



# A 700 M LONG PSEUDOKARST CAVE IN CALCAREOUS SANDSTONE IN THE INTERIOR OF A DOLOMITIC KARST CAVE (DACHSTEIN, EASTERN ALPS)?

## 700 M DOLGA PSEVDOKRAŠKA JAMA V APNENČASTEM PEŠČENJAKU V NOTRANJOSTI DOLOMITNE KRAŠKE JAME (DACHSTEIN, VZHODNE ALPE)

Lukas PLAN<sup>1\*</sup>, Robert SEEBACHER<sup>2</sup>, Veronika KOUKAL<sup>1</sup> & Susanne GIER<sup>3</sup>

### Abstract

**Lukas Plan, Robert Seebacher, Veronika Koukal & Susanne Gier: A 700 m long pseudokarst cave in calcareous sandstone in the interior of a dolomitic karst cave (Dachstein, Eastern Alps)?**

The Südwandhöhle, located in the Dachstein karst massif, is a 12 km long cave system. It is primarily formed in dolomite (Middle Triassic Wetterstein Formation), a rare occurrence in the Northern Calcareous Alps. The cave is 509 m deep and notable for its rock overburden of 1.5 km, and its huge passage cross-sections of up to 250 m<sup>2</sup>. In the remote parts, there is a 0.7 km-long tube that is almost entirely formed in lithified clastic cave sediments. The setting suggests that this relatively small tube (cross-sections: 0.5 to 2 m<sup>2</sup>) developed as a continuation of a large palaeo-phreatic gallery. The walls and ceilings of the tube are made up of well-lithified sandstone, which often shows erosional features. The sandstone components consist of calcite, partly dedolomite, as well as some quartz, small amounts of dolomite, and iron hydroxide and can be classified as impure dolomitic calcarenite. The cement is calcite, giving a total calcite content of 40–70% in the analysed thin sections. Unusually, the tube does not run along the ceiling of the corridor, as is common in many caves, but winds its way through the large, sediment-filled corridor. As there are no structures in the calcareous sandstone or active tectonics that could have acted as initial fissures, the formation of the proto-conduit is difficult to explain. One possible explanation is that the sand was cemented by pore water from the surrounding dolomite host rock, with parts inside being less lithified or not consolidated at all. Water flowing through this porous sand further increased the

### Izvleček

**Lukas Plan, Robert Seebacher, Veronika Koukal & Susanne Gier: 700 m dolga psevdokraška jama v apnenčastem peščenjaku v notranjosti dolomitne kraške jame (Dachstein, vzhodne Alpe)**

Jama Südwandhöhle, ki je v kraškem masivu Dachstein, je 12 km dolg jamski sistem. Nastala je predvsem v dolomitu (formacija Wetterstein iz srednjega triasa), kar je v Severnih apneniških Alpah redek pojav. Jama je globoka 509 m, njena posebnost pa so 1,5 km obsežna krovina in ogromni prečni hodniki, ki merijo do 250 m<sup>2</sup>. V oddaljenih predelih je 0,7 km dolg rov, ki je skoraj v celoti izoblikovan v litificiranih klastičnih jamskih sedimentih. Iz okolice je razvidno, da se je ta razmeroma majhen rov (prerez: 0,5 do 2 m<sup>2</sup>) oblikoval kot nadaljevanje velikega paleofreatičnega hodnika. Stene in stropi rova so iz dobro litificiranega peščenjaka, na katerem so pogosto vidne erozijske značilnosti. Elementi peščenjaka so iz kalcita, delno nastalega z dedolomitizacijo, ter nekaj kremena, majhnih količin dolomita in železovega hidroksida, razvrščajo pa se kot nečisti dolomitni kalkareniti. Cement je kalcit, kar pomeni, da je skupna vsebnost kalcita v analiziranih zbruzkih 40–70 %. Nenavadno je, da se rov ne vije ob stropu hodnika, kot je to običajno v številnih jamah, ampak je razvit znotraj sedimenta. Ker v apnenčastem peščenjaku ni nobenih struktur niti aktivne tektonike, ki bi lahko delovale kot začetne razpoke, je nastanek protokanala težko pojasniti. Ena izmed možnih razlag je, da je pora voda iz okoliške dolomitne matične kamnine zacementirala pesek, pri čemer so nekateri deli v notranjosti manj litificirani ali se sploh niso sprijeli. Voda, ki je tekla skozi ta porozni pesek, je še dodatno povečala poro-

<sup>1</sup> Natural History Museum Vienna, Burgring 7, 1010 Wien, Austria, e-mail: [lukas.plan@nhm.at](mailto:lukas.plan@nhm.at), [veronika.koukal@nhm.at](mailto:veronika.koukal@nhm.at)

<sup>2</sup> Verein für Höhlenkunde in Obersteier, Sonnenalm 78, 8983 Bad Mitterndorf, Austria, e-mail: [robert.hoehle@a1.net](mailto:robert.hoehle@a1.net)

<sup>3</sup> Universität Wien, Institut für Geologie, Josef Holabek-Platz 2, 1090 Wien, Austria, e-mail: [susanne.gier@univie.ac.at](mailto:susanne.gier@univie.ac.at)

\* Corresponding Author

porosity and released insoluble rock grains and subsequently created a tube by piping and eroding the conduit walls through flux enriched with sand. Due to the carbonate content, dissolution probably played only a limited role. Therefore, we interpret this tube as a pseudokarst cave, that was formed primarily through mechanical erosion of sandstone that had deposited within a karst cave.

**Keywords:** pseudokarst, piping, cave sediments, sandstone, dolomite cave, Northern Calcareous Alps.

znost, izplavila netopna kamninska zrna ter ustvarila rov, pri čemer je s tokom, ki je nosil pesek, erodirala stene vodnega kanala. Zaradi vsebnosti karbonatov je raztapljanje verjetno imelo le manjšo vlogo. Zato ta rov razlagamo kot psevdokraško jamo, nastalo predvsem z mehansko erozijo peščenjaka, ki se je odložil v kraški jami.

