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DIVERSITY OF DRIPSTONES IN HISTORIC ANTHROPOGENIC UNDERGROUND FACILITIES – CASE STUDY OF THE SUDETY MOUNTAINS (SW POLAND)

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Abstract: The article discusses the dripstone structures in underground anthropogenic objects in the Sudety Mts. This region provides a good model area for studying dripstones due to the great diversity of the geological structure and the nature of underground facilities. The examined objects are primarily historical mines, but also military facilities and a pumped-storage power plant in the construction phase. Based on the recognition of 23 objects, the diversity of dripstones in this area is presented – their forms, the types of minerals that compose these deposits, and the environments in which they form. Atypical forms and dripstones not previously described in the literature have been characterized, such as: crystalline splash-cups, equivalents of cave balloons composed of iron oxides, conical stalactites formed by corrosion of steel elements in subaquatic conditions or forms called here stalagmitites. Based on these observations, comments are presented on terminology used to describe dripstones formed in different environments. The introduction of the terms hypogeothem and anthropothem is proposed.

***Keywords*:** *Sudety Mts., historic mines, dripstones, caltemites, minothems, hypogeothems, anthropothems*

1. INTRODUCTION

Dripstones are an interesting subject of research, reflecting certain aspects of the dynamics of underground environments. They are an element of geo- and often also

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biodiversity. Sometimes the presence of dripstones is an indirect indication of the existence of mineral accumulations deep in the rock mass, invisible neither on the surface of the earth nor in underground structures. In the case of anthropogenic objects, they are also clear indicators of the location of significant discontinuities in the rock mass (fracture or fault zones) or building structures (gaps in concrete support), which are zones of more intensive drainage.

Dripstones have been observed and well-recognized in caves for centuries, but those occurring in anthropogenic underground objects were not the subject of much interest for a long time. It should be noted however, that in some respects, these anthropogenic environments are more diverse than cave ones. These subsurface sites differ significantly in terms of their origin and purpose, size and form, and also (very importantly) for natural reasons – geological, environmental, and biological.

The dripstones that occur in underground anthropogenic structures are very diverse. Most are identical or analogous to cave forms, although their parameters are different – e.g., wall thickness of tubular stalactites, porosity or growth rate (Hill and Forti 1997; Carbone et al. 2016; Broughton 2020; Smith 2023). There are also unique forms and minerals not found in caves, or large mineral accumulations that rarely occur in caves. The origin of the material forming the dripstones varies (natural or anthropogenic).

The presence of speleothems in anthropogenic objects has been occasionally noticed since the end of the 17th century (see: Hill and Forti 1997), in the 20th century, for decades, they were studied only sporadically, remaining in the shadow of cave structures (e.g., Ver Steeg 1932; Mackin and Coombs 1945; Beltyukov 1972). In recent years, they have been gradually attracting increasing interest. However, their systematic identification raises the need to consider certain terminological issues.

At first, the formation of such mineral accumulations takes place in artificial environments, sometimes they are formed from anthropogenic substances or those activated as a result of human activity (e.g., drivage, causing a violation of the geochemical stability of the rock mass), and moreover, they often have an amorphous structure. Therefore, they do not meet the criteria of the geological definition of a mineral (crystalline structure, natural origin). Nevertheless, in the sense of technical mineralogy, where a mineral is considered to be any crystalline or amorphous phase with specific and repeatable physicochemical characteristics, formed naturally or as a result of anthropogenic transformation of natural mineral substances (see Szymański 1997), the substances that build dripstones are called minerals and this should be considered correct.

There are also some doubts regarding the terminology of dripstones formed in man-made underground structures.

Dripstones occurring in caves are in general called speleothems (from the Greek spēlaion – cave and théma – sediment, a term introduced in the 1950s). This term covers all cave dripstones, regardless of their mineral composition, which are systematized according to their forms and chemical composition (see: Hill and Forti 1997; Onac 2012; White and Culver 2012). Due to the etymology, it obviously does not include dripstones that form outside cave environments.

Carbonate dripstones formed in artificial objects were also previously referred to as speleothems, "manmade speleothems", "non cave stalactites", "concrete speleothems" or "urban dripstones" (see: Smith 2015). Finally, Smith (2015) proposed introducing the term calthemites (from Latin calx – limestone) to refer to them, defining it first as "derived from man-made structures" and later as "derived from concrete, lime, mortar or other calcareous material". This term in the literature refers rather to dripstones made of calcium carbonate leached from carbonate binding materials and formed in structures such as bridges and tunnels (e.g., Broughton 2020; Smith 2016; 2023).

