the lower part of the Südwandhöhle. This area covers the zones A, B and C defined above. The next higher zone combines phreatic lengths between 1625 and 2100 m a.s.l. and thus forms almost the entire Zone D. Here, the upper part of the Südwandhöhle and the Sammler are of particular importance. This is fol-

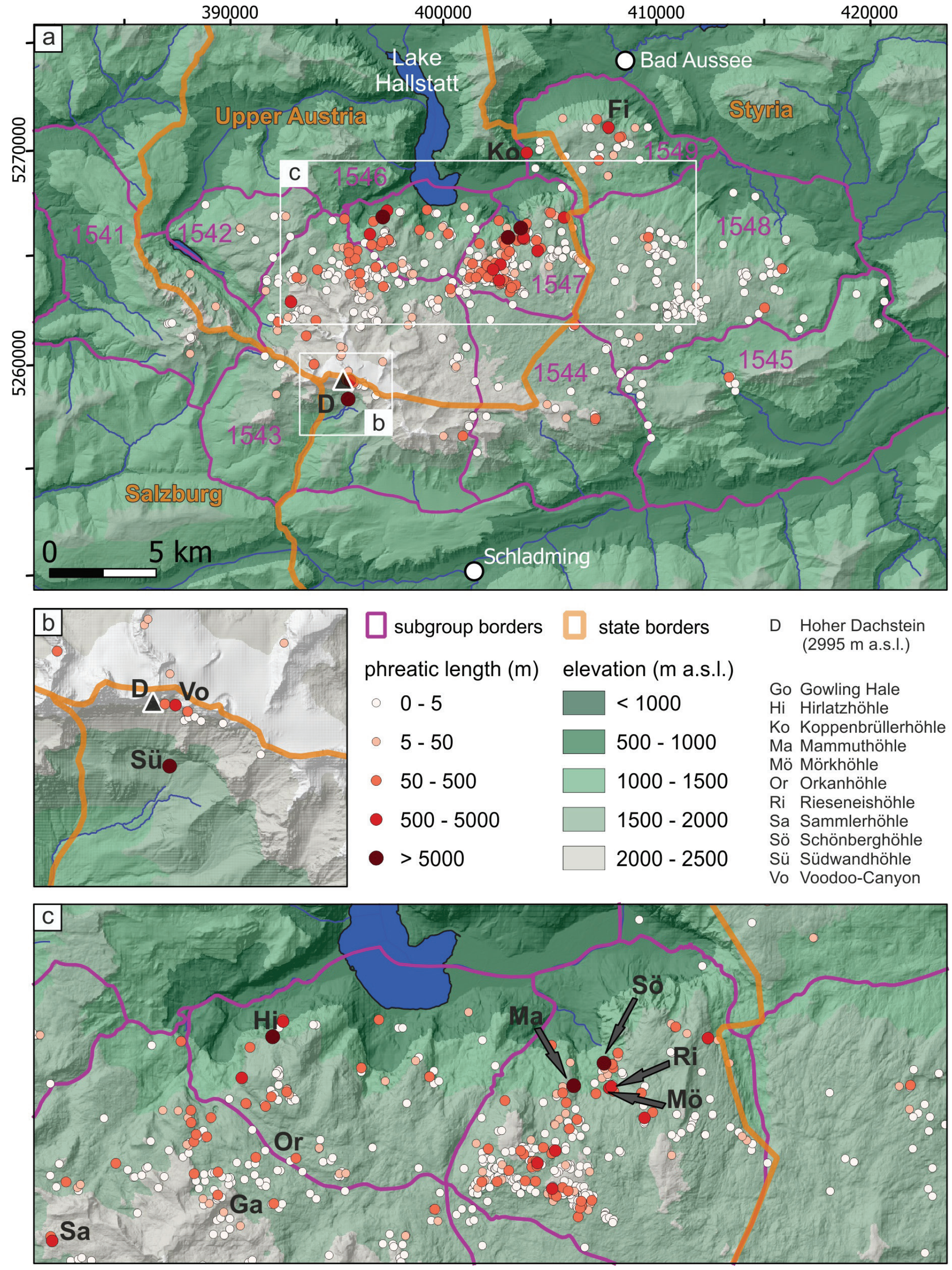

**Figure 3:** Map of the Dachstein area and caves classified according to their phreatic length. (a) whole study area, (b) summit area, (c) northern area. Coordinates: UTM 33N.