**Ključne besede:** psevdokras, cevna erozija, jamski sedimenti, peščenjak, dolomitna jama, Severne apnenčaste Alpe.

## 1. INTRODUCTION

Most caves worldwide, and especially the long and deep ones, are karst caves formed by dissolution of limestone or other soluble rocks (e.g. De Waele & Gutierrez, 2022). Karst-like features and caves formed by processes other than dissolution are often referred to as pseudokarst (e.g. Halliday, 2004; Holler, 2019) even though the term is problematic (e.g. Eberhard & Sharples, 2013). Beside lava tubes or boulder caves, an important pseudokarst cave-forming process is piping or suffosion. This is the subsurface mechanical erosion of fine-grained, poorly lithified particles by groundwater (e.g. Martini, 2000; Halliday, 2004; Bernatek-Jakiel & Poesen, 2018). Materials that are particularly susceptible to piping are loess, volcanic ash, mudstone, soil, and peat. While some authors exclude dissolution (e.g. Holler, 2019) others state that dissolution can have a limited effect (Halliday, 2004; Klimchouk, 2004). Alongside these piping caves, there are also pseudokarst caves, which are formed in hard, insoluble rock like sandstones or granite. The main processes are intergranular dissolution, silicate weathering and mechanical

erosion by fast moving water and the emerging tubes are referred to as stream cut caves (e.g. Wray & Sauro, 2013; De Waele & Gutierrez, 2022).

Here we would like to present a special case of a 12 km long karst cave that hosts a small-diameter tube, almost entirely developed in lithified clastic cave sediments. The cave, Südwandhöhle, is mainly formed in dolomite and many conduits have large diameters with cross sectional areas of 200 m<sup>2</sup> and more. The conduit in the lithified cave sediment is developed in the most distant parts of the cave. To date, it has been mapped over a length of 705 m, but due to the physical challenges, the continuation remains unknown.

The objective of this paper is to document the morphology of the tube and its surrounding as well as the properties of both, the dolomite host rock and the lithified cave sediment. On the basis of these results, it is assumed that the most probable cause of development is due to piping and mechanical weathering, following dissolution in the initial phase.

## 2. CAVE SETTING

The Dachstein karst massif is the second largest in the Northern Calcareous Alps (NCA), with an area of 576 km<sup>2</sup>. Its peak, Hoher Dachstein, reaches 2995 m a.s.l. (Behm et al., 2016; Figure 1). The entire mountain range and the vast plateau area are mainly composed of Upper Triassic limestone of the Dachstein Formation (Fm), which reaches thicknesses of up to 1.5 km. It is underlain by Middle Triassic dolomite of the Wetterstein Fm, which only crops out in the south of the massif. The base of this sequence is the aquiclude Lower Triassic Werfen Fm which consists of silt to sandstone, marls and impure limestone. Due to faulting it crops out a few tens of me-

tres below the entrance of Südwandhöhle (Figure 2). As a result of nappe stacking, Middle Triassic rocks occur below the Werfen Fm.

The Dachstein limestone is very pure and particularly rich in caves, some of them are exceptionally large. To date, 810 caves with a cumulative length of 290 km have been documented in the Dachstein Massif. The Hirlatzhöhle (no. of Austrian Cave Register 1546/7) is the longest and deepest cave, with a length of 118 km and a height difference of 1560 m (Plan et al., 2022).

However, a large cave exists that is primarily developed in dolomite, a rarity in the NCA. The Südwandhöh-



Figure 1: Extent of Südwandhöhle (yellow) with the tube in the lithified sediment (red) in relation to the surface. Inset shows the location (red star) within the Northern Calcareous Alps (NCA), Austria and neighbouring countries.

le (No. 1543/28; UTM 33N: 395 157 / 5 257 994) opens 0.9 km SSE and 1.2 km below the summit at the foot of the impressive south wall of the Dachstein at 1831 m a.s.l. The cave was discovered in 1886 and in 1910 around 400 m of passages were thoroughly surveyed (Bock, 1913). Only in 1980, climbing a chimney brought the breakthrough and vast spacious parts were discovered but not properly surveyed. In 2001, members of the Upper Styrian

Caving Club started a systematic survey and discovered many new passages (Seebacher, 2006, 2012). So far, 11.6 km have been mapped in this complex and challenging cave with a depth of 509 m.

Most known parts of the cave developed under phreatic or epiphreatic conditions. However, deep vadose canyons have cut into some of the tubes, creating keyhole profiles up to 80 m high. So far, only some of the vadose canyons and shafts, which reach depths of up to 120 m, have been explored.

Only the parts close to the entrance are developed in limestone of the Wetterstein Fm. They are characterised by small tubes and paragenetic and vadose canyons, with cross-sectional areas ranging from 1 to 10 m<sup>2</sup>. However, most parts of the Südwandhöhle are developed in dolomite of the Wetterstein Fm, which in some parts is present as dolomite cataclasite. Most galleries in the dolomite are much larger, with passage cross sections ranging up to 250 m<sup>2</sup>. In addition to being primarily developed in dolomite, the cave is notable for its overburden. As some passages reach below the summit area of Hoher Dachstein, the maximum thickness of the rock above the cave is 1.5 km, which is the highest recorded value in the Eastern Alps. In some places, there are several tens of metres of the glacier on top of it (Figure 1).

### 3. STUDY SITE

The tube in the lithified cave sediment is located in the north-eastern most part of the cave (Figure 1 and 2). This area of the cave system is characterised by fewer branches in contrast to some cave sections which are more labyrinthic. The surroundings of the tube in the lithified sedi-

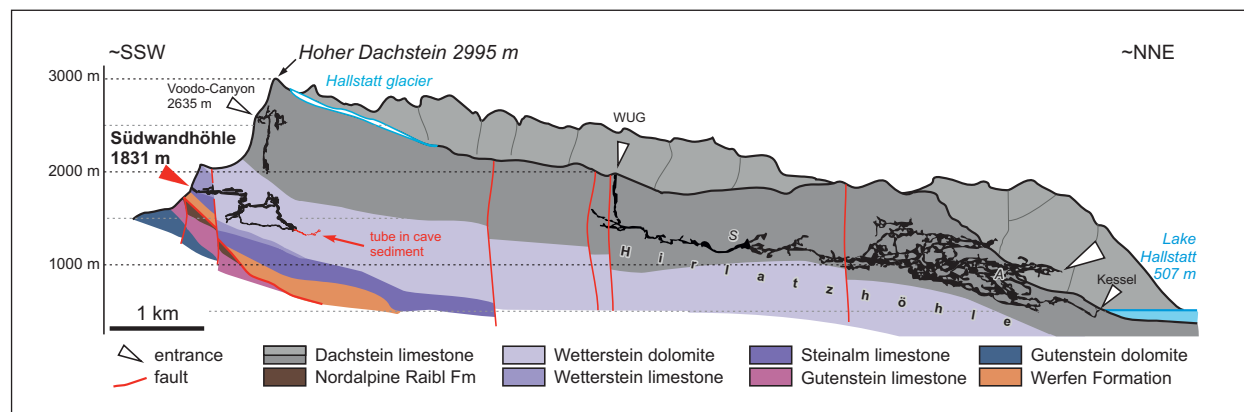


Figure 2: Generalised geological section of the Dachstein massif with the extend of major caves. WUG: What U Got Pot; S: Sahara; A: Alter Teil; Cave survey data: Caving Clubs of Hallstatt-Obertraun as well as Obersteier; Geology based on Mandl (1998). Drawing: Robert Seebacher.



