Annales Societatis Geologorum Poloniae (2021), vol. 91: 363–373 doi: https://doi.org/10.14241/asgp.2021.19

ORIGIN OF FINE-GRAINED CLASTIC SEDIMENTS IN CAVES OF THE HOHER GÖLL MASSIF (THE NORTHERN CALCAREOUS ALPS, AUSTRIA)

Ditta KICIŃSKA

Institute of Geology, Adam Mickiewicz University
Bogumiła Krygowskiego 12, 61-680 Poznań, Poland
e-mail: kicinska@amu.edu.pl

Kicińska, D., 2021. Origin of fine-grained clastic sediments in caves of the Hoher Göll massif (the Northern Calcareous Alps, Austria). *Annales Societatis Geologrum Poloniae*, 91: 363–373.

Abstract: The Hoher Göll Massif is situated 20 km south of Salzburg and belongs to the Northern Calcareous Alps (Austria). It is a ridge ca. 11 km long and 3 km wide with the highest summit Hoher Göll (2522 m a.s.l.), encircled by deeply incised valleys with bottoms ca. 2,000 m below it. Cave clastic deposits were studied in the Hochschartehöhlensystem, Dämchenhöhle and Hintere caves. The caves belong to the Giant Cave Level, with the exception of part of the Hochschartehöhlensystem, that is Der Sprechender Steine Cave, the highest parts of which belong to the Ruin Cave Level. The sources of the cave sediments have been identified from the composition of the heavy fractions. Preliminary studies of the Hoher Göll caves reveal that the cave fills were derived from the Oligocene to earliest Miocene Augenstein Formation, the deposits of the Palaeo-Inn River and the siliciclastic basal strata of the Northern Calcareous Alps. The clastic material deposited as the Augenstein Formation was transported from southern parts of the Eastern Alps and by the Palaeo-Inn river from their western part. According to heavy minerals, the sources of the clastic material were on the Palaeozoic terrains, the post-Palaeozoic sequence, and the Middle Austroalpine Unit. Later, during or after the mountain uplift, weathered materials from the Augenstein and Palaeo-Inn deposits were eroded and transported from the surface into caves by allogenic streams. Some of the sediments were likely to have been transported later to the Giant Cave Level from the southern part of the Northern Calcareous Alps.

Key words: Cave sediments, heavy minerals, Augenstein Formation, Northern Calcareous Alps.

Manuscript received 9 November 2020, accepted 25 October 2021

INTRODUCTION

Caves preserve sediments that are derived from geological processes at the surface. Clastic cave sediments represent an important source of information, not only about the phases of cave evolution and the direction of palaeoflow, but also on the palaeoclimatic conditions, the development and incision of valleys, and the palaeogeographical/geomorphic evolution of mountains (Bosch and White, 2004; Springer, 2005; Ford and Williams, 2007; Sasowsky, 2007; White, 2007; Bella *et al*., 2021). The mineralogical composition of these sediments indicates the alimentation zone and the transport direction (e.g., Hercman, 1986; Mange and Mauer, 1992; Morton and Hallsworth, 2007; Ford and Williams, 2007; Palmer, 2007).

In contrast to the large mountains of the Northern Calcareous Alps (NCA), there have been relatively few scientific studies in the Hoher Göll Massif caves. In the 1970s, hydrogeological studies were carried out for the Federal Agency for Water Management (Klappacher and Knapczyk, 1979). As part of a wider study performed at the same time, two samples of clastic sediments were collected from the Grubernhornhöhle cave; they contained amphibole, muscovite, and garnet (Klappacher and Knapczyk, 1979).

Modern research on the genesis and evolution of karst systems in the Northern Calcareous Alps has been conducted by Frisch *et al.* (2001), Audra *et al.* (2002, 2007), Plan and Decker (2006), Spötl *et al.* (2007), Meyer *et al.* (2009), Plan *et al.* (2009) and Dertnig *et al.* (2017). According to Frisch *et al.* (2001) and Audra *et al.* (2002), the clastic sediments in the NCA massifs indicate that a frequent source is the so-called Augenstein Formation (AF) or locally eroded deposits that have disappeared from the plateau. Sediments of the AF commonly are found in the Northern Calcareous Alps, both at the surface and redeposited in caves, e.g., in the caves of the Dachstein, Tennengebirge and Hochschwab massifs (Frisch *et al.*, 2001; Audra *et al.*, 2002; Plan and Decker, 2006). The Augenstein Formation consists of sandstones and conglomerates (Simony, 1851; Götzinger, 1913; Winkler-Hermaden, 1957; Frisch *et al.*, 2001). It was formed on the subsided Dachstein palaeosurface in the Oligocene to earliest Miocene, when the western part of the Northern Calcareous Alps was a mountainous landscape. This area served as the area of alimentation, from which clastic materials were transported by rivers (Augenstein rivers) from the south to the north and east, while the central and eastern parts of the Northern Calcareous Alps subsided (Brügel, 1998; Frisch *et al.*, 1998, 2000, 2001). According to Frisch *et al.* (2001) and Audra *et al.* (2002), these sediments later were eroded and transported northeastwards, where currently quartz, iron oxides and coarse-grained gravels with rounded iron-oxide nodules are found. In the western part of the Eastern Alps, there was the Palaeo-Inn river system, which in its lower course followed the Inntal Fault. Its formation was initiated in the Oligocene and the main activity took place in the Miocene (Ortner and Sachsenhofer, 1996). The Palaeo-Inn River transported crystalline material from the Middle Austroalpine basement and from the Periadriatic volcanic chain (Frisch *et al*., 2001).

The aim of this work is to present a study of the cave sediments in the Hoher Göll Massif and a reconstruction of the alimentation area of the cave sediments, based on heavy mineral analysis. The results obtained add new information about the extent of occurrence of the Augenstein Formation and the Palaeo-Inn sediments and also the palaeogeography of this part of the Northern Calcareous Alps in the Palaeogene and Neogene. It should be emphasized that these are preliminary studies of the cave sediments in the Hoher Göll Massif.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Hoher Göll Massif is located in the Berchtesgaden Alps, some 20 km to the south of Salzburg City (Fig. 1). The massif is ca. 11 km long and 3 km wide, with the highest peak the Hoher Göll (2,522 m a.s.l.). The altitude difference between the highest peaks and valley bottoms reaches 2,000 m. The Hoher Göll Massif is limited by the Weissenbachtal Valley in the north, the Bluntautal Valley in the south, the Salzach Valley in the east and Königssee Lake and the Königsseeache River in the west. The central and eastern parts of the massif are drained by the Schwarzbachfall/Gollinger Wasserfall karst spring (Fig. 2). The entire karst covers an area of ca. 25 km^2 (Klappacher and Knapczyk, 1979).

The Hoher Göll Massif, as a part of the Northern Calcareous Alps, belongs to the Austroalpine mega-unit of the Eastern Alps (Tollman, 1980; Froitzheim *et al*., 2008; Fig. 1). The mega-unit is made up of Late Carboniferous to Eocene sedimentary sequences (Tollman, 1980; Pfiffner, 2014). The massif is composed of Mesozoic rocks, mostly Middle and Upper Triassic carbonates (Plöchinger, 1955; Bolz, 1971; Braun, 1998; Missoni, 2003) and Jurassic limestones and radiolarites in the north (Diersche, 1980; Braun, 1998). Most of the caves are developed in the Dachstein Limestone (Upper Triassic; Zankl, 1969; Klappacher and Knapczyk, 1979), which is 2 to 3 km thick.