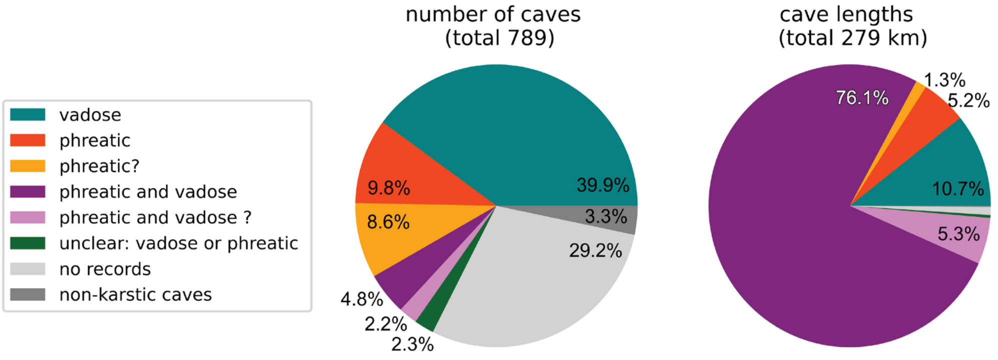

**Figure 4:** Classification of Dachstein caves according to their genesis as of May, 2022.

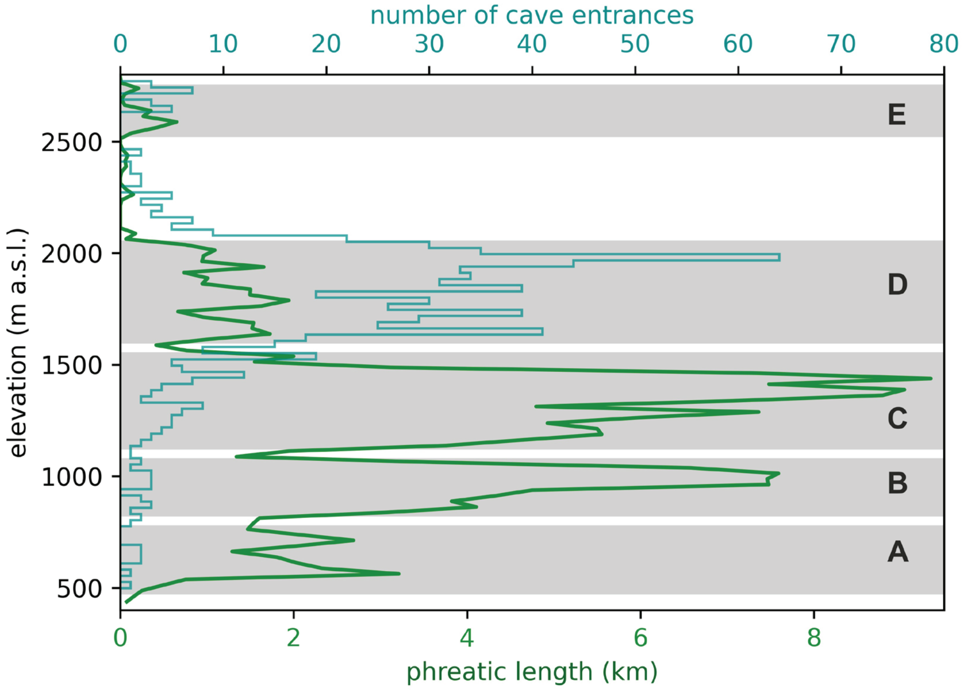

**Figure 5:** Vertical distribution of the phreatic passage lengths (green) and cave entrances (blue) of the Dachstein caves grouped in 25-m intervals. Gray bars show cave levels A-E which were interpreted as follows: A = Spring Cave Level, B = Berger Cave Level, C = Giant Cave Level, D = Ruin Cave Level, E = previously unknown level.

lowed by 450 m of altitude without significant phreatic sections. Above this, mainly the Voodoo-Canyon forms the uppermost part between 2550 and 2750 m a.s.l. This forms zone E, which occurs exclusively in the center region; all other regions miss such high elevations (Fig. 7). Following the altitude profile of the mountain, the northern part of this region with the Hirlatzhöhle contains rather the lower part of the distribution. In the south, where the summit of the Dachstein is located, the caves of the upper part are located.