It should be emphasized, however, that in anthropogenic underground structures (or more broadly – any structures with a ceiling, vault or roof) carbonate dripstones made of mineral substances of a different origin, as well as dripstones composed of a number of other substances, also form. The latter have been much less noticed in the literature (e.g., Cabała and Bzowska 2008), although in recent years you can find, for example, works of Carbone et al. (2016) or Galliano et al. (2022). Additionally Carbone et al. (2016) proposed the name "minothems" (from Latin mine) for dripstones occurring "in any artificial underground environment".

In relation to the group of dripstones formed in man-made objects, there are therefore two specific terms. The first one covers a numerous but narrow group of one chemical type, and the second one is supposed to refer to all dripstones in anthropogenic objects, but one may wonder whether it is appropriate also for structures such as underground garages or cellars. In the author's opinion, a more adequate term may be the anthropothems (Greek: ánthropos – man), i.e., deposits created as a result of any human activity (construction of underground and above-ground structures, supply of artificial substances, activation of the circulation of natural substances). So we will include here both calthemites (Smith 2015) and minothemes (Carbone et al. 2016), "manmade speleothems", "urban dripstones" (see: Smith, 2015) etc. occuring in "artificial caves" (Hill and Forti 1997). And, to be consistent, to all dripstone forms that arise in any way in natural underground environments or in anthropogenic objects or structures, dripstones in many aspects similar, and often even identical, we can propose the term hypogeothems (from the Greek ypógeios – underground; Fig. 1).

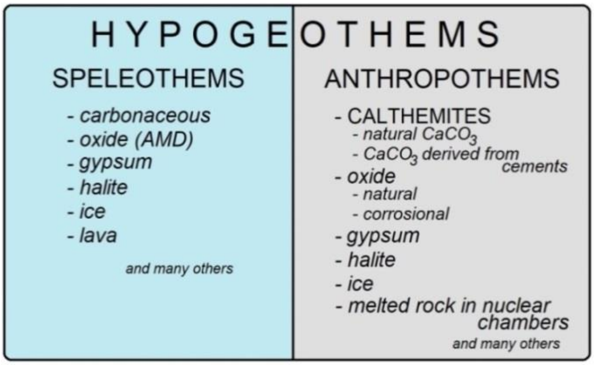

Fig. 1. Schematic comparison of speleothems and anthropothems

In further discussion, one could consider, for example, whether to distinguish anthropothems made of natural material from those made of anthropogenic materials or whether dripstones formed in natural underground structures as a result of human activity (e.g., disturbance of water relations in the rock mass – cf. Kotula et al. 2019, or penetration of building materials into caves – Hill and Forti 1997) should be included in anthropothems.

Historical, mainly post-mining underground objects in the Sudety Mountains are specific environments subject to various research studies. They are recognized in terms of historical-archaeological, geological and biological aspects (a broad review of the literature in Zagożdżon, 2019). In the scope of geology the following issues were recognized here: tectonic zones (Kasza 1964; Banaś 1965), contact of the granitoid pluton with the metamorphic cover (Żaba 1979), systematic mapping of objects (e.g., Zagożdżon and Zagożdżon 2013), mineralogy of the hypergene zone phases (Parafiniuk and Siuda 2006; Siuda et al. 2008; Siuda and Kruszewski 2013), hydrogeological issues (Staśko and Wojtkowiak 2004; Marszałek et al. 2012), mine atmosphere gases (Fijałkowska-Lichwa 2016; Przylibski 2001) and others. For several reasons, these objects also constitute a good research ground enabling us to learn about the diversity of dripstones.

The Sudety area is characterized by a complicated, so-called mosaic geological structure (Fig. 2), individual tectonic units are made of various silicate and carbonate rocks. Very diverse deposits have been exploited here using underground mining methods (metal ores, including uranium, fluorite, barite, pyrite, carbonate minerals, hard coal, water, etc.). The Sudety area has been heavily developed for a long time, so in addition to mining facilities, tunnels, extensive underground military infrastructure and other underground engineering facilities were also built here. Individual objects are of different ages, the oldest of those described here can be dated to the 15th–16th century, while the youngest were created in the 1970s and 1980s. Individual excavations provide access to a geological environment diversified in terms of petrography, mineralogy, structure and hydrogeology. The moderate climate of this region favors the circulation of water in the surface zone, and the periodic occurrence of temperatures below 0°C allows the formation of ice dripstones in winter.