The present-day relief of the Hoher Göll Massif was formed during the Palaeogene and Neogene uplift. Nevertheless, the late Eocene to early Oligocene Dachstein palaeosurface is still preserved, in spite of the fact that the massif is narrow and with steep slopes. The nature of the palaeosurface of the Northern Calcareous Alps has been discussed from two viewpoints: whether it represents the result of a single stage of evolution, or is polyphase in nature. Remnants of the surface are preserved only in extensive limestone outcrops (Lichtenecker, 1924; Winkler-Hermaden, 1957; Frisch *et al.*, 2001). Seefeldner (1961) recognized the remains of the Hochkönig denudation surface on the Hoher Göll peak (2,522 m a.s.l.) and the Brett-Archenkopf-Freieckkamm ridge (ca. 2,350 m a.s.l.), the Tennen denudation surface on the Umgang Kar, and the Gotzen denudation surface on the Kleiner Göll (1,752 m a.s.l.) and Grutred Kar in the massif studied.

Frisch *et al.* (2001) distinguished the Dachstein palaeosurface, that later subsided and was covered by the Augenstein Formation, with a thickness of over 1.3 km (Frisch *et al.*, 2001). Remnants of a terrestrial succession of conglomerates and sandstones are preserved on plateaus in an allochthonous situation or as re-deposited materials. The composition of the deposits indicates that the alimentation area is located in the south, mostly on Variscan terrains (Palaeozoic units, weakly metamorphosed) and the post-Variscan siliciclastic basement of the Northern Calcareous Alps (Fig. 1; Götzinger, 1913; Winkler-Hermaden, 1957; Frisch *et al.*, 2001). Frisch *et al.* (2001) also noted the transport of crystalline material from the western part of the Eastern Alps (greenschist and amphibolite facies grade of the Middlealpine units). The late Palaeogene planation surface has been faulted and uplifted since the Miocene (Linzer *et al.*, 1997; Frisch *et al.*, 1998).

Three cave levels have been identified in the Northern Calcareous Alps (Fischer, 1980; Frisch *et al.*, 2001): (1) the highest, the Ruin Cave Level (ca. 2,000 ± 300 m a.s.l.), developed during the middle Eocene and early Oligocene; (2) the Giant Cave Level (ca. 1,600 ± 500 m a.s.l.) formed in the lower Miocene, and (3) the lowest and the youngest Spring Cave Level, with active caves, dated as Pliocene and Quaternary (ca. ~800 ± 300 m a.s.l.). The cave levels were formed in periods, when uplift of this part of the Northern Calcareous Alps had ceased, therefore they might reflect individual phases of stagnation of the base levels of erosion (Frisch *et al.*, 2001; Audra *et al.*, 2002). The Hoher Göll Massif was glaciated during the Pleistocene, like the rest of the Northern Calcareous Alps (Penck, 1905; Pomper *et al.*, 2017).

A total of 351 caves are registered in the cave cadastre in the Hoher Göll Massif (unpublished data, stored in the archives of Landesverein für Höhlenkunde Speleological Club in Salzburg), including the Grubernhornhöhle cave and two caves that are 1,000 m deep: the Hochschartehöhlensystem and the Jubilaümschacht.

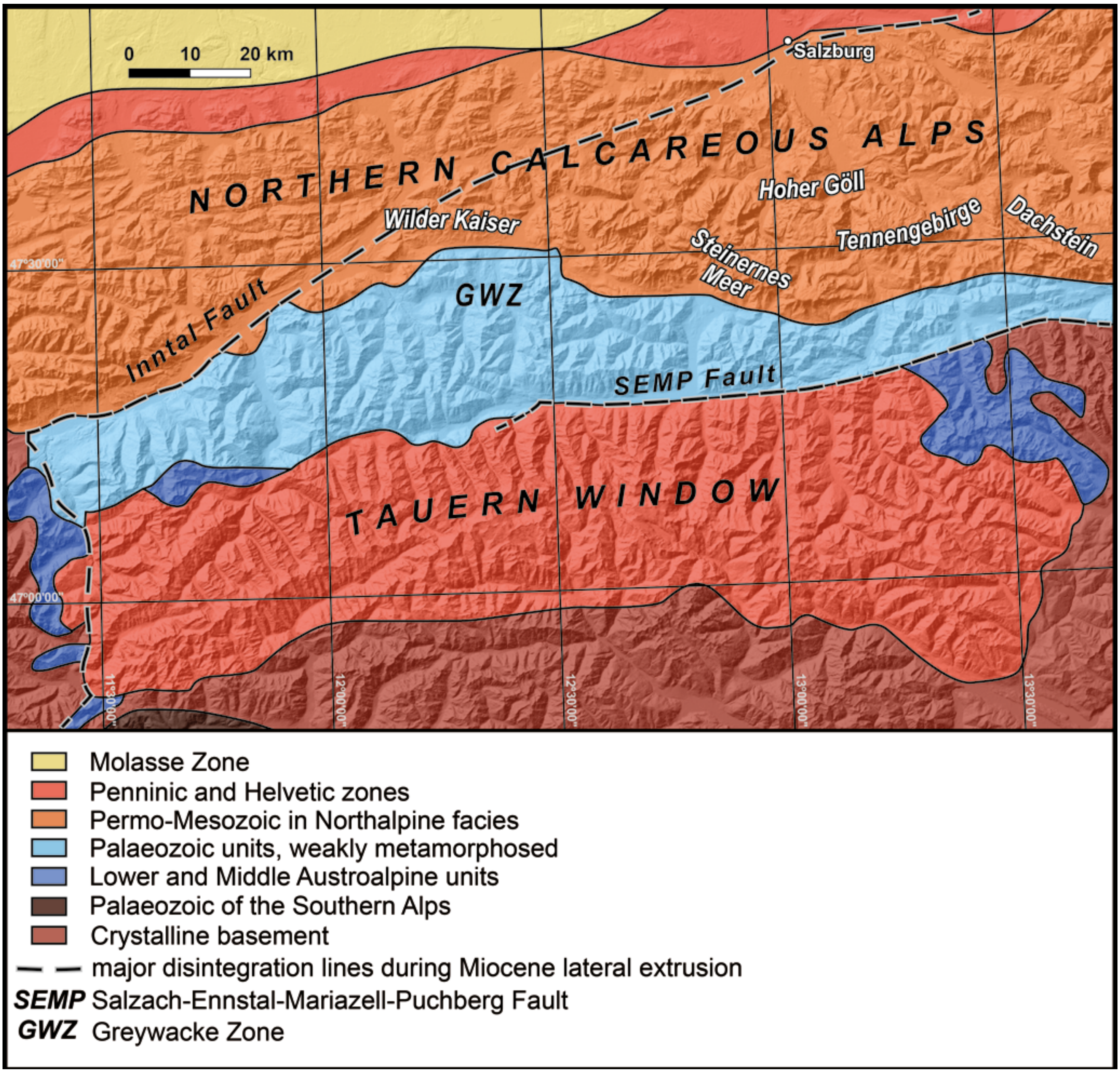

Fig. 1. Tectonic sketch of the Northern Calcareous Alps with adjacent areas and the locations discussed, after Beck-Mannagetta and Matura (1980) and Frisch and Gawlick (2003), simplified and redrawn.

The field research was carried out in the cave system of the Hochschartehöhlensystem (consisting of the Höhle der Sprechender Steine, Engstellenschacht, Kammerschartenhöhle and Unwollendeteschacht caves), the Hinterehöhle and the Dämchenhöhle caves (Fig. 3). The caves mentioned above are located in the middle part of the Hoher Göll Massif. The research was carried out in one of the highest and in the middle parts of the Hochschartehöhlensystem, i.e., in the Höhle der Sprechender Steine cave, with its entrance at 2,003 m a.s.l. The total length of the system is 14,668 m and the vertical extent is 1,394 m (Golicz, 2013). The short (76 m long) and shallow (19 m deep) Dämchenhöhle Cave is located at 1,690 m a.s.l. The entrance of the Hinterehöhle Cave is situated at 1,500 m a.s.l. The cave is 598 m long and 269 m deep (Rysiecki, 2004). The highest part of the Höhle der Sprechender Steine Cave represents the Ruin Cave Level. The other parts of the caves studied belong to the Giant Cave Level (Fig. 3).