The Südwandhöhle (No. of cave register: 1543/28) opens below the Dachstein south face and has been known since 1886. The cave is outstanding with two respects: on the one hand the host rock is primarily Wettersteindolomit. On the other hand, the rock overburden exeeds 1.5 km, since the cave extends almost below the summit of the Dachstein (Behm et al., 2016). Many sections of the cave show keyhole profiles with large-scale phreatic passages often exceeding 100 m$^2$ in cross section (Fig. 8a) with canyons (often still active) incised into the floor. Mazes are rare, large chambers are found near the entrance and in remote sections of the Südwandhöhle. The modern drainage system of the cave is relatively horizontal, sloping gently to the north (Behm et al., 2016). Almost all sections of the Südwandhöhle were classified as phreatic. Just the sections below the Hauptgang and the Paläoenns were classified as vadose. The cave has a depth of about 500 m. In it, the vertical distribution of

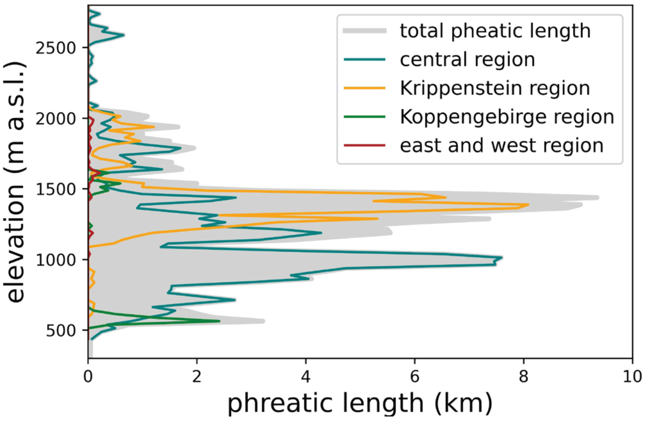

**Figure 6:** Vertical distribution of the phreatic passage lengths of different compared regions grouped in 25-m intervals.

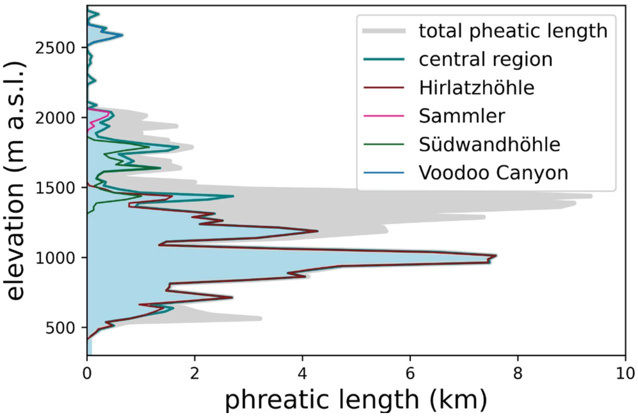

**Figure 7:** Central region: Vertical distribution of the phreatic passage lengths grouped in 25-m intervals.

**Figure 8:** Photos of the Dachstein Caves. (a) The huge, originally phreatic tunnel (Paläoenns) in Südwandhöhle has developed in Wettersteindolomit. (b) Example of an active epiphreatic gallery in Hirlatzhöhle, which developed at the intersection of a subhorizontal bedding plane and a fault. (c) Epiphreatic gallery in Hirlatzhöhle. (d) The so-called Paläotraun in Mammuthöhle is a phreatic gallery with a cross section of c. 100m$^2$. (e) Almost vertical view down a vadose canyon shaft in the Mammuthöhle with an active stream (during low water). Photographs by Lukas Plan, except (a) by Robert Seebacher and (d) by Lina Rummler.

the cave passages shows three narrow maxima, around 1800, 1650 and 1450 m a.s.l. with the upper two maxima located in level D and the lower, more clearly separated, in level C.

The Sammler (1543/133) is located northeast of the Grünbergkogel and consists of inclined labyrinthine passages and some probably vadose shafts. Out of 1.6 km of the Sammler, almost 1.3 km have been classified as phreatic. In vertical distribution, the cave is at the upper boundary of Zone D.