In these objects, over decades or centuries after mining and other activities ceased, extensive or otherwise interesting dripstones developed in some places. Due to the lack of current technical activity, these structures are relatively accessible for study.

Observations of varying detail were conducted in 23 underground facilities (Fig. 2), diversified in terms of origin, purpose, age and size. Most of them were the drifts after exploitation and search for ore deposits. The most important of these sites were the Main and Upper Adits of the iron and uranium ore mine Freiheit – Wolność and drift no. 19 of the uranium ore mine Podgórze in Kowary, the Middle Uranium Adit in Marcinków, including drifts excavated in 1950 and a part of the 16th-century erbstollen (the deepest adit in the mining area, with a primarily drainage function), the Ochre Adit and newly discovered (nameless) adit in Złoty Stok, the Leopold Stollen in the St. John tin ore mine in Krobica and the drifts and exploitation chamber of the gold mine Rudne Doly in Zlate Hory (Czech Republic). Observations carried out in other adits were also used, such as Gesellen Glückstolle and Barbora in Ciechanowice (polymetallic ores) Gnade Gottes in Modliszów (silver), Anna Maria in Przecznica (cobalt) and the adit in Wieściszowice (pyrite). Further mining objects were the Hellmuth Stollen of the pre-war hard coal mine Consolidierte Wenceslaus Grube (Sowina near Nowa Ruda), a water adit in Boguszów-Gorce, a former exploitation adit, which is currently the mineral water intake for the health resort in Długopole-Zdrój and chambers after the exploitation of limestone raw materials in the Wałbrzych area (Daisy Adit), in Ciechanowice (Wapienna Adit) and Uniemyśl (Podkowiec Adit). The observations were also conducted in non-mining sites, as: the Młoty pumped-storage power plant under construction, at German military sites from World War II (the Osówka complex in Głuszyca, the underground of the Książ Castle and the site in Widna Mountain in Kamienna Góra) and at the 18th-century mining galleries of the Kłodzko Fortress.

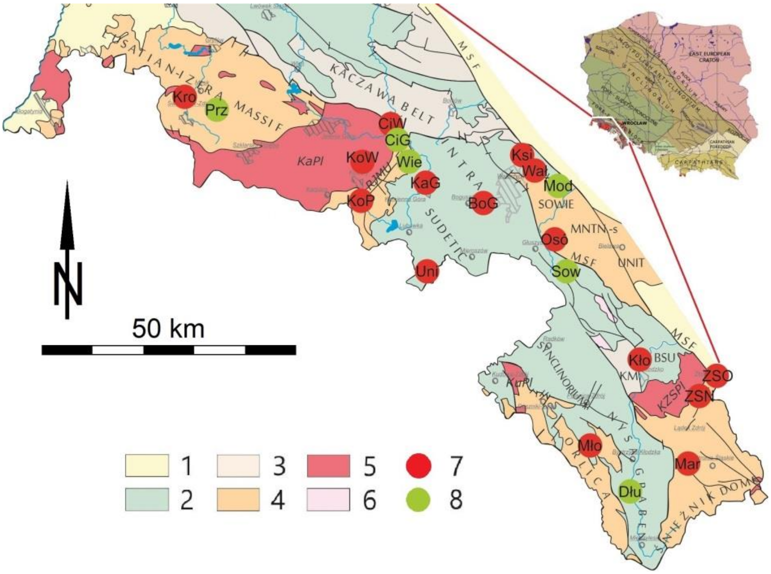

Fig. 2. Location of observation sites on the simplified geological map of the Sudety Mts.: 1 – Cenozoic sedimentary cover, 2 – older sedimentary units, 3 – low-grade metamorphic units, 4 – high-grade metamorphic units, 5 – granitoid massifs, 6 – gabbro massifs, research sites: 7 – main, 8 – others; BSU – Bardo Structural Unit, KM – Kłodzko Massif, MSF – Marginal Sudetic Fault, MIS – Main Intra-Sudetic Fault, ŚSU – Świebodzicie Structural Unit, KaPl – Karkonosze Pluton, KuPl – Kudowa Pluton, KZSPl – Kłodzko-Złoty Stok Pluton, RJMU – Rudawy Janowickie Metamorphic Unit; symbols of research sites: BoG – Boguszów-Gorce, CiG – Ciechanowice (Gesellen Glückstolle and Barbora), CiW – Ciechanowice (Wapienna Adit), Dłu – Długopole-Zdrój, KaG – Kamienna Góra, Kło – Kłodzko, KoP – Kowary (Podgórze mine), KoW – Kowary (Wolność mine), Kro – Krobica, Ksi – Książ, Mar – Marcinków, Mło – Młoty, Mod – Modliszów, Osó – Osówka, Prz – Przecznica, Sow – Sowina, Uni – Uniemyśl, Wie – Wieściszowice, Wał – Wałbrzych, ZSN – Złoty Stok (new adit), ZSO – Złoty Stok (Ochre Adit)