MATERIALS AND METHODS

Sediments from allochthonous sources and rarely also autochthonous deposits are preserved in the abandoned and upper parts of cave systems in the Hoher Göll Massif as coarse- to fine-grained clastic sediments, sometimes with pebbles. The sediments are poorly sorted and mostly located in sumps, passage bottoms and in rare outcrops. In most cases, these are remnants of deposits. In the larger fraction, there is mainly the local Triassic limestone. Sediment samples were taken from the upper (Ruin; G1, G2 and G3 samples) and the

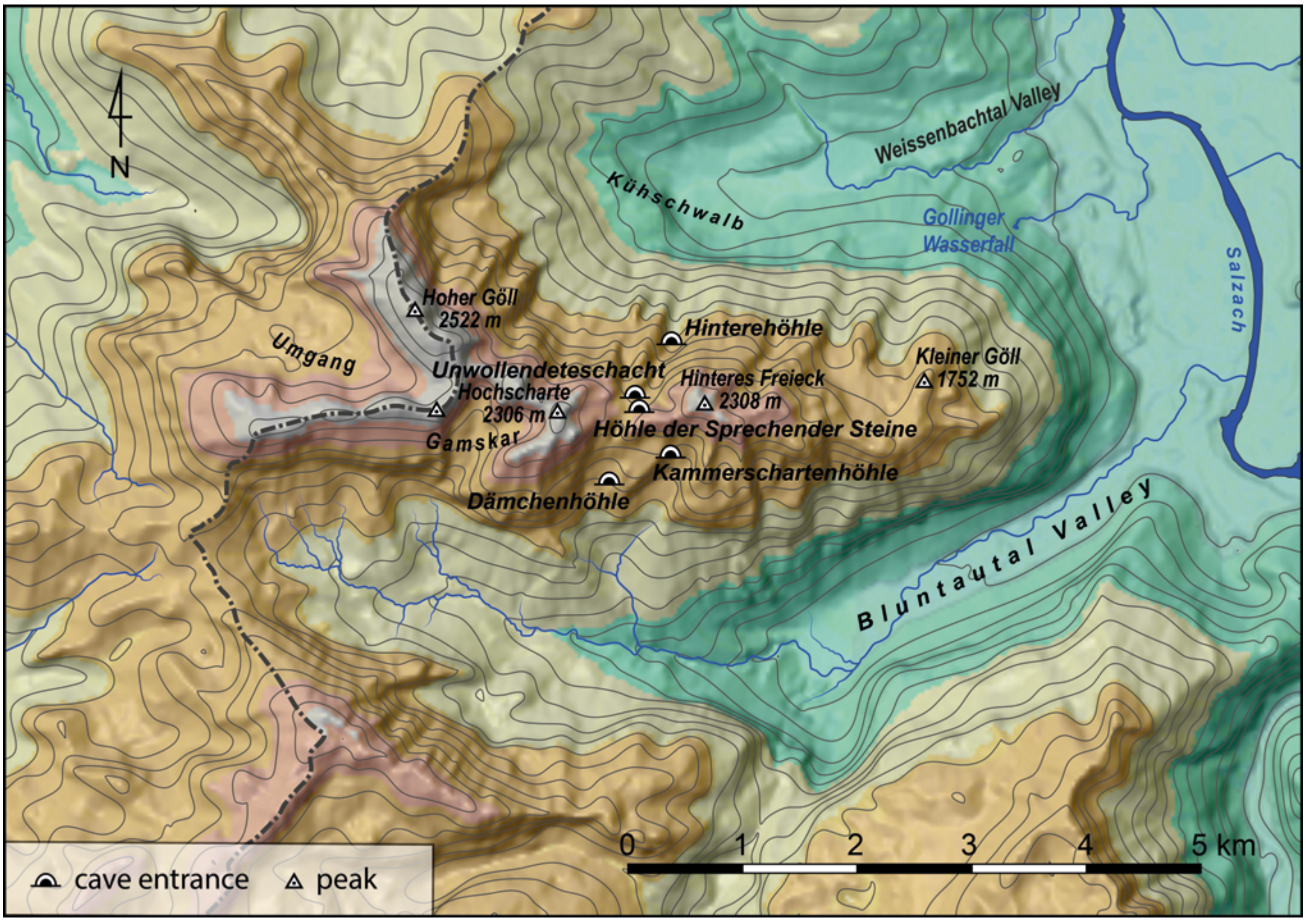

Fig. 2. The Hoher Göll Massif with locations of caves studied.

middle (Giant; K1, K2, D1, P1, P2, T1) cave levels (Fig. 3). In the Hochschartehöhlensystem, clastic sediments were sampled at six locations, that is in the Höhle der Sprechender Steine near the entrance (G1), in a short horizontal tube 80 m from the entrance (G2), and in a passage ca. 2 m high above a big pit (G3), in the Kammerschartenhöhle in the Zweiautosgang Gallery (K1) and in the Metro Passage (K2). Two samples (P1 from the near entrance part and P2 from a further part of the cave) were taken in the Dämchenhöhle and one in the Hinterehöhle (T1).

Heavy fraction analyses were performed at the Institute of Geology, Faculty of Geographical and Geological Sciences of the Adam Mickiewicz University in Poznań (Poland). The separation of heavy fractions from the grain-size fraction of 0.125 to 0.25 mm was performed in sodium polytungstate ($3Na_2WO_4$ x $9WO_3$ x H_2O) with a density of 2.85 gcm^{-1}. The analyses of the minerals were conducted on the basis of their physical and optical properties (Mange and Maurer, 1992). At least 300 transparent grains were examined in each sample.

RESULTS

The results of the heavy fraction analyses are presented in Table 1 and Figure 4. Opaque minerals predominate, particularly in the samples from the Höhle der Sprechender Steine (G1, G2, G3), Kammerschartenhöhle (K2) and Hinterehöhle (T1). Heavy minerals typical for metamorphic rocks, such as kyanite and sillimanite, occur in all samples. Andalusite was detected in samples from the Kammerschartenhöhle (K1) and the Dämchenhöhle (P1 and P2), and staurolite in those from the Kammerschartenhohle (K2), the Höhle der Sprechender Steine (G2) and the Dämchenhöhle (P2).

Zircon, tourmaline, apatite and garnet are also abundant, although different percentages of these minerals were found at the cave levels studied. For example, larger amounts of apatite were found in the sediments of the Giant Cave Level. All minerals in this group are extremely rounded. The high muscovite content is noteworthy. There is a low carbonate content in the samples analysed. In the middle cave level, there is a noticeably higher content of apatite, amphibole, biotite, and chlorite than in the sediments sampled from the upper cave level. The apatite-tourmaline index (Morton and Hallsworth, 1994), reflecting the degree of change that took place in the sediments during weathering, indicates lower values in the upper cave level.