The Voodoo-Canyon (1543/225) is 4.4 km-long and the entrance is located at 2635 m a.s.l. in the Dachstein south face. Therefore, the cave is the highest such extensive cave in Austria. The cave is developed in steeply bedded Dachsteinkalk and extends almost to the underlying Wettersteindolomit and to Südwandhöhle (Seebacher, 2010). 1.8 km have been classified as phreatic and include the horizontal sections of the entrance area, the Vogonenwurm and Quirlgang, as well as the Helikoptergang. The rest of the cave is characterized by deep vadose shafts. Due to its high elevation, Voodoo-Canyon dominates Zone E.

The Hirlatzhöhle (1546/7) currently ranks third in length and second in depth in Austria. It is situated in the northern Dachstein and is primarily formed in Dachsteinkalk, with some portions in the southeast extending into the Wettersteindolomit (Plan et al., 2022). The cave consists of a branched system with some loops and is arranged in levels. Most phreatic galleries are large with cross sections exceeding a few 10 m$^2$ (Fig. 8b, c). The cave is bounded to north-dipping bedding planes as well as to faults. Divers reached the deepest point of Hirlatzhöhle, 63 m below the level of Lake Hallstatt. The cave contains two separate drainage systems, one in the east and one in the west. During floods, large sections of the cave fill with water and complex overflow mechanisms activate different springs at the surface (Plan et al., 2022). 103 km of the 114 km of passages of the Hirlatzhöhle have been classified as phreatic which is half of the total phreatic passage lengths of the Dachstein. Mainly the shafts below the uppermost entrance (the What U Got Pot) were classified as vadose, as well as some canyons in the Alter Teil, Schwabenland and the Oberes System. In addition, Megalodonten Canyon and Eine Spur von Nagellack were assumed to be vadose canyons. The vertical distribution of these phreatic lengths shows two significant maxima. The clearly larger one lies between 900 and 1050 m a.s.l. and a smaller one around 1200 m a.s.l. In comparison with the distribution of the total phreatic passage lengths of the Dachstein, the Hirlatzhöhle forms almost alone the above defined zone B. The remaining cave sections significantly contribute to the upper parts of Zone A as well as the lower of Zone C. In the remote sections of the Hirlatzhöhle, temporarily flooded (epiphreatic) passages of both drainage systems could be traced up to about 600 m above the local base level. It can therefore be assumed that the Wettersteindolomit, which generally underlies the Dachsteinkalk but whose extent is often not known exactly, acts partly as an aquitard. However, at least the eastern drainage system reaches significantly into the dolomite layer which speaks against this assumption (Plan et al., 2022).

### *4.3.2 Krippenstein region*

The region around Krippenstein (summit 2108 m a.s.l.) covers subgroup 1547 and more deep and long caves. The vertical distribution of phreatic passages in this region shows two more district areas (Fig. 9). The lower one between 1150 and 1550 m a.s.l. forms the major part of zone C. The most important caves here are Mammut-, Schönberg-, Mörk- and Rieseneishöhle. The area above consists of several comparable small maxima between 1650 and 2000 m a.s.l. Here the uppermost part of the Mammuthöhle is located as well as several smaller caves and caves with non-extended phreatic sections.