2. DRIPSTONE'S FORMATION ENVIRONMENTS IN ANTHROPOGENIC STRUCTURES

Underground anthropogenic environments are highly diversified, which is the result of the intersection of human factors (genesis and purpose of objects, age), morphological (geographical location, form of objects), biological (type and intensity of activity of living organisms), geological (lithological diversity, mineralization, influence of tectonics) and hydrological and hydrogeological (parameters of water, drainage intensity).

This mainly concerns post-mining structures, but also various engineering facilities, such as tunnels and water distribution infrastructure, as well as basements, warehouses, underground garages, various military facilities, etc. They are characterized by horizontal or vertical development, but many are inclined structures. They are corridor- or chamber-based, and their length varies from a few meters (e.g., isolated exploration tunnels) to hundreds of kilometers (excavation systems in areas of intensive mining). The vast majority were built in the modern period (especially between the 19th and 21st centuries), but some date back to the Middle Ages, Antiquity, and even prehistoric times (Hill and Forti 1997; Coulson 2012).

Geographical location, including the height of the facility (facility's inlet) above sea level, has a significant impact on the conditions within these structures. In the case of deep objects (mines, tunnels), the rock mass structure, often exceptionally complex, is decisive, the main factors here are the type of rocks (dominant and subordinate), the presence of mineralization (sometimes very high), and tectonic phenomena (primarily faults of various size). In the case of mines, exceptionally high petrographic and geochemical diversity of the rock mass is evident, as we are talking about excavations occurring within deposits of various types (Beltyukov 1972; Marszałek et al. 2012; Parafiniuk et al. 2016; Zagożdżon 2019; Carbone et al. 2016; Syczewski et al. 2022). The origin of the dripstone material in these facilities is also important, especially in relation to calthemites (natural material occurring in the rock mass or anthropogenic – e.g., leached from mortar and concrete – Smith 2015; 2016; Zagożdżon 2019; Broughton 2020).

Climate is influenced by varying temperatures, most commonly from a few to about 20°C, but in the polar and mountain regions falling below 0°C (Bryant 1987), and in extreme cases causing the melting of rock (chamber after nuclear test – Gard 1963). Factors such as the intensity of air movement (or its absence), and varying humidity resulting from the presence (amount) of water have a significant impact. Based on water conditions, sites can be classified from dry to those with intensive water migration or stagnation (including excavations entirely or partially filled with water).

From a geochemical point of view, very specific environments can be distinguished, enabling the development of silicate, carbonate, salt, or ice dripstones, as well as AMD (Acid Mine Drainage) environment (see examples of Beltyukov 1972; Bryant 1987; Carbone et al. 2016).

Additionally, in many cases, the influence of living organisms, such as rodents, bats (e.g., accumulations of excrements) or microorganisms (in the form of microbial mats, biofilms, or snottites) is noticeable (Hill and Forti 1997; Czerwik-Marcinkowska et al. 2017).

3. DRIPSTONES IN SUDETIC MAN-MADE UNDERGROUND FACILITIES

Dripstones in artificial objects in the Sudety have not been comprehensively studied, so far. Only the diversity of secondary minerals of AMD environments has been shown in detail in the literature. The presence of iron oxide compounds was detected, but also manganese oxides and copper sulphates (Parafiniuk and Siuda 2006; Siuda and Kruszewski 2013; Parafiniuk et al. 2016) and uranyl minerals (Siuda et al. 2008; Syczewski et al. 2022).

In the studied group of Sudety sites, there are dripstone forms diversified in terms of chemical composition, shape and genesis. These are primarily carbonate dripstones and those formed in the AMD environment, furthermore ephemeral (forming only in winter) ice dripstones, secondary uranyl minerals and mixed – organic-mineral.

The dominant dripstone forms are various stalactites and flowstones, but there are also a number of other forms, sometimes not common or atypical. The formation of dripstones is caused by precipitation from various solutions, sometimes supported by the activity of living organisms, as well as by a physical process – freezing of water.