DISSCUSION

The provenance of the minerals studied

The composition of the heavy fraction indicates allochthonous sources. The presence of heavy minerals, typical of both igneous and metamorphic rocks, such as

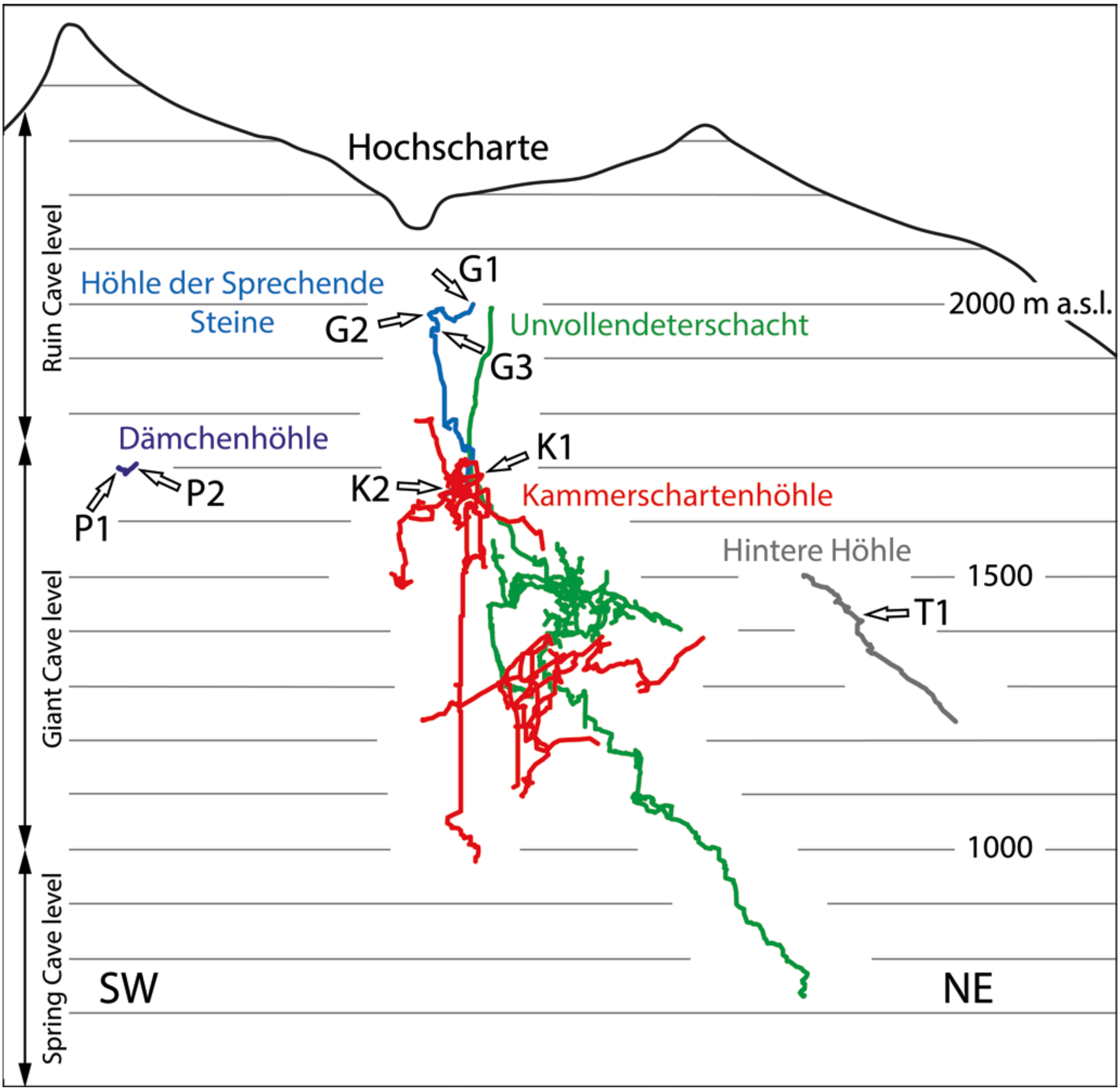

Fig. 3. Schematic cross-section of the caves studied with sampling sites of clastic deposits.

zircon, tourmaline or sillimanite and kyanite was identified in all samples. As well, staurolite occurs in sediments of the Kammerschartenhöhle cave and andalusite in the Dämchenhöhle cave (Fig. 4). Host rocks for these minerals do not occur in the close surroundings of the Hoher Göll Massif. Today, these rocks are located in the southern and western parts of the Eastern Alps.

The results of heavy fraction analyses of fine-grained clastic sediments in caves of the Hoher Göll Massif confirm studies of the Northern Calcareous Alps, which were carried out by Frisch *et al.* (2001). The research of these authors included an analysis of heavy minerals from sediments, known as the Augenstein Formation, found at the surface. Frisch *et al.* (2001) noted zircon, tourmaline, rutile, garnet, hornblende, apatite, and epidote in the massif of the Northern Calcareous Alps studied (e.g., Tennengebirge, Hochkönig, Dachstein). However, kyanite and garnet have been found only in the westernmost occurrences (Wilder Kaiser and Steinernes Meer Massifs). Garnet was also found in the eastern part of the Northern Calcareous Alps. According to these authors, the sources of the Augenstein Formation could have been the Palaeozoic (Variscan) units, which are composed of the Greywacke Zone and the siliciclastic basal strata of the Northern Calcareous Alps (the Late Carboniferous to Scythian). The Greywacke Zone contains slates, phyllites and metapyroclastics that rest on conglomerates with pebbles of orthogneiss (Hoschek *et al.*, 1980; Pfiffner, 2014).

On the basis of the composition of the heavy minerals and pebbles in gravels/conglomerates and zircon and apatite fission-track data, Frisch *et al.* (1998, 2001) reconstructed the geomorphological evolution of the Northern Calcareous

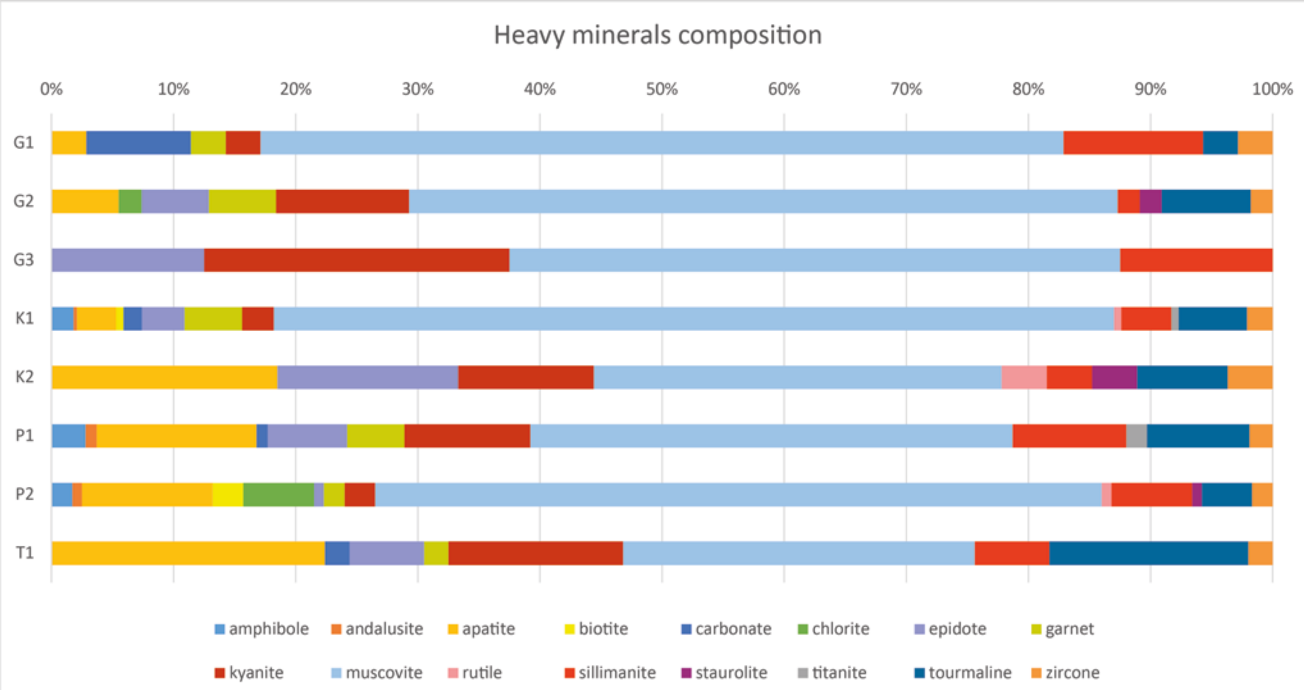

Fig. 4. Composition of heavy minerals.