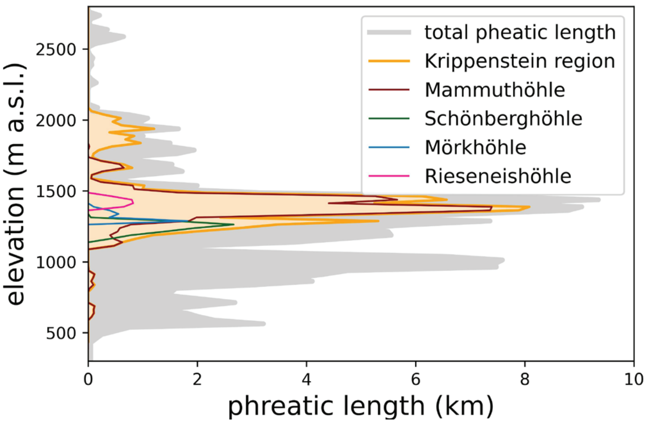

**Figure 9:** Krippenstein region: Vertical distribution of the phreatic passage lengths grouped in 25-m intervals.

The Mammuthöhle (1547/9) is both the second longest and the second deepest cave in the Dachstein Massif. It is located below the Dachstein's northern rim in the area of the Anger- and Schönbergalm as well as the Mittagskogel and Krippenstein (Behm et al., 2016). The cave represents a complex arrangement of sub-horizontal phreatic passages with cross sections in the order of 10 to sometimes 100 m$^2$ (Fig. 8d) and smaller-scale bedding-controlled labyrinths. There are also a few shafts up to 90 m deep that formed under phreatic conditions (Plan and Xaver, 2010). These old phreatic sections are intersected by younger vadose systems of shafts and canyons (Fig. 8e). Some of them have significant extensions and are arranged in several storeys and exceed heights of 200 m. Many canyon-shaft systems are active and in the most significant one the stream could be traced for 940 m vertically and 1.6 km horizontally. In Mammuthöhle, 49 km of the almost 68 km length have been classified as phreatic. This includes large sections of the Alter Teil, the Oedlhöhle and all the mazes like Edelweiss, Minotaurus, and Wiener Labyrinth. Long passages such as the Krippensteingang and the Heli-Schöner-Gang have also been classified as phreatic. From there, vadose shafts and canyons, such as the HR-Virus Canyon or the Pilz Canyon, branch off again. In the predominantly vadose Wasserschacht, and adjacent sections (Mortonhöhle, Dampfende Schächte, Schuppenhöhle), just a few sections were assumed to be phreatic. The vertical distribution of phreatic lengths shows a clear maximum between 1300 and 1500 m a.s.l.

The Mörkhöhle (1547/12) is located above the Schönbergalm near the Rieseneishöhle. The cave has vadose canyons and shafts, as well as phreatic passages and halls. 3.3 km of the 4.2 km total length have been classified as phreatic. These include the Eingangs-, Block- und Káferhalle, with the shafts in between interpreted as vadose. In addition, Bärenzahngang, Lehmhölle and Pionierhalle, as well as Mesepotamien, were classified as phreatic. The narrower and steeper passages such as the Konglomerat- and Nordcanyon, the Pracht- as well as Lapenschirmschacht and Neuer Teil were classified as vadose. The phreatic sections of the cave are located between 1275 and 1400 m a.s.l. and thus in zone C.

The Dachstein-Rieseneishöhle (1547/17) is the most important show cave in the region because of its extensive ice formations. With a depth of just 90 m, it is the shallowest of the longer Dachstein caves. The cave consists mainly of large-scale passages (some 10 m$^2$) and chambers, but canyon-shaft systems are absent (Behm et al., 2016). The 2.7 km-long cave has been classified as fully phreatic. Because just coordinates of points surveyed with a theodolite and no 3D survey shots were available, lengths per elevation interval were estimated and compared to the distribution of survey points to improve the estimate.

The Schönberghöhle (1547/70), like the four previously described caves, is developed in the bedded Dachsteinkalk and is formed along bedding planes and secondarily along faults (Plan, 2022). It mainly consists of small-scale (normally <10 $m^2$) tubes with relatively few side branches. The cave was classified as phreatic except for a few vadose shafts. In vertical distribution it lies with the other large caves of this region in zone C.

### *4.3.3 Koppengebirge region*

The Koppengebirge region represents subgroup 1549 with the summit of Zinken (1854 m a.s.l.). It contains significantly fewer caves, which are situated in two district levels (Fig. 10). The lower one between 525 and 650 m a.s.l., characterized by the Koppenbrüllerhöhle significantly forms the lower maximum of Zone A. The upper range is between 1450 and 1625 m a.s.l. without a clear maximum with just a short length and is around the boundary of zones C and D. The Fischermeisterloch has the greatest influence on this area.

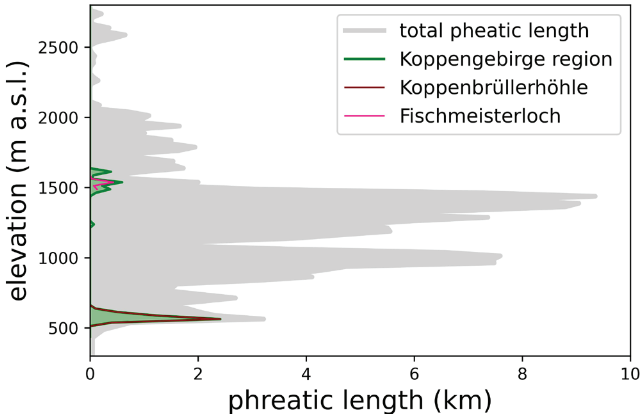

**Figure 10:** Koppengebirge region: Vertical distribution of the phreatic passage lengths grouped in 25-m intervals.

The 4.7 km-long Koppenbrüllerhöhle (1549/1) is the lowest known large cave of Dachstein and is developed in Hauptdolomit. It can be divided into two different cave sections, each contributing a stream to the spring below or additionally at the entrance during floods. One part is developed along a fault and leads to the north where some passages are permanently water filled. The northeastern part of the cave is more extensive, labyrinthine and a bit higher (Fritsch, 2010). The cave was classified as completely phreatic. 3D data were available just from the northern part of the cave, the phreatic lengths per altitudinal interval in the northeastern part had to be estimated. At its elevation, it forms just under the middle of Zone A.