Figure 3: Looking down the large Abschlundgang at its lower part, where sediments already reduce the free cross-section. Photo: Lukas Plan.

ment can be described as follows: from a big and more than 80 m high chamber, a large dimensioned passage (*Abschlundgang*) with up to 250 m<sup>2</sup> across leads steeply downhill along a fault dipping 45° to the NW (Figure 3). It gets flatter and, due to sediments covering the floor, the dimension decreases progressively until it becomes horizontal and reaches a constriction due to sandy sedi-

ments, which had to be dug out. In total this gallery leads down 230 m vertically (Figure 4).

Already in the lower section of the *Abschlundgang*, lithified fine-grained cave sediments are exposed on the floor and partly the walls. Shortly after the constriction, the dimensions widen to around 3 x 3 m and a pit at the side forms the entrance to the tube in the lithified sedi-

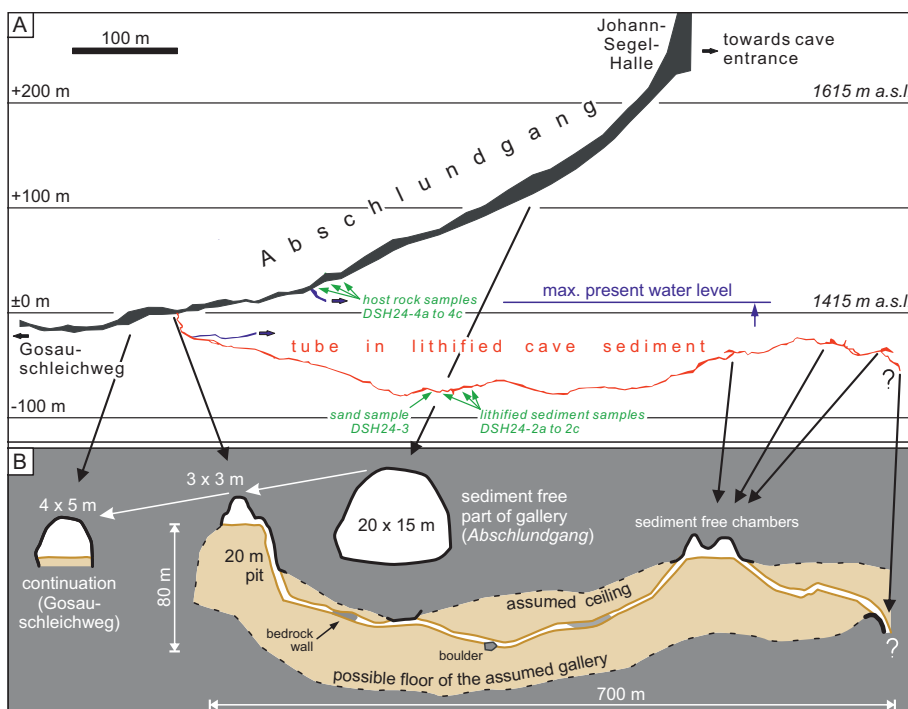


Figure 4: (A) Extended elevation of Abschlundgang and the tube in the lithified sediment. The left depth bar is relative to the beginning of the tube. (B) Schematic profile through the tube in lithified cave sediment with the assumed passage walls; grey: dolomite host rock, brown: lithified cave sediment, white: air filled (not to scale, the tube is significantly enlarged).