Alps during post-Eocene time. In the late Oligocene, the western part of the Northern Calcareous Alps had mountainous relief with strong erosion, while the eastern part represented a depositional basin (Brügel, 1998; Frisch *et al.*, 1998, 2000, 2001). The eroded materials were carried northward and eastward by the Augenstein and Palaeo-Inn rivers and were deposited on the Dachstein palaeosurface, which is of late Eocene to early Oligocene age (Winkler-Hermaden, 1957; Frisch *et al.*, 1998, 2001).

Sediments transported from the south were composed of a terrestrial succession of conglomerates and sandstones, known as the Augenstein Formation with a thickness of over 1.3 km, according to the thermochronology of Frisch *et al.* (2001). The Augenstein Formation probably was deposited between ca. 30 and 20 Ma owing to the beginning of the end of orogenic processes (Kuhlemann, 2000). Frisch *et al.* (2000, 2001) suggested late early Miocene as the uppermost limit for the age of the Augenstein Formation, which means the time, when the rivers transporting material over long distances ceased to be active. At this time, the transport of sediments became impossible because of longitudital faulting south of the Northern Calcareous Alps (the Salzach-Ennstal-Mariazell-Puchberg Fault, Fig. 1). The faulting cut the transport of sediments from the alimentation area and caused dissection of the Dachstein palaeosurface by valleys. It should be also mentioned that the E-W extension in the Eastern Alps was estimated to have attained 50% (Brügel, 1998; Frisch *et al.*, 1998, 2000). Recently, sediments of the Augenstein Formation are preserved mainly in an allogenic setting; only formation remnants occupy an autochthonous setting. According to Frisch *et al.*, (2000, 2001) and Kuhlemann *et al.* (2006), autochthonous remnants comprise the lowest and the oldest part of the Augenstein Formation.

Frisch *et al.* (2001, p. 509) proved that in the western part of the Northern Calcareous Alps, "the westernmost Augenstein area shared Middle Austro-Alpine units with the Inntal Tertiary in its the source terrains, where Scythian quartzites and garnetiferous basement schists were exposed". In the case of heavy minerals typical for metamorphic rocks, the authors indicated that their origin was from the Middle Austroalpine Unit in the western part of the NCA. These rocks locally were subjected to Eo-Alpine (Cretaceous) metamorphism, up to greenschist and ampfibolite facies (cf. Hoinkes *et al.*, 1999).

Later, the Augenstein and Palaeo-Inn sediments were weathered, transported further north and east and trapped in caves of the Northern Calcareous Alps. With respect to the conclusions of Frisch *et al.* (2001), the alimentation area of allogenic cave sediments in the Hoher Göll Massif was located both in the southern and western parts of the Northern Calcareous Alps (Fig. 5). The materials analysed contain minerals typical for igneous and metamorphic rocks, which confirms the early studies of Frisch *et al.* (2001). The presence of minerals typical of metamorphic rocks (staurolite, kyanite and sillimanite) should be emphasized; they indicate the direction of palaeoflow from the southwest and/or the west. These minerals are characteristic of the amphibolite facies, which indicates a direction of palaeotransport from the Middle Austroalpine rocks.

In summary, the composition of heavy minerals indicates that the terrestrial materials were transported by allogenic Augenstein rivers from the south and Palaeo-Inn rivers from the southwest and/or the west. According to Frisch *et al.* (1998, 2001), this took place before the early late Miocene, when the catchment area of the Palaeo-Inn River was reduced, owing to the exhumation of the Tauern Window.

The above data show transport of the Hoher Göll cave sediments from distant source areas and indicate that the palaeotransport of these materials could have taken place in a different topographic configuration of the Eastern Alps.

The composition of the heavy fraction in the lower parts (the Giant Cave Level) of the caves studied may indicate two sources of the material. In the sediments of this level, the presence of both the above mentioned and larger amounts of unstable minerals, such as apatite or amphibole, were found. After the formation of the lower level, it may have been filled with Augenstein and Palaeo-Inn sediments, both redeposited from the upper level of the cave system and from the surface. This higher content of apatite and amphibole also may be related to their transport from nearby areas. The origin of these minerals could be associated with occurrences of the Lower Triassic siliciclastics, located in the southern part of the Northern Calcareous Alps (Fig. 1; Permo-Mesozoic in the Northalpine facies). These siliciclastics belong to the Alpine Buntsandstein in the western part of the Northern Calcareous Alps and to a major extent the Werfen Formation (Stingl, 1984). A minor occurrence of the Werfen Formation is located in the Bluntautal Valley (southern part) and a larger one in the southern parts of the carbonate massif adjacent (the Hagengebirge Massif) to the southern part of the Hoher Göll Massif (Klappacher and Knapczyk, 1979). According to Krainer (1987) the presence of such heavy minerals as apatite, tourmaline, zircon, and garnet is typical for the Lower Triassic siliciclastics. These rocks probably were more widespread in the past. The author did not mention amphibole among the identified minerals, which does not exclude its presence in the Werfen Formation, but it requires more detailed research.

Ratios of apatite to tourmaline (index ATi) may also prove the differentiation of sediments from the caves studied (see Morton and Hallsworth, 1994). The index ATi is an important provenance-sensitive parameter, which provides a lot of important information about the history of transport (Morton and Hallsworth, 1999). The index values for the minerals analysed from the Ruin Cave Level are lower than for those from the Giant Cave Level (Tab. 1). According to Morton and Hallsworth (1994, 1999), weathering at the source could have reduced the proportion of apatite to tourmaline and the loss of

Table. 1

Amounts of opaque and translucent heavy minerals and apatite:tourmaline index ATi)
from sediments in caves of the Hoher Göll Massif

Sample	G1	G2	G3	K1	K2	P1	P2	T1
opaque minerals	86.0	85.1	96.2	52.4	91.4	80.1	74.7	89.3
translucent minerals	14.0	14.9	3.8	47.6	8.6	19.9	25.3	10.7
amphibole	-	-	-	1.8	-	2.8	1.7	-
andalusite	-	-	-	0.3	-	0.9	0.8	-
apatite	2.7	5.5	-	3.2	18.5	13.1	10.7	22.4
biotite	-	-	-	0.6	-	-	2.5	-
carbonates	8.1	-	-	1.5	-	0.9	-	2.0
chlorite	-	1.9	-	-	-	-	5.8	-
epidote	-	5.5	12.5	3.5	14.8	6.5	0.8	6.1
garnet	2.7	5.5	-	4.7	-	4.7	1.7	2.0
kyanite	8.1	10.9	25.0	2.6	11.1	10.3	2.5	14.3
muscovite	62.2	58.1	50.0	68.8	33.4	39.5	59.5	28.8
rutile	-	-	-	0.6	3.7	-	0.8	-
sillimanite	10.8	1.8	12.5	4.1	3.7	9.3	6.6	6.1
staurolite	-	1.8	-	-	3.7	-	0.8	-
titanite	-	-	-	0.6	-	1.7	-	-
tourmaline	2.7	7.3	-	5.6	7.4	8.4	4.1	16.3
zircone	2.7	1.8	-	2.1	3.7	1.9	1.7	2.0
Index ATi	50.0	43.0	-	63.3	71.4	60.0	72.0	58.0