The Fischmeisterloch (1549/4) is located below the Zinken summit and is 748 m long and 114 m deep. The cave consists mostly of relatively wide passages with narrower side passages. It has been classified as a completely phreatic cave. It is located at the upper edge of zone C in its altitude.

### *4.4.4 East region and west region*

The western region includes subgroups 1541 and 1542, the eastern region includes the subgroups 1544, 1545, and 1548. Both regions have relatively few caves and low phreatic lengths. Compared to the other regions, they barely contribute to cave levels on the Dachstein (Fig. 6).

## 5. Interpretation

The vertical distribution of phreatic cave passages of the Dachstein Massif shows five distinct levels. Based on correlations with data from adjacent karst massifs, the four lower cave levels can be assigned to the classical cave levels. Zone A (475-775 m a.s.l.) defined above can be assigned to the Spring Cave Level, which in many cases is hydrologically active and has partially water filled passages. Zone B (825-1075 m a.s.l.), dominated by the Hirlatzhöhle, corresponds to the Berger Cave Level, which has been described from the northwest of the Tennengebirge and later only found in the Reiteralm and Untersberg. Zone C (1125-1550 m a.s.l.), which contains most of the phreatic and many large passages, can be assigned to the Giant Cave Level. Due to its inhomogeneity, Zone D (1600-2050 m a.s.l.) represents a cave level only to a limited extent. It fits best with the Ruin Cave Level. Many caves in this zone show the typical characteristics of buried material or many day shafts (as described by Haseke-Knapczyk, 1989). Zone E (2525-2725 m a.s.l.) is so high that it has not been described before. This zone therefore represents a previously unknown and most likely older cave level.

## 6. Discussion

The analysis of cave levels and their correlation with former base levels requires several assumptions and introduces several sources of error, which are discussed below. Geometric errors due to the determination of the entrance elevation (for long systems < 1 m, generally < 20 m) and due to cave surveying (less than about 1 m per 100 m vertically) can be neglected, especially for the overall picture. As already mentioned, only phreatic caves and sections of caves should be included in the analysis of cave levels in order to get a clearer picture. Since 39 % of the Dachstein caves are vadose, a differentiation seems to be important. In earlier studies the cave entrances or the lengths of all caves were used for the analysis of the cave levels, but in more recent works the analysis has already been restricted to the phreatic sections (e.g. Wisshak and Jantschke, 2010; Zagler, 2016). The vertical distribution of cave entrances on the Dachstein is clearly different from that of the phreatic lengths (Fig. 5).

However, the classification of cave passages is subject to error, especially if it is just based on (incomplete) maps or 3D survey data, or if passages were heavily overprinted by collapse, obscuring the original corrosion morphology. However, due to the skewed distribution of cave length among the number of caves, the long caves are the most important for cave level analysis. Significant sections of the long caves are known to the authors from the field or to the speleologists consulted, and in general the database of the longest caves is quite good. For caves smaller than 10 km, the method of using only survey shots with an inclination of less than 70° to eliminate vadose shafts and of estimating the lengths per height interval only according to extended elevation maps seems to have only a limited influence on the overall picture. In our opinion, the time required for further field work to improve the classification is questionable.

Another condition for correlating the height of a cave passage with the former base level is that it is not controlled by aquiclude rocks. Aquiclude rocks that often influence cave formation in the NCA are negligible at in the Dachstein Massif. Sandstones and shales of the Werfener Schichten occur only in the south, where no caves are known. Also non-karstic Jurassic rocks are missing. Due to the dominance of the more than 1 km thick Dachsteinkalk, only the underlying dolomite rocks are potential aquitard rocks in the central and northern Dachstein. The only cave where Wettersteindolomit seems to influence speleogenesis is Hirlatzhöhle. However, some sections of this cave are developed in dolomite without significant changes in passage cross sections compared to passages in limestone (Plan et al., 2022). In addition, the Dachstein hosts two outstanding examples of caves in dolomite host rocks: Südwandhöhle with its large passage diameters in Wettersteindolomit and Koppenbrüllerhöhle in Hauptdolomit.