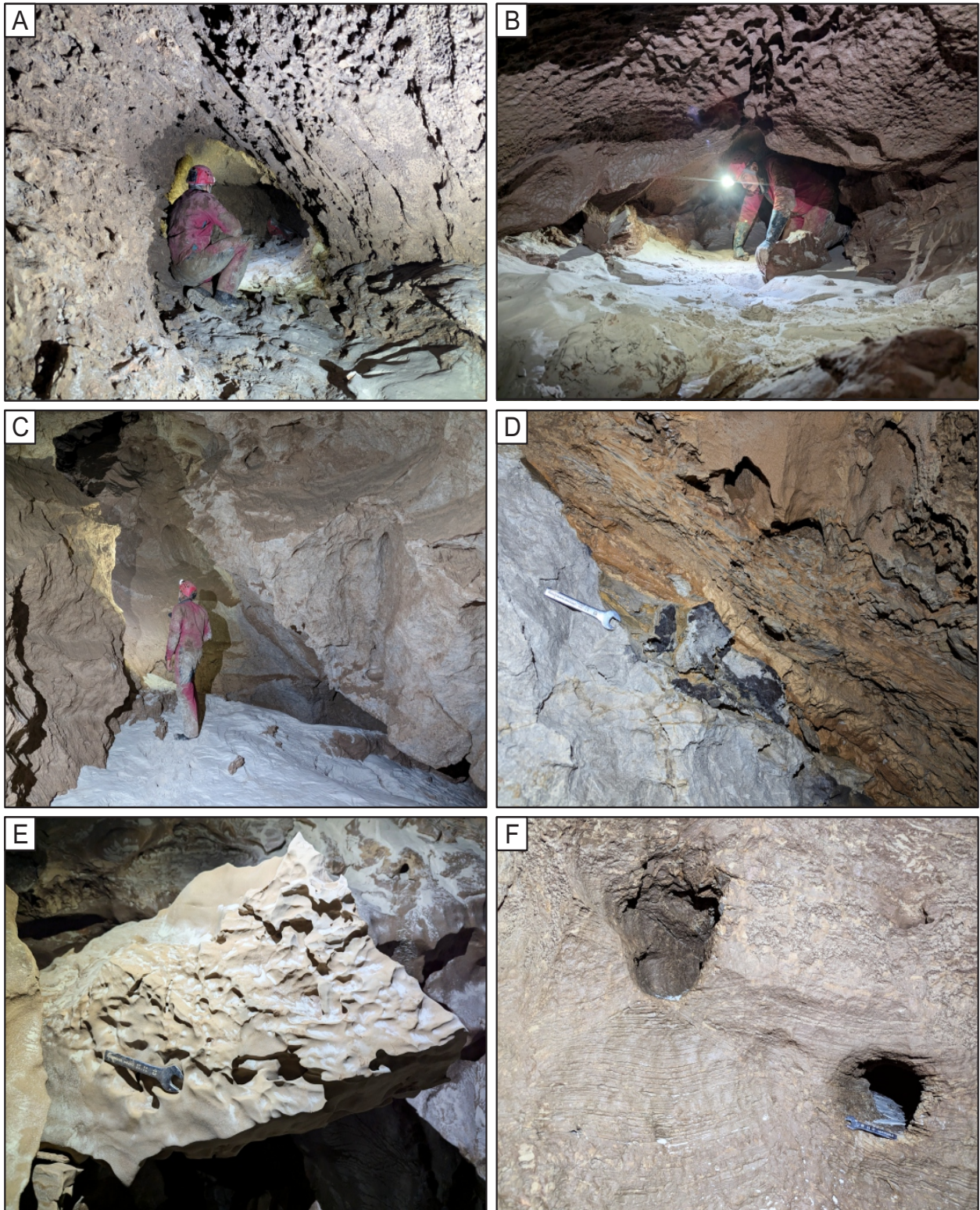


Figure 5: (A, B) Typical profiles of the tube in the lithified cave sediment; the bottom is covered with a thin layer of white dolomite sand. (C) Chamber where the tube reaches a cupola like dome in the dolomite host rock. The floor is covered with white sand. (D) Contact of the dolomite host rock and the lithified cave sediment close to the end of the known part. Note the bedding which is sub-parallel to the contact and black Fe-Mn crusts in the centre (12 cm long spanner for scale). (E) Erosional features in the sedimentary rock (episodic flow from left to right); spanner for scale). (F) Small tubes in the lithified cave sediment (note the cross-stratification; spanner for scale).

ment. With only a short side branch immediately after that, the passage (from here on called *Gosauschleichweg*) continues for 1.05 km without any branching.

The almost vertical shaft that forms the entrance to the tube in the lithified sediment is 20 m deep, whereby in the upper section only the ceiling consists of dolomite host rock and the walls of lithified cave sediment (Figure 4). The shaft then turns into a sub-horizontal tube formed entirely within the sedimentary rock (Figure 5A, B). The tube runs a bit uphill and downhill and also in plan view it shows many small curves and is more or less constantly winding. The cross-sections are only 0.5 to 2 m<sup>2</sup>, apart from a few extensions. Only about 5% of the passage walls are made of the dolomite host rock and these are mostly side walls. In some cases, dolomite boulders are exposed in the sedimentary rock or protrude from the walls. In the middle section, the passage runs for a few metres along a ceiling (?) fissure in the dolomite. In the backmost so far known section, the passage leads up-

wards three times and opens into small chambers in the dolomite host rock, characterised by chimneys and cupolas, where no traces of a former sediment filling can be seen (Figure 5C). In between and after these chambers, the tube dives back into the lithified sediment. In the current final section, the tube descends steeply and reaches the dolomite at the base of sedimentary rock (Figure 5D). The current end is an unexplored 8 m deep pit.

The length of the tube, as mapped by now, is 705 m. From the top of the entrance shaft it reaches down 80 m (forming the deepest known point of the cave system), but then extends again 60 m upwards.

The tube is still temporarily flooded and sediment marks in the *Abschlundgang* indicate a maximum water depth of up to 89 m for the deepest point between 2014 and 2024. Flow direction is to the east (into the massif) which is inferred from features eroded into the surface of the lithified sediment and sediment structures in loose silty sand (Figure 5E).

## 4. MATERIALS AND METHODS

Three samples of the dolomite host rock were taken at different places in the *Abschlundgang* (DSH24-4a to 4c; location see Figure 4). Three samples were taken from the lithified cave sediment in the middle section of the gallery close to the deepest point of the cave (DSH24-2a to 2c). Nearby, a sample of the loose white sand was taken as well (DSH24-3).

To study the structure and composition of the rocks samples, thin sections of the six samples were prepared

and partially stained with Alizarin Red S (C<sub>14</sub>H<sub>7</sub>NaO<sub>7</sub>S) and potassium ferricyanide (K<sub>3</sub>[Fe(CN)<sub>6</sub>]).

To determine the bulk mineralogical composition of five samples, X-ray diffraction (XRD) measurements were undertaken with a PANalytical PW3040/60 X'Pert PRO diffractometer (Cu K $\alpha$  radiation; 40 kV, 40 mA, step size 0.0167, 5 s per step). The interpretation was carried out with the program PANalytical X'Pert High-Score Plus.

## 5. RESULTS OF HOST ROCK AND CAVE SEDIMENT ANALYSIS

In the dolomite host rock, bedding is generally not recognisable and although faults with cataclasites are often exposed, they rarely seem to have an influence on the direction of the passage - at least over longer distances. The most prominent exception is the fault-controlled upper part of *Abschlundgang* mentioned above. The gal-

leries often run in a zigzag pattern with no recognisable dominant initial fissure. Rarely, fossils like crinoids are preserved in the dolomite.

The three host rock samples consist of dolomite with low iron content and minor calcite veins in some of the samples (DSH24-4b). The cataclastic parts are composed

Table 1: Results of XRD Analysis.

| type                    | sample no. | main components | minor components           |
|-------------------------|------------|-----------------|----------------------------|
| dolomite host rock      | DSH24-4b   | dolomite        | calcite                    |
| lithified cave sediment | DSH24-2a   | calcite, quartz | dolomite                   |
| lithified cave sediment | DSH24-2b   | calcite, quartz | dolomite                   |
| lithified cave sediment | DSH24-2c   | calcite, quartz | dolomite                   |
| white sand              | DSH24-3    | dolomite        | calcite, quartz, muscovite |

of dolomite fragments of various sizes, embedded in a matrix of fragmented dolomite or scarce secondary sparitic cement. Some veins are filled with secondary sparite, too (Figure 6A). In the one sample that was prepared for XRD (DSH24-4b), beside dolomite minor portions of calcite were detected (Table 1).