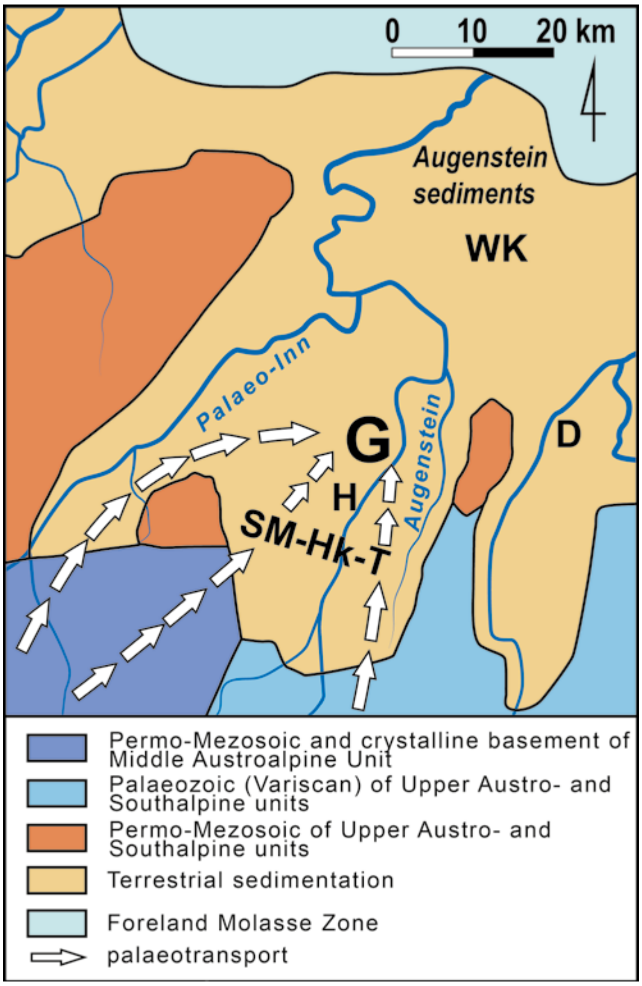

Fig. 5. Palaeogeography of Augenstein and Palaeo-Inn river deposition in the Late Oligocene after Frisch *et al.* (2001, simplified and redrawn) including the results of research in caves of the Hoher Göll Massif. Massifs: G – Hoher Göll, H – Hagengebirge, SM-Hk-T – Steinernes Meer, Hochkönig, Tennengebirge.

apatite during near-surface weathering conditions could have taken place, for example, in the source terrain in time periods of alluvial storage and at the depositional site, in fluvial systems. Such conditions may have occurred during the weathering and transport of the Oligocene sediments from uplifted areas in the south and southwest of the Northern Calcareous Alps, accumulated as Augenstein and Palaeo-Inn deposits and subsequently subjected to further weathering, erosion, and transport to the north and northeast. Higher values of the ATi index for the heavy minerals of the Giant Cave Level may indicate that the sediments were subjected to weathering for a shorter period of time.

The composition of heavy minerals at the Giant Cave Level indicates that they could have entered into the cave in a different palaeogeographical situation. Part of these minerals in the sediments could be linked to deglaciation, but probably they already had been transported to the surface in the vicinity of the cave system. Material from the Lower Triassic siliciclastics had to be transported from the south before incision of the Bluntautal Valley (Fig. 2).

All samples contain a high muscovite content. The content of this mineral is higher in samples taken from the upper part of the cave system (the Ruin Cave Level). This material could be related to the sources, located both in the western and southern parts of the Northern Calcareous Alps, from which the material studied was eroded. The low carbonate content is a small proportion of autogenous material. This means that there was no long-distance transport within the carbonate rocks. Most of the transport took place outside the caves. It should be added that zircon fission-track data could provide more information on the source of the sediments in Hoher Göll Massif caves, e.g., from the Periadriatic volcanic chain (Frisch *et al.*, 2001).

Cave levels and their clastic sediments

The highest part of the Hochschartehöhlesystem belongs to the oldest and inactive Ruin Cave Level, occurring at ca. 2,000 ± 300 m a.s.l. in the NCA (Fischer, 1990; Frisch *et al.*, 2001). The level developed during the middle Eocene and early Oligocene (Fischer, 1990; Frisch *et al.*, 2001) includes the upper part of the Hochschartehöhlensystem (Höhle der Sprechender Steine). The ATi index indicates an origin from an area with a long-lasting depositional history (e.g., Bosák, 1989). The presence of more weathered material in the upper level of caves in the Tennengebirge Massif (adjacent to the Hoher Göll Massif) was noted by Audra *et al.* (2002). A similar trend was observed in studies of cave clastics in the Tatra Mts. in Poland (cf. Kicińska *et al.*, 2017). Allogenic sediments transported into the cave systems often reflect changes, for example, in cycles of weathering, transport and re-transport or the tectonic regime before entry into the cave systems.

The period of the oldest inflow into the highest part of cave systems in the Northern Calcareous Alps could have been in the upper Miocene or even earlier. The latest research of Häuselmann *et al.* (2020) indicates that the cosmogenic-nuclide dating of clastic sediments from the Hirlatz Cave in the Dachstein Massif and the Schaflschacht cave in the Tennengebirge Massif shows ages of 6.6 Ma. These massifs are adjacent to the study area. Therefore, by analogy it might be assumed that the palaeotranport of clastic sediment into the Höhle der Sprechender Steine happened at the same time. The above information indicates that the material studied in the Ruin Cave Level represents remnants of the Augenstein Formation and the Palaeo-Inn sediments, its weathering products, which later were re-transported into the caves.

A high percentage of opaque minerals in the samples analysed indicates the high weathering rate (cf. Van Loon and Mange, 2007). These sediments require further research. The weathered materials from the Augenstein Formation and the Palaeo-Inn presumably were reworked several times during the Cenozoic. These materials were subjected to various processes, as evidenced also by soil research in this area. Until the middle Miocene, the Augenstein Formation was subjected to weathering in subtropical climatic conditions, which contributed to the formation of reddish-brown soils (Solar, 1964). Red clay from palaeosoils were formed (Kuhlemann *et al.*, 2008): (1) during the Palaeogene and early Miocene, when the tropical or subtropical weathering of crystalline host-rocks caused kaolinite formation, and (2) during the late Miocene and early Pliocene with high precipitation and temperate weathering conditions on uplifting plateaus in the Northern Calcareous Alps.

The palaeogeographic situation also had to be different during the formation of the Giant Cave level (at ca. 1,600 ± 500 m a.s.l.) with numerous big galleries (Zweiautosgang and Metro) of the Kammerschartenhöhle part of the Hochschartehöhlensystem. Large scallops (70 cm in diameter) were observed in the Dämchenhöhle near its entrance and somewhat smaller ones (30–55 cm in diameter) also were found in the Kammerschartenhöhle between the Sauerland Passage and the Amphitheatre Chamber. Large passages with large scallops and their weathered surfaces indicate slow palaeoflow of substantial water volumes during long periods of stable climatic and tectonic conditions. It is unlikely that these forms could have developed in a modern palaeogeographic situation. Similar observations in the extensive passages of the Eisriesenwelt Cave (the Tennengebirge Massif) were described by Audra *et al.* (2002).

The Giant Cave Level was formed during the late Miocene (Frisch *et al.*, 2001; Audra *et al.*, 2002). The youngest limit for the Augenstein Formation deposition is late early Miocene, owing to the displacement of the Northern Calcareous Alps to form individual massifs by faulting (Frisch *et al.*, 1998, 2000, 2001; Linzer *et al.*, 1997). Therefore, the transport of the Augenstein Formation and the Palaeo-Inn sediments to the Hoher Göll Massif and adjacent areas should have been active before the faulting and block displacement. Later, the transport of these sediments into passages of the Hochschartehöhlesystem took place at the time of vadose development of the Giant Cave Level. The same alimentation area for both the Ruin and Giant cave levels is indicated by minerals derived from the Augenstein and Palaeo-Inn sediments. However, the mixture of the deposits mentioned above and higher contents of such minerals as apatite or amphibole in the cave sediments of the Giant Cave Level may indicate a second source of materials. The less resistant minerals may have come from the siliciclastics of the Werfen Formation, located in the southern part of the Northern Calcareous Alps. A small part of this formation occurs also in the Bluntautal Valley. It is likely that there were more occurrences of this formation in the past. Furthermore, this source closer to the study area would later be exposed from beneath the overburden rocks.