Besides the correctness of the genetic classification of caves, the distribution of known cave length (as well as its ratio to unknown passage length) is important for the resulting cave levels. Therefore, the state of exploration is important for the Dachstein - as for many other large massifs - it has to be stated that probably only a small number of caves with natural entrances are known. This can be deduced from cave distribution maps (e.g. Behm et al., 2016), where known caves are mainly clustered around valleys, mountain huts or cable cars, which allow easy access, but large areas, which are more difficult to reach, lack caves. In particular, the lowest and highest levels rely heavily on data from a few, but large, caves. The Mammuthöhle and the Hirlatzhöhle contain 74 % of the known phreatic lengths, and the ten longest caves contain 90 %. Therefore, further cave exploration could change the picture of the cave levels. Figure 2 compares data from Untersberg from 1984 (about 30 km of cave passages; Haseke-Knapczyk, 1989) with data from 2015 (112 km; Zagler, 2016). The newly discovered cave passages (largely characterized by the Riesending-Schachthöhle discovered in 1996) show that the Berger Cave Level is also present and well developed at the Untersberg, while the other cave levels showed only minor changes there.

To test whether the derived cave levels are meaningful or just statistical noise, different ranges of elevation intervals (25, 50, and 100 m) were compared. The division of the vertical distribution into five zones proved to be robust. Only the interpretation of zone D (the Ruin Cave Level) with its three similarly prominent local maxima (Fig. 5) as a single cave level seems somewhat questionable. As already mentioned, the caves are not evenly distributed and most of the known caves, especially the long phreatic ones, are concentrated on the northern edge of the Dachstein (Fig. 3). A comparison of the caves between the south and the north is not very meaningful.

In contrast to previous studies in the NCA that distinguished three to four cave levels, this study found five distinct levels for the Dachstein Massif. The newly discovered uppermost cave level extends between 2525 and 2750 m a.s.l. (Fig. 2). Within the part of the NCA where cave levels have been studied, this elevation is only reached in the Steinernes Meer with its highest peak (Schönfeldspitze) at 2653 m a.s.l. However, the summit areas in the Steinernes Meer are generally narrow peaks or ridges where very few short caves are known. Since Voodoo-Canyon cave is almost entirely responsible for this new level, we suggest naming it Voodoo Cave Level. However, it should be noted that caves at this altitude are often iced over and difficult to access, and new discoveries are likely (Seebacher, 2010). This could change the overall picture of cave levels at these high elevations and possibly narrow the gap between Voodoo Cave Level and the Ruin Cave Level below.

Originally, cave levels were defined not only by altitude, but also by hydrological, morphological and sedimentological characteristics (e.g. Haseke-Knapczyk, 1989). However, in our opinion, these criteria are mainly artifacts of elevation. The occurrence of cave loams up to several meters thick in the Berger Cave Level (Klappacher and Haseke-Knapczyk, 1985 p. 101) has nothing to do with the original cave development, but is due to the fact that caves up to this level were mainly affected by Pleistocene backflooding (e.g. Audra et al., 2002) and sediments were not removed by later streams as in the underlying Spring Cave Level. The common occurrence of cave collapses in the Ruin Cave Level is caused by the intersection with the flat land surface at the top of the plateaus and the lower temperatures that cause enhanced frost weathering at higher elevations. Therefore, we have not considered any other criteria for correlating cave levels other than elevation.