The lithified cave sediment shows light to medium brown colours. It is a calcareous sandstone with lenses of fine conglomerate, where quartz and dolomite components can reach sizes up to 1.5 cm. It also includes re-worked centimetre to decimetre sized clasts of siltstone and claystone. The rock is well lithified and poorly lith-

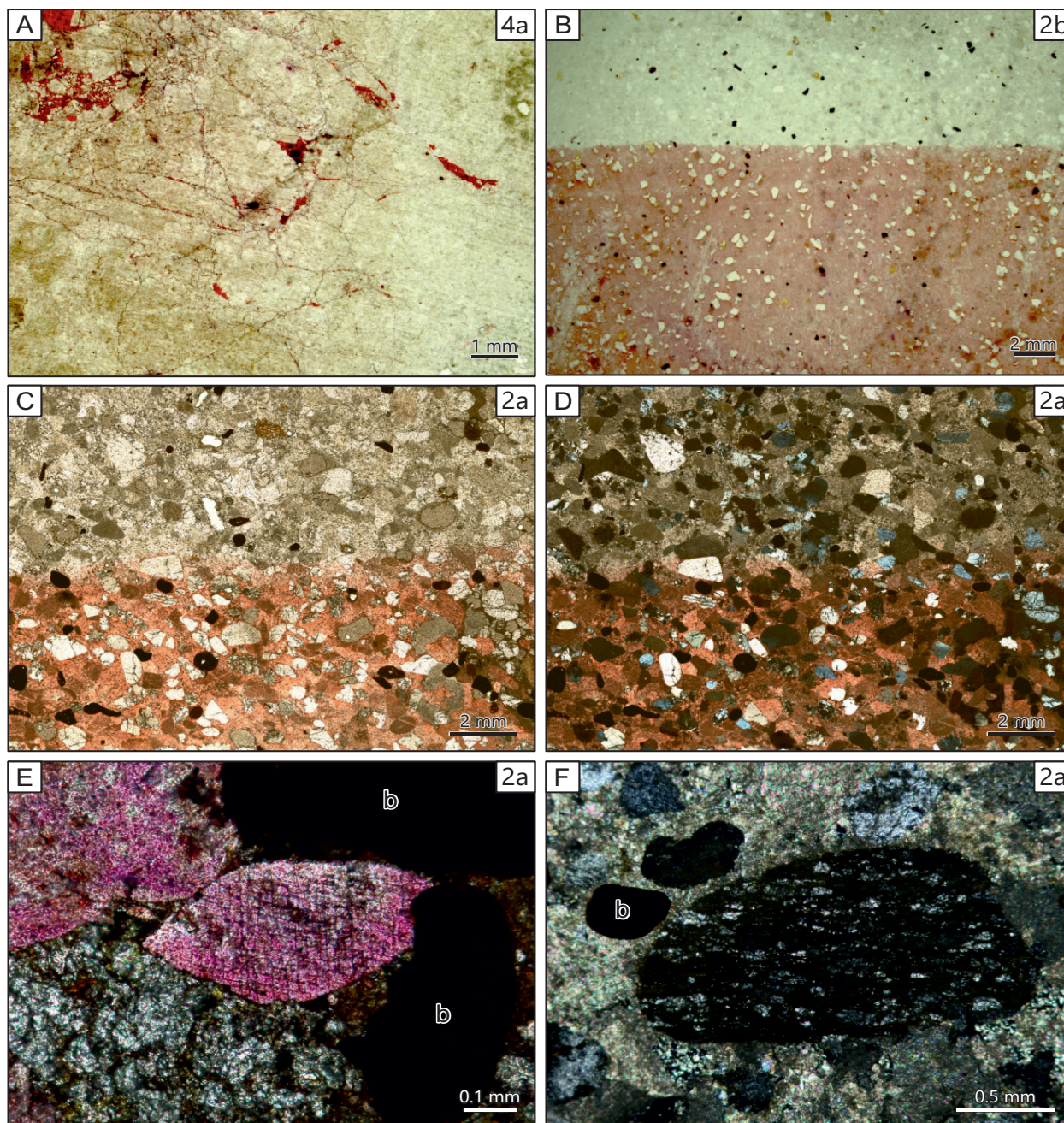


Figure 6: Thin-section photomicrograph. (A) The dolomite host rock after staining with Alizarin Red S. Only few veins appear red indicating calcite; Sample DSH24-4a (PPL). (B-D) Lithified cave sediments. Only the lower parts are stained with Alizarin Red S. Coarse sand grains composed of mainly calcite, quartz, dolomite, and opaque components are cemented by calcite. (B) Sample DSH24-2b (PPL). (C) DSH24-2a (PPL). (D) Same section part as C but under cross polarized light (XPL). (E) Detail of a grain with rhombohedral pattern that appears red when stained with Alizarin Red S. It is interpreted as dedolomite. Two opaque grains (marked with b) are interpreted as Pseudo-Bohnerze (PPL). (F) Detail of a lithic fragment (XPL).

ified parts have not been observed. The sedimentary rock often shows bedding and elongated finger-like structures. The freshly exposed surfaces show dissolution features like small holes and elongated openings.

As visible in the thin sections (Figure 6), the calcareous sandstone consists of angular to rounded calcite / limestone components, mostly (sub-)rounded mono and polycrystalline quartz components, and few mostly rounded to sub-rounded dolomite grains. Some components that are coloured red in the stained parts of the thin sections, show the rhombohedral patterns typical for dolomite, and can therefore be interpreted as dedolomite (Figure 6E). Lithic fragments, such as phyllites and pelites are scarce (Figure 6E). Further some dark brown to black grains up to 1 mm in diameter are presumably iron-hydroxides, which make up around 5% in some thin sections (DSH24-2a). These iron-hydroxides are common in caves of the NCA and are termed Pseudo-Bohnerze (Seemann, 1979).

The components are encased in sparry calcite cement, in some cases embedded in an iron-bearing clayey matrix. From the stained thin sections, it can be estimated that about half of the sandstone consists of calcite (components and matrix). XRD analysis confirms the

dominance of calcite and quartz, as well as the presence of small amounts of dolomite (Tab. 1).

Concerning the overall composition and in order to make assumptions about the karstification properties, the rock can be classified as “impure dolomitic calcarenite” as it has 10 to 50% of insoluble impurities (quartz grains and clayey matrix) and 10 to 50% detrital calcite grains (De Waele & Gutierrez, 2022: 19).

As already mentioned, the surface of the calcareous sandstone often shows features indicative for mechanical erosion such as elongated scallop-like carvings (Figure 5B and E) also known as scour marks (Lundberg, 2012). At a few places small hollows in the ceiling (Figure 5B) and tubes with some centimetres in diameter can be observed (Figure 5F).