Part of this material probably was transported into the caves during glacial melting through vadose invasion down vertical shafts and chimneys. The presence of larger amounts of these minerals in the lower part of the cave system and their absence or occurrence in lower amounts in the upper level prove that at later stages they were not transported into the passages of the upper level (cf. Häuselmann *et al.*, 2020).

CONCLUSIONS

Although the Hoher Göll Massif is not an extensive flat plateau like the Tennengebirge, Hagengebirge or Totes Gebirge massifs, traces of the Dachstein palaeosurface with occurrences of the Augenstein Formation are preserved. In cave sediments of the Hoher Göll Massif, remnants of the Palaeo-Inn sediments also were found, which proves that material was transported into the massif studied, not only from the south, but also from the west or the southwest. According to Frisch *et al.* (2001), the source area for these materials is the Palaeozoic terrains (Greywacke Zone and its equivalents), the siliciclastic base of the Northern Calcareous Alps, and the Middle Austroalpine unit. All the sources mentioned have found in the cave sediments of the Hoher Göll Massif.

On the basis of heavy mineral composition, it is considered that clastic material in cave sediments of the Hoher Göll Massif was transported (1) from the western part of the Eastern Alps by the Palaeo-Inn River with source areas in the Middle Austroalpine unit, and (2) from the southern part of the Eastern Alps by the Augenstein rivers from the Variscan and post-Variscan terrains. The composition of the heavy minerals sampled from the Giant Cave Level probably points to a closer source, possibly sediments of the Werfen Formation. These results complement the data on the palaeogeography of this area in the Palaeogene and Neogene. However, these are preliminary studies and more exact interpretations require further studies of the cave sediments of the Hoher Göll Massif.

Three general cave levels were developed in the Hoher Göll Massif. The oldest level includes the Der Sprechender Steine Cave and belongs to the Ruin Cave Level. As in other carbonate plateaus in the Northern Calcareous Alps, the largest caves, big chambers, and passages were developed at the middle Giant Cave Level. The youngest and active caves include the Schwarzbachfall/Gollinger Wasserfall and Schönbachquelle karst springs. The levels reflect the base level of erosion and were created in periods, when uplift of the Northern Calcareuos Alps had ceased (cf. Audra *et al.*, 2002). The number of cave levels could be related to the palaeosurfaces with some modifications that were distinguished by Seefeldner (1961). This would require extended studies for the whole massif, especially the cave systems occurring in its eastern part.

Acknowledgements

The author thanks the Landesverein für Höhlenkunde in Salzburg Club and in particular Walter Klappacher and Gerhard Zehntner for help and the Department of Nature Conservation in the Federal State Government Salzburg (Amt der Salzburger Landesregierung, Abteilung Naturschutz) for permission; the colleagues from the clubs (Wielkopolski Klub Taternictwa Jaskiniowego from Poznań and Katowicki Klub Speleologiczny in Katowice), who assisted during the field work; Anthony Moult for correcting the English text; Krzysztof Najdek, Mateusz Golicz and Miłosz Dryjański for preparing the figures and basic morphometrics; and Helena Hercman, Michał Gradziński and Jacek Szczygieł for constructive comments and helpful suggestions. I am especially grateful to the reviewers Dorota Salata and Pavel Bosák for constructive comments and helpful suggestions that significantly improved the final manuscript.

REFERENCES

Audra, P., Bini, A., Gabrovsek, F., Häuselmann, P., Hoblea, F., Jeannin, P. Y., Kunaver, J., Monbaron, M., Sustersic, F., Tognini, P., Trimmel, H. & Wildberger, A., 2007. Cave and karst evolution in the Alps and their relation to paleoclimate and paleotopography. *Acta Carsologica*, 36: 53–67.

Audra, P., Quinif, Y. & Rochette, P., 2002. The genesis of the Tennengebirge karst and caves (Salzburg, Austria). *Journal of Cave and Karst Studies*, 64: 153–164.

Beck-Mannagetta, P. & Matura, A., 1980. *Geologische Karte von Österreich 1:500 000 – 1 Bl., Farbdruck*. Geologische Bundesanstalt, Wien.

Bella, P., Gradziński, M., Hercman, H., Leszczyński, S. & Nemec, W., 2021. Sedimentary anatomy and hydrological record of relic fluvial deposits in a karst cave conduit. *Sedimentology*, 68: 425–448.

Bolz, H., 1971. Die Zlambach-Schichten (alpine Obertrias) unter besonderer Berücksichtigung der Ostracoden, 1: Ostracoden der Zlambach-Schichten, besonders Bairdiidae. *Senckenbergiana Lethaea*, 52: 129–283.

Bosák, P., 1989. Clays and sands in paleokarst. In: Bosák, P., Ford, D. C., Głazek, J. & Horáček, I. (eds), *Paleokarst, A Systematic and Regional Review*. Academia, Praha, pp. 431–442.

Bosch, R. F. & White, W. B., 2004. Lithofacies and transport of clastic sediments in karstic aquifers. In: Sasowsky, I. D. & Mylroie, J. E. (eds), *Studies of Cave Sediments.* Kluwer Academic/Plenum Publishers, New York, pp. 1–22.

Braun, R., 1998. *Die Geologie des Hohen Gölls. Torrener-Joch-Zone/Jenner/Hoher Göll eine durch Kontinent/Kontinent-Kollision ausgelöste Gleitdecke in den auglbodenschichten (mittlerer Oberjura) der Berchtesgadener Alpen. Nationalpark Berchtesgaden, Forschungsbericht*, 40. Plenk, Berchtesgaden, 192 pp.

Brügel, A., 1998. Provenance of alluvial conglomerates from the East Alpine foreland: Oligo-Miocene denudation and drainage evolution of the Eastern Alps. *Tübinger Geowissenschaftliche Arbeiten, Reihe A*, 40: 1–168.

Dertnig, F., Stüwe, K., Woodheadb, J., Stuart, F. M. & Spötl, C., 2017. Constraints on the Miocene landscape evolution of the Eastern Alps from the Kalkspitze region, Niedere Tauern (Austria). *Geomorphology*, 299: 24–38.

Diersche, V., 1980. Die Radiolarite des Oberjura im Mittelabschnitt der Nördlichen Kalkalpen. *Geotektonische Forschunge,* 58: 1–217.

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

Ford, D. C. & Wiliams, P. W., 2007. *Karst Geomorphology and Hydrology*. Unwin Hyman, London, 601 pp.

Frisch, W. & Gawlick, H. J., 2003. The nappe structure of the central Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion – a contribution to understanding the orogenic evolution of the Eastern Alps. *International Journal of Earth Sciences*, 72: 712–727.

Frisch, W., Kuhlemann, J., Dunkl, I. & Brügel, A., 1998. Palinspatic reconstruction and topographic evolution of the Eastern Alps during late Tertiary extrusion. *Tectonophysisc*, 279: 1–15.

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 Sciences*, 90: 500–518

Frisch, W., Székely, B., Kuhlemann, J. & Dunkl, I., 2000. Geomorphological evolution of the Eastern Alps in response to Miocene tectonics. *Zeitschrift fur Geomorphologie*, 44: 103–138.

Froitzheim, N., Plašienka, D. & Schuster, R., 2008. Alpine tectonics of the Alps and Western Carpathians. In: McCann, T. (ed.), *The Geology of Central Europe*. Geological Society, London, pp. 1141–1232.

Golicz, M., 2013. Recent activity in Hoher Göll. In: Kicińska, D. (ed.), *Polish Caving 2009–2013*. Komisja Taternictwa Jaskiniowego Polskiego Związku Alpinizmu (Caving Commision of Polish Mountaineering Association), Kraków, pp. 13–14.