In the analysed objects dripstones occur often, but mostly only in points or narrow zones. However, some of these objects can be indicated as unique due to the mass occurrence (Marcinków) and diversity (Młoty, Sowina) of dripstone forms.

3.1. COMMON DRIPSTONES

The most frequent type of dripstones are **tubular stalactites** (commonly called soda straws). The vast majority of them are calthemites, both: made of carbonate substance originating from mortars and composed of calcium carbonate of natural origin, however in some sites ferrous straws are also very common.

Calcite straws have different forms. Their “embryonic” development phase was observed in the adits in the Kłodzko fortress, slightly better developed forms, e.g., in water adit in Boguszów, in the Fröhliche Anblick adit (Ciechanowice) or Gnade Gottes adit (Modliszów). In Hellmuth Stollen, in Sowina, they are much longer (>20 cm), partly they are helictites and colored with iron oxides from steel construction elements. Interesting soda straws bands appear in some parts of the penstocks of the pumped-storage power plant in Młoty and in the shaft chamber at level 80 of the Wolność mine in Kowary – where they reach a length of about 1 m. In the two last sites a clear dependence of the location of caltemite straws on the structure of the support is well visible, especially in Młoty, where they are formed consistently at the contacts of individual segments of the concrete support, along the existing fissures through which water penetrates from the rock mass (Fig. 3a) (Zagożdżon 2019).

A very common are ferrous (composed of iron oxides and hydroxides) straw stalactites of AMD environment, occurring in old metal ore and hard coal mines, but also in non-mining objects. They usually occur only in limited areas and their length does not exceed several centimeters (like in Przecznica and Wieściszowice). However, in the best site for studying them, in the Middle Uranium adit in Marcinków, they occur in the number of many hundreds (Fig. 3b), and their length sometimes reaches 50 cm. They show a certain variability of form – mostly are straight, a few are helictites. Sometimes you can observe their transverse striations, expressed by the variability of colour, in other cases the colour variability is more irregular (Zagożdżon 2019). Generally, in the examined objects, tubular stalactites showing dark grey to black (Mn compounds) or light blue (Cu compounds) colours have been very rarely encountered, and their formation must be the result of the presence of small amounts of these metals scattered in the rock mass.

Fig. 3. Exemples of stalactites: a – rows of caltemite straws along the gaps in concrete support in Młoty (Zagożdżon 2019), b – mass occurrence of ferrous straws in Marcinków, c – large, about 30-cm long ferrous stalagmite with signs of multi-stage corrosion in Leopold Adit in Krobica (Photos a, b: K.D. Zagożdżon)

In Marcinków and Zlate Hory, few organic-mineral dripstone structures were identified. In the first site, a specific occurrence of a diversified cyanobacterial-algal association was described (Czerwik-Marcinkowska et al. 2017), but in the deeper part of the excavation, typical snottites developed on some ferrous straw stalactites were also observed, and one of these stalactites is a mixed structure, probably composed partly of Cu compounds and partly of a biofilm (Zagożdżon 2019). Larger concentrations of snottites occur in some exploitation chambers of the gold mine in Zlate Hory.

Calcite **conical stalactites** are rare, among them ferrous ones are more frequent, they usually reach a length up to 10–15 cm and often occur in groups, smoothly changing into curtains and drapery-type dripstones on the sidewalls. Specific conditions for the growth of stalactites of this type prevailed in the Leopold Adit in Krobica, before its opening in 2010 (Zagożdżon and Zagożdżon 2012). AMD leachates stagnated in the excavation, but their level fluctuated significantly, so there were many phases of stalactite growth in subaerial conditions, and their corrosion in subaquatic environment (Fig. 3c). Ice stalactites (icicles) are not a popular form of dripstones, their presence was noted in the Osówka facility.

Typical **stalagmites**, both calcite and those formed in AMD environments, are also not common. In both cases they have low, rounded forms with flattened tops, but in ferruginous ones the splash cups occur sometimes. The AMD stalagmites are both solid, although fragile structures, as well as accumulations of cohesive, soft, "jelly" material, strongly permeated with water. In isolated cases there were observed stalagmites, formed of a pitch-black mineral substance with a high gloss, which underwent contractional cracking and collapse, probably as a result of gradual dehydration. The ice stalagmites occur commonly, but some sites draw special attention to their mass occurrence, as Osówka and Upper Adit in Kowary. In the first of them these dripstones reached a height of up to 3 m, with a relatively small diameter – around 10–30 cm. The ice is usually coarse crystalline, colorless and perfectly transparent or finely crystalline, white, translucent. In some zones, e.g., in the vicinity of significant amounts of wooden support, it shows a light brown color resulting from the content of dispersed organic matter (Zagożdżon 2019).