The only unconsolidated fine-grained sediment in the tube in the lithified cave sediment is white sand (Figure 5A, B, C, and E). It generally occurs in the deepest parts of Südwandhöhle (below about 1450 m), most of which lie in the recent epiphreatic zone. It is a well-sorted silty fine sand, up to several decimetres in thickness. It consists almost exclusively of dolomite and smaller portions of calcite, quartz, and muscovite as revealed in the XRD analysis (Table 1).

## 6. INTERPRETATION AND DISCUSSION

The composition of the lithified siliciclastic sediment and its occurrence on the floor and walls of *Abschlundgang* make it clear that this sedimentary rock is not part of the stratigraphic sequence of the NCA. Further at some places, where the contact of the lithified sediment and the dolomite is exposed, layers of Fe-Mn crusts can be seen (Figure 5D), which are common at walls of phreatic galleries in caves of the NCA (Gruber et al., 2023). Siliciclastic cave sediments with similar composition but different granulometric composition and lithification (e.g. layers of poorly lithified, coarse sand), can be observed in many parts of Südwandhöhle and can reach thicknesses of several metres. The Lower Triassic Werfen Fm at the base of the stratigraphic sequence of the NCA, can contain siliciclastic sandstones, but they differ in composition and, of course, diagenesis. According to Tollmann (1976: 57) the sandstones of the Werfen Fm are bright and consist of quartz with significant amounts of muscovite and feldspar.

Also, the size of some quartz grains, measuring up to 1.5 cm, speaks against the Werfen Fm being the source rock of the cave sediment. Quartz or quartzite are absent from the stratigraphic sequence of the NCA above the Lower Triassic Werfen Fm up to the so-called Augen-

stein Fm (Frisch et al., 2001), which was deposited in the Upper Eocene to Oligocene. These are fluvial gravels and sands which were deposited on top of the NCA or in very old, more elevated caves (above around 2000 m a.s.l.) and later washed into caves at a lower elevation like Südwandhöhle (Holzer et al., 2025). According to Frisch et al. (2001, 2002) the source rocks of the Augenstein Fm are weakly metamorphosed Palaeozoic sedimentary rocks and volcanic rocks dominated by quartz, which occur to the south of the NCA. Also, the few lithic fragments observed in the thin sections derive from weakly metamorphosed rocks.

The Pseudo-Bohnerze frequently occur on the surface of the Dachstein and in many caves, mostly originating from fissure fillings predating the caves (Seemann, 1979). Consequently, they offer no insight into the origin of the cave sediments.

Therefore, the source for the calcareous sandstone can only be sediments that were transported through the Südwandhöhle and partially deposited there. From the geometry of the tube and the observations concerning the lithified cave sediment in relation to the original cave walls consisting of dolomite, the most obvious interpre-

tation is that the tube runs in a big gallery that was once completely sediment-filled, except for some cupola-like ceiling features (Figure 5B). It can be either a branch or the continuation of the spacious *Abschlundgang*.

Cave passages that are created by the re-emptying of cave sediment - both unconsolidated and lithified - are very common. However, they usually run between the top of the cave sediment and the bedrock ceiling. This position is due to the fact that the former profile was not fully filled with sediment, or that voids were created between the sediment and the bedrock ceiling due to compaction of the sediment. This so-called paragenesis (or antigravitative erosion) leads to special dissolutional features like ceiling pendants, -meanders or -canyons (e.g. Pasini, 2009; Farrant & Smart, 2011). Sometimes passages are created between the sediment and bedrock side walls of the cave, especially due to canyons in the vadose zone, or pits are excavated by waterfalls splashing on the sediment.

However, the described tube in the lithified cave sediment in Südwandhöhle at most parts does not run along any bedrock cave wall at all, but for most of its course completely in the sedimentary rock without any relation to a cave wall.

The first big question is what could have served as the initial pathway for the waters forming the tube. Neither sedimentary structures nor inhomogeneities that could have led to enhanced porosity and flow focusing can be traced over long distances, nor are there any active faults that could have acted as initial fissures within the sandstone. This makes it difficult to understand why the more than 0.7 km long tube has not formed at the dolomite-sandstone contact and the associated inhomogeneity that could have acted as initial fissure.

One possible explanation would be that the sediment was cemented by calcium-rich pore water from the surrounding dolomitic bedrock walls, leaving non or less lithified sediment in the interior of the gallery (Figure 7). The necessary calcium carbonate could derive from the Dachstein limestone, which lies a few 100 m above the Wetterstein dolomite and is around 1 km thick (Figure 2).

The second big question is the mechanism of formation: was it a mechanical process, dissolution, or both. From a compositional point of view the sandstone can be classified as impure dolomitic calcarenite. Most authors agree that more than 10 to 30% of insoluble impurities like clay minerals and quartz in carbonate rocks form no or little endokarstic features. The reason is that the dispersed fine particles will clog the protoconduits (e.g. Ford & Williams, 2007: 28; De Waele & Gutierrez, 2022: 144). Therefore, the predominant enlargement of the conduit by solely dissolution - like in a classical karst cave - is unlikely. If the above-described process of lithification of the sediment towards the centre played a role, water might have flowed through the less lithified sand and dissolved the carbonate particles forming an initial conduit.

Presently the walls of the tube are made of well-lithified sandstone. The surface rather shows mechanical erosion features like scour marks (Figure 5E) than dissolutional features. Therefore, dissolution does not appear to be the main mechanism in the further evolution of the tube. However, due to the calcite content of about 40 to 70%, some degree of dissolution is likely. In a later stage also mechanical erosion and piping of the predominantly sandy sediment played the dominant role. At least in recent times, the white dolomite sand that accumulates on the ground in the shadow of the current could be responsible for the mechanical erosion. Similar white carbonate sands are also common in the episodically flooded parts of Hirlatzhöhle (e.g. *Alter Teil, Sahara*; Figure 1; Plan et al., 2022). They can be dominated by limestone or dolomite components and a glacial origin is assumed (Holzer et al., 2025).