Götzinger, G., 1913. Neue Funde von Augensteinen auf den östlichen Kalkhochalpenplateaus. *Verhandlungen der Geologischen Bundesanstalt*, Wien: 61–65.

Häuselmann, Ph., 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.

Hercman, H., 1986. Pochodzenie allochtonicznych osadów Jaskini Magurskiej i Kasprowej Niżnej (Tatry) w świetle analizy minerałów ciężkich. *Przegląd Geologiczny*, 34: 100–103. [In Polish.]

Hoinkes, G., Koller, F., Rantitsch, G., Dachs, E., Höck, V., Neubauer, F. & Schuster, R., 1999. Alpine metamorphism of the Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 79: 155–181.

Hoschek, G., Kirchner, E. Ch., Mostler, H. & Schramm, J. M., 1980. Metamorphism in the Austroalpine Units between Innsbruck and Salzburg (Austria) – a synopsis. *Mitteilungen der* Österreichischen *Geologischen Gesellschaft*, 71/72: 335–341.

Kicińska, D., Hercman, H. & Najdek, K., 2017. Evolution of the Bystrej Valley caves (Tatra Mts, Poland) based on corrosive forms, clastic deposits and U-series speleothem dating. *Annales Societatis Geologorum Poloniae*, 87: 101–119.

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

Krainer, K., 1987. Zusammensetzung und fazielle Entwicklung des Alpinen Buntsandsteins und der Werfener Schichten im westlichen Drauzug (Kärnten/Osttirol). *Jahrbuch Geologische Bundesanstalt,* 130: 61–91.

Kuhlemann, J., 2000. Post-colisional sediment budget of circum-Alpine basins. *Memorie dell'Istituto geologico della R. Università, Padua*, 52: 1–91.

Kuhlemann, J., Dunkl, I., Brügel, A., Spiegel, C. & Frisch, W., 2006. From source terrains of the Eastern Alps to the Molasse Basin: Detrital record of non-steady-state exhumation. *Tectonophysics*, 413: 301–316.

Kuhlemann, J., Taubald, H., Vennemann, T., Dunkl, I. & Frisch, W., 2008. Clay mineral and geochemical composition of Cenozoic paleosoil in the Eastern Alps (Austria). *Austrian Journal of Earth Sciences*, 101: 60–69.

Lichtenecker, N., 1924. Das Bewegungsbild der Ostalpen. *Naturwissenschaften*, 13: 739–743.

Linzer, H. G., Moser, F., Nemes, F., Ratschbacher, L. & Sperner, B., 1997. Build-up and dismembering of the eastern Northern Calcareous Alps. *Tectonophysics*, 272: 97–124.

Mange, M. A. & Maurer, H. F. W., 1992. *Heavy Minerals in Colour*. Chapman and Hall, London, 147 pp.

Meyer, M. C., Cliff, R. A. & Spötl, C., 2009. Speleothems from the earliest Quaternary: snapshots of paleoclimate and landscape evolution at the northern rim of the Alps. *Quaternary Science Reviews*, 26: 1374–1391.

Missoni, S., 2003. *Analyse der mittel- und oberjurassischen Beckenentwicklung in den Berchtesgadener Kalkalpen – Stratigraphie, Fazies und Paläogeographie*. PhD-Thesis University of Leoben, 150 pp.

Morton, A. C. & Hallsworth, C., 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sedimentary Geology,* 90: 241–256.

Morton, A. C. & Hallsworth, C., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology*, 124: 3–29.

Morton, A. C. & Hallsworth, C., 2007. Stability of detrital heavy minerals during burial diagenesis. In: Mange, M. A. & Wright, D. T. (eds), *Heavy Minerals in Use*. *Developments in Sedimentology*, 58: 215–245.

Ortner, H. & Sachsenhofer, R. F., 1996. Evolution of the Lower Inn Valley Tertiary and constraints on the development of the source area. *European Association of Geoscientists and Engineers*. 5: 237–247.

Palmer, A. N., 2007. *Cave Geology*. Cave Books, Dayton, Ohio, 454 pp.

Penck, A., 1905. Glacial features in the surface of the Alps. *The Journal of Geology*, 13: 1–19.

Pfiffner, O. A., 2014. *Geology of the Alps*. Wiley-Blackwell, Chichester, 377 pp.

Plan, L. & Decker, K., 2006. Quantitative karst morphology of the Hochschwab plateau, Eastern Alps, Austria. *Zeitschrift für Geomorphologie, N.F.*, 147: 29–54.

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.

Plöchinger, B., 1955. Zur Geologie des Kalkalpenabschnittes vom Torrener Joch zum Ostfuss des Untersberges; die Göllmasse und die Halleiner Halstätter Zone. *Jahrbuch der Geologische Bundesanststalt*, 3: 93–144.

Pomper, J., Salcher, B. C., Eichkitz, Ch., Prasicek, G., Lang, A., Lindner, M. & Götz, J., 2017. The glacially overdeepened trough of the Salzach Valley, Austria: Bedrock geometry and sedimentary fill of a major Alpine subglacial basin. *Geomorphology*, 295: 147–158.

Rysiecki, Z., 2004. Göll – 2004. *Jaskinie*, 36: 10–12. [In Polish.]

Sasowsky, I. D., 2007. Clastic sediments in caves – Imperfect recorders of processes in karst. *Acta Carsologica*, 36: 143–149.

Seefeldner, E., 1961. *Salzburg und seine Landschaften: Eine geographische Landeskunde*. Bergland-Verlag, Salzburg, 573 pp.

Simony, F., 1851. Beobachtungen über das Vorkommen von Urgebirgsgeschieben auf dem Dachsteingebirge. *Jahrbuch der Kaiserlich Königlichen Geologischen Reichsanstalt*, 2: 159–160.

Solar, F., 1964. Zur Kenntnis der Böden auf dem Raxplateau. *Mitteilungen der* Österreichischen *Bodenkundlichen Gesellschaft*, 8: 1–71.

Spötl, C., Offenbecher, K. H., Boch, R., Meyer, M., Mangini, A., Kramers, J. & Pavuza, R., 2007. Tropfstein-Forschung in österreichischen Höhlen – ein Überblick. *Jahrbuch der Geologischen Bundesanstalt*, 147: 117–167.

Springer, G. S., 2005. Clastic sediments in caves. In: Culver, D. & White, W. (eds), *Encyclopedia of Caves*. Elsevier Academic Press, Burlington, San Diego, London, pp. 102–108.

Stingl, V., 1984. Alpiner Buntsandstein und Werfener Schichten bei Leogang (Salzburg). *Geologisch-Paläontologische Mitteilungen Insbruck*, 14: 1–19.

Tollman, A., 1980. Geology and tectonics of the Eastern Alps (middle sector). *Abhandlungen der Geologischen Bundesanstalt*, 34: 197–255.

Van Loon, A. J. & Mange, M. A., 2007. 'In situ' dissolution of heavy minerals through extreme weathering, and the application of the surviving assemblages and their dissolution characteristics to correlation of Dutch and German silver sands. In: Mange, M. A. & Wright, D. T. (eds), *Heavy Minerals in Use*. *Developments in Sedimentology*, 58: 189–213.

White, W. B., 2007. Cave sediments and paleoclimate. *Journal of Cave and Karst Studies*, 69: 76–93.

Winkler-Hermaden, A., 1957. *Geologisches Kräftespiel und Landformung*. Springer-Verlag, Wien, 822 pp.

Zankl, H., 1969. Der Hohe Göll. Aufbau und Lebensbild eines Dachstein-Riffes in der Obertrias der nördlichen Kalpalpen. *Abhandlungen der Senckenberg Gesellschaft*, 519: 1–120.