Flowstones occur quite often in the studied objects, generally in two forms. In places you can observe their concentrated accumulations that cover the walls and bottom of the workings with the thick layers. But much larger surfaces (walls and roofs) are covered by very thin, sometimes barely visible coatings or encrustations. An example of well-developed calthemites of these types can be found in the exploitation chamber of the Daisy Adits. In several places there are dripstone cascades formed from pure, almost white calcite but the extensive surfaces of sidewalls are covered with a thin carbonate coating of dark gray or slightly brownish color (caused by the admixture of dust from non-carbonate rocks and perhaps by combustion products of explosives (Zagożdżon 2019). It is worth mentioning the flowstone occurrence in the Wapienna Adit in Ciechanowice, where local, but constant and very intensive inflow of water, gives the final section of the excavation a character typical for a cave (see: Zagożdżon 2019). In Marcinków there are various ferrous flowstones. In many parts of the main working of Middle Uranium adit, on the walls, they are linear, forming along the water flow paths. Their density gradually increases and they transform into continuous, fairly hard, dark brown covers. Significant sections of the 16th-century erbstollen are covered with a continuous, in places very thick layer of flowstones (Fig. 4a). In the side exploration galleries, more massive dripstone forms have developed. These are thick flowstones on all walls, massive, multi-colored accumulations at the base of the walls, and multi-level rimstone dams across the entire width of the workings. They were partially formed as a result of merging of conical stalactites and draperies groups (Zagożdżon 2019).

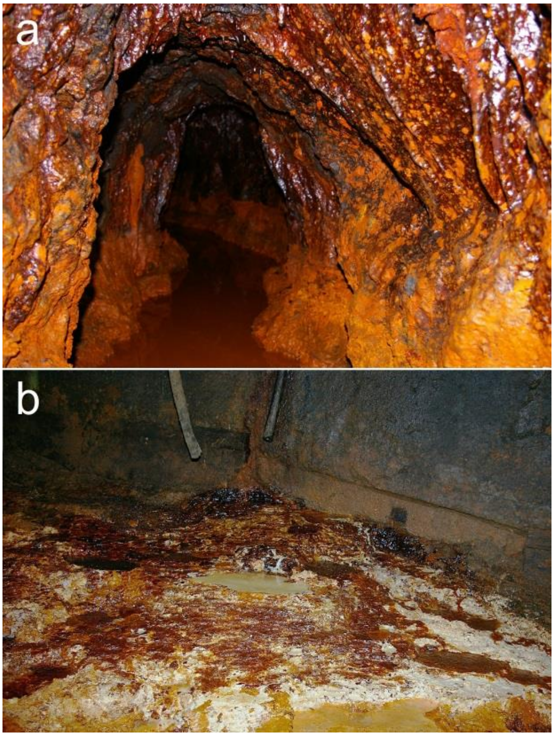

Fig. 4. Examples of flowstone occurences: a – continuous ferrous cover in oldest workings of Middle Uranium adit in Marcinków, b – calthemite-ferrous flowstone with a rimstone dam in Młoty, in the upper part of photo the drill hole supplying the solutions is visible (Photo a: K.D. Zagożdżon)

Specific flowstones developed in Młoty. Some of the research and injection holes drilled in the concrete sidewalls became the routes providing the inflow of various solutions to the workings. Initially, around 1989, they probably leaked out the excess cement laitance injected behind the support. Later, waters carrying calcium compounds, formed as a result of leaching of the concrete support, began to flow out. As a result, soft accumulations of substance with the character of moonmilk were formed in the lower parts of the sidewalls and on the floor, as well as hard calcite flowstones, with small rice terraces and rimstones. The same channels bring high-ferrous waters from the rock mass, thus the highest part of these dripstone concentrations consist of rusty deposits characteristic for AMD environment. In places, groups of rimstone dams or rice terraces develop on their surface (Fig. 4b) (Zagożdżon 2019).

3.2. SPECIAL DRIPSTONES

Some other dripstones were also found in the examined objects – rare, unusual, e.g., due to the type or source of the mineral substance, or of unknown for now origin.

Atypical forms of calthemites have been described in Młoty, where on the exposed fragments of the steel support mesh grew dripstones