In some work outside of the NCA, cave levels have been defined by vadose-phreatic transitions (e.g., Audra and Palmer, 2011; also known as canyon-tube transitions; Häuselmann et al., 2002). This is a more precise way, but canyon-tube transitions are rarely observed in caves of the NCA - at least in the high-Alpine massifs. For example, in the Demänová Cave (Western Carpathians, Slovakia), Droppa (1966) distinguished nine cave levels within 140 m vertically, with inclinations ranging from 0.6 to 1.1°. Another example comes from the caves north of Lake Thun in central Switzerland (Siebenhengste-Hohgant-Höhlensystem, Bärenschacht and other caves). There, Häuselmann et al. (2002; 2007) distinguish 14 "cave levels" (which they termed "speleogenetic phases") with vertical distances of 50 to 290 m and inclinations of 1.3 to 2.1°. For the NAC, the cave levels were described only from the accumulation of cave passages and show intervals in the order of 0.5 km. The reason for the rarity of canyon-tube transitions and the lack of cave levels with smaller intervals in the caves of the NCA can only be speculated. A possible explanation is the large extent of the epiphreatic zones that obliterate canyon-tube transitions. Fluctuations of the water table of 200 m have been reported for modern caves (e.g. Plan et al., 2022) and of 275 m for fossil passages (Plan and Xaver, 2010). Also, when several smaller maxima are treated as single levels instead of combining them, the interpretation of cave levels may vary. Thus, the cave levels described from the NCA probably reflect only major tectonic or climatic changes over the past several million years, but not smaller changes such as glacial cycles as interpreted by Droppa (1966). The vertical distribution of caves in the Dachstein (and other massifs) also shows many smaller oscillations that may reflect smaller climatic or tectonic changes, but a correlation between the massifs or with surface features such as planation surfaces has not been successful so far.

So far, cave levels have been studied in detail for the massifs in the central and eastern part of the NCA, which extend over an area of 190 km in east-west direction and 35 km from south to north (Fig. 1). Haseke-Knapczyk (1989, p. 190) already noted that there is a dip from south to north for the Ruin Cave Level and Giant Cave Level. This can be confirmed by the compilation of more recent data in Figure 2, where these two levels show a decreasing trend for the five left columns (which were derived from karst massifs west of the Salzach River) arranged from south to north. The dip is very roughly 300 m over 30 km, or 0.6°. This is a comparatively low gradient compared to the values above (Slovakia and Switzerland) but it is in the same range and its northward tilt can be seen as an indicator that the cave levels are related to a former base level in the north. Interestingly, this gradient of 0.6° for the inclination of the cave levels west of the Salzach River is three times higher than the one of the modern river for the parallel distance, which is 0.2°.

## 7. Conclusion

In this work, the Dachstein Massif was analyzed for the existence and location of cave levels. For a clearer result, only phreatic caves and cave sections should be included in the analysis. For this purpose 789 caves of the Dachstein massif were investigated. 72 % of them could be classified, which corresponds to a total length of 279 km. Of these 599 caves, 36 % were classified as phreatic, probably phreatic, or partially phreatic. The phreatic sections of these caves were divided into 25 m height intervals and the vertical distribution of passage lengths was plotted. In this study five district zones are apparent, more than the expected three or four cave levels. Most of them could be assigned to the classical cave levels (Fig. 2):

- Between 475 and 775 m a.s.l., some hydrologically active cave passages are found. This level was assigned to the Spring Cave Level.
- Hirlatzhöhle and some smaller caves form a level between 825 and 1075 m a.s.l. As a level between the Spring Cave Level and the Giant Cave Level, this accumulation is assigned to the Berger Cave Level. However, sections of it are hydrologically active, which is not the case in the Bergerhöhle (Tennengebirge), from where it was first described.
- The level between 1125 and 1550 m a.s.l. shows the highest peak in the statistics. It contains large caves such as the Mammuthöhle, sections of the Hirlatzhöhle and others. It can be assigned to the Giant Cave Level.
- Between 1600 and 2050 m a.s.l. there are three levels of cave passages with a similar importance. This composite zone is located in the area of the Ruin Caves.
- From 2525 to 2750 m a.s.l., there are fewer caves than in the other levels. A cave level this high has not been described before and represents a new cave level for which the name Voodoo Cave Level is proposed.

The vertical distribution of entrances used in earlier studies of cave levels does not relate to the levels of phreatic cave passages in the Dachstein. A review of previous studies in the NAC (Fig. 2) suggests that cave levels are meaningful and correlate with former base levels. However, the characterization of cave levels based on common morphologic, sedimentologic, and hydrologic features, as has been done in the past, is questioned. The upper limit of the cosmogenic $^{26}$Al/$^{10}$Be burial age dating method at c. 6 Ma and low Uranium content in most speleothems in the NCA impedes U/Pb dating causing the lack of numerical ages above the Giant Cave Level. As a consequence, timing of elevated levels such as Ruin Cave Level and Voodoo Cave Level remains unclear.

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