Similar processes have been identified as being responsible for the formation of extensive cave systems in silica-rich rock formations, such as the 26 km-long Krem Puri cave in Meghalaya, India (Sauro et al., 2020). Detailed geochemical and morphological analyses revealed that, in its early stages, speleogenesis is mainly guided by the dissolution of carbonate-rich layers. This allows the

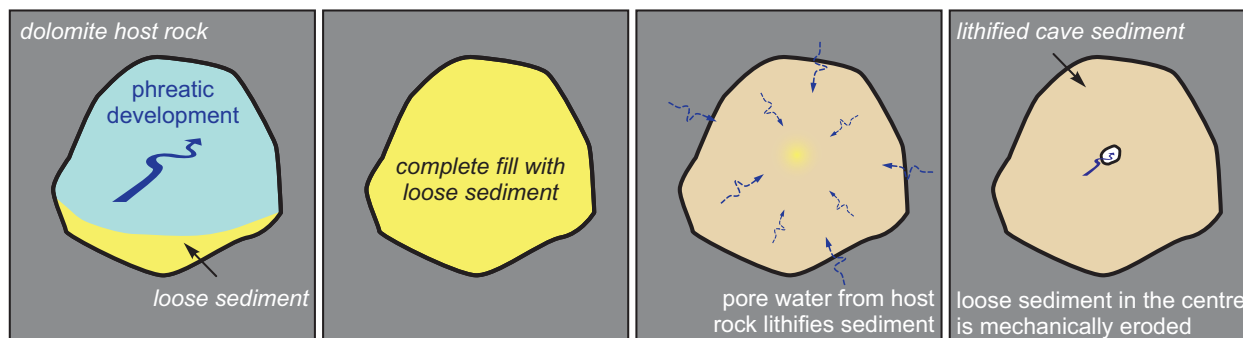


Figure 7: Sketch of the evolution of the tube in the sandstone within the passage in dolomite host rock due to partial lithification due to pore waters from the host rock.

piping of residual quartz grains, and subsequently, the enlargement of sandstone layers with less calcite.

While in other areas high precipitation appears to be an important factor in the formation of caves in poorly soluble rock, (e.g. Martini, 2000; Sauro et al., 2020), in the Dachstein, the potentially high hydraulic gradient could have been important for both, creating an initial conduit and enlargement by mechanical erosion. With the summit at almost 3000 m a.s.l. and the Lake Hallstatt acting as a base level at 508 m, the Dachstein has a large potential hydraulic gradient of 2.5 km. While it is unlikely that the entire range was active, Pleistocene glaciations could still have had a significant impact on the hydraulic gradient. During the Last Glacial Maximum, the Enns Glacier in the south of the Dachstein summit reached slightly above 2000 m a.s.l. (Van Husen, 1987), which is approximately 200 m above the current cave entrance. Water from the Enns Glacier could have flooded the cave, and if the Traun Glacier in the north reached 1600 m a.s.l., as reconstructed by Van Husen (1987), this results in a gradient of 0.4 km. Stages of ice accumulation or degradation could have led to differences in ice elevation and to even higher hydraulic gradients.

Another feature of the tube is the relatively uniform cross-section of 0.5 to 2 m<sup>2</sup> over a length of 0.7 km. This is unusual for karst caves - at least in the NCAs. This may be explained by the fact that mechanical erosion is more

likely to trigger feedback processes that regulate the diameter than dissolution. Higher flow velocities in areas with smaller cross-sections lead to increased erosion, compensating for the reduced area and contributing to the homogenisation of cross-sections over the entire length.

As far as the composition of the sandstone is concerned, it is striking that calcite components dominate, while dolomite components are subordinate, as the host rock of the Südwandhöhle consists mainly of dolomite. One explanation could be that the calcite components are actually dedolomite (e.g. Schoenherr et al., 2018), but only a few grains have been identified in thin section, which could possibly be dedolomite. For the dedolomitization calcium sulphate rich waters are necessary. They could have originated from the Werfen Fm that often hosts gypsum and crops out close to the present cave entrance.

To our knowledge, no such tubes in lithified fine-grained cave sediment, at least with a comparable length, have been described so far. The Humpleu-Poienita Cave System in the Bihor mountains is the second longest cave in Romania (Häuselmann, 2019, 2025). Häuselmann (pers. comm.) reported large galleries in cave sediment from the remote parts (*Amphitheater*) of this cave. However, it rather looks like it is just dried and unconsolidated fine-grained cave sediment, but detailed observations were not carried out.

## 7. CONCLUSIONS

According to our interpretation a big (several tens of square metres) phreatic gallery in the remote parts of Südwandhöhle was filled with sediment. This sand is dominated by calcite clasts, quartz and minor portions of dolomite and was later cemented by calcite. The total calcite content is about 40 - 70% in the analysed thin sections. In this calcareous sandstone, a more than 0.7 km long tube with rather uniform cross-sectional areas of 0.5 to 2 m<sup>2</sup> has formed. Outstandingly it has not formed between the top of the sediment and the cave ceiling but mainly independent from the original cave walls in dolo-

mite host rock. Therefore, it is particularly difficult to explain the formation of the initial conduit. The most likely explanation is that Ca-rich pore water from the dolomite host rock caused lithification - especially between the walls and the sediment - but left some less lithified parts in the interior. Dissolution of the calcitic sand grains followed by mechanical erosion, eventually some piping and some dissolution created the tube. If our interpretation, that dissolution only played a limited role in the creation of the tube, is correct, the tube is a pseudokarst cave within a karst cave.

## ACKNOWLEDGMENTS

Heidrun Andre and Andreas Glitzner were involved in exploration and surveying of the tube. For scientific discussion we thank Sven Bauer, Jiri Bruthans, Philipp

Häuselmann and Rudolf Pavuza. Francesco Sauro and an anonymous reviewer are thanked for their valuable input.

## REFERENCES

- Behm, M., Plan, L., Seebacher R., Buchegger, G., 2016. Dachstein. In: Spötl, C., Plan, L., Christian, E. (Eds.), *Höhlen und Karst in Österreich*. OÖ-Landesmuseum, Linz pp. 569–588.
- Bernatek-Jakiel, A., Poesen, J., 2018. Subsurface erosion by soil piping: significance and research need. *Earth-Science Reviews* 185: 1107–1128.
- Bock, H., 1913. Die Höhle in der Dachstein-Südwand. – In: Bock, H. Lahner, G., Gaunersdorfer, G. (Eds.): *Höhlen im Dachstein*, Graz, pp. 52–59.
- De Waele, J., Gutiérrez, F., 2022. Karst hydrogeology, geomorphology and caves. Wiley, Chichester, 888 p. <https://doi.org/10.1002/9781119605379>
- Eberhard, R.S., Sharples, C., 2013. Appropriate terminology for karst-like phenomena: the problem with ‘pseudokarst’. *International Journal of Speleology* 42 (2): 109–113. <https://doi.org/10.5038/1827-806X.42.2.2>
- Farrant, A.R., Smart, P.L., 2011. Role of sediment speleogenesis; sedimentation and paragenesis. *Geomorphology*, 134: 79–93. <https://doi.org/10.1016/j.geomorph.2011.06.006>
- Ford, D.C., Williams, P., 2007. *Karst Hydrogeology and Geomorphology*. John Wiley & Sons, Chichester, 562 pp.
- Frisch, W., Kuhlemann, J., Dunkl, I., Székely, B., 2001. The Dachstein paleosurface and the Augenstein Formation in the Northern Calcareous Alps - A mosaic stone in the geomorphological evolution of the Eastern Alps. *International Journal of Earth Science*, 90: 500–518. <https://doi.org/10.1007/s005310000189>
- Frisch, H., Kuhlemann, J., Dunkl, I., Székely, B., Vennemann, T., Rettenbacher, A., 2002. Dachstein-Altfläche, Augenstein-Formation und Höhlenentwicklung – die Geschichte der letzten 35 Millionen Jahre in den zentralen Nördlichen Kalkalpen. *Die Höhle* 53: 1–36.
- Gruber, B., Plan, L., Gier, S., Neuhuber, S., Bethke, K., Birgel, D., 2023. Schwarze Sedimente in ostalpinen Karsthöhlen. *Die Höhle*, 74: 95–115.
- Halliday, W.R., 2004. Piping caves and badlands pseudokarst. In: Gunn, J. (Ed.), *Encyclopedia of Caves and Karst Science*. Fitzroy Dearborn, New York, pp. 589–593.
- Häuselmann, P., 2019. Bihor Mountains: Humpleu–Poinita Cave System. In: Ponta, G., Onac, B. (Eds.), *Cave and Karst Systems of Romania*. Cave and Karst Systems of the World. Springer, Cham, pp. 347–355. [https://doi.org/10.1007/978-3-319-90747-5\\_40](https://doi.org/10.1007/978-3-319-90747-5_40)
- Häuselmann, P., 2025. Humpleu cave, Romania: 23 years of (waiting for) remapping: done! Proceedings of the 19<sup>th</sup> International Congress of Speleology, Vol. 4, pp. 175–179.
- Holler, C., 2019. Pseudokarst. In: White, W., Culver, C., Pipan, T. (Eds.), *Encyclopedia of Caves*. 3 ed. Elsevier B.V., pp. 836–849. <https://doi.org/10.1016/B978-0-12-814124-3.00101-1>
- Holzer, F., Plan, L., Gier, S., 2025. Constructing a cave sediment stratigraphy for the Dachstein Massif sheds light on landscape evolution (Eastern Alps). *The Depositional Record*, 2025: 1–30. <https://doi.org/10.1002/dep2.70028>
- Klimchouk, A., 2004. Caves. In: Gunn, J. (Ed.), *Encyclopedia of Caves and Karst Science*. Fitzroy Dearborn, New York, pp. 203–205.
- Lundberg, J., 2012. Karren, Cave. In: White, W.B., Culver D.C. (Eds.), *Encyclopedia of caves*. 2nd ed., Elsevier, Amsterdam, pp. 419–425. <https://doi.org/10.1016/B978-0-12-383832-2.00059-1>
- Mandl, G.W., 1998. Profile zur geologischen Karte der Dachsteinregion. – Geologische Bundesanstalt, Wien.
- Martini, J.E.J., 2000. Quartzite caves in Southern Africa. In: Klimchouk, A., Ford, D.C., Palmer, A., Dreybrodt, W. (Eds.), *Speleogenesis: Evolution of karst aquifers*. National Speleological Society, Huntsville, pp. 458–461.
- Pasini, G., 2009. A terminological matter: paragenesis, antigravitative erosion or antigravitational erosion? *International Journal of Speleology*, 38 (2): 129–138. <https://doi.org/10.5038/1827-806X.38.2.4>
- Plan L., Buchegger G., Kaminsky E., Koltai G., Racine T., Szczygiel J., 2022. Flow regime evolution of a major cave system in the Eastern Alps (Hirlatzhöhle, Dachstein). *International Journal of Speleology*, 51: 181–191. <https://doi.org/10.5038/1827-806X.51.3.2433>
- Sauro, F., Mecchia, M., Tringham, M., Arbenz, T., Columbu, A., Carbone, C., Pisani, L., DeWaele, J., 2020. Speleogenesis of the world's longest cave in hybrid arenites (Krem Puri, Meghalaya, India). *Geomorphology*, 359: 107160. <https://doi.org/10.1016/j.geomorph.2020.107160>
- Schoenherr, J., Reuning, L., Hallenberger, M., Lüders, V., Lemmens, L., Biehl, B.C., Lewin, A., Leupold, M., Wimmers, K., Strohmenger, C.J., 2018. Dedolomitization: review and case study of uncommon mesogenetic formation conditions. *Earth-Science Reviews*, 185: 780–805. <https://doi.org/10.1016/j.earscirev.2018.07.005>
- Seebacher R., 2006. Aktuelle Forschungen in der Süd-

- wandhöhle (Dachsteinloch, 1543/28), Stmk/OÖ. Die Höhle, 57: 76–89.
- Seebacher, R., 2012. Aktueller Forschungsstand in der Südwandhöhle (Dachsteinloch) (1543/28). Mitteilungen des Vereines für Höhlenkunde in Obersteier, 29-31: 197–199.
- Seemann, R., 1979. Die sedimentären Eisenvererzungen der Karstgebiete der Nördlichen Kalkalpen. Annalen des Naturhistorischen Museums Wien, 82: 209–289.
- Tollmann, A., 1976. Analyse des klassischen nordalpinen Mesozoikums. Stratigraphie, Fauna und Fazies der Nördlichen Kalkalpen, Bd. 2. – Deuticke, Wien, 580 pp.
- Van Husen, D., 1987. Die Ostalpen und ihr Vorland in der letzten Eiszeit (Würm). map 1:500.000, Geologische Bundesanstalt, Wien.
- Wray, R.A.L., Sauro, F., 2013. An updated global review of solutional weathering processes and forms in quartz sandstones and quartzites. Earth-Science Reviews, 171: 520-557. <https://doi.org/10.1016/j.earscirev.2017.06.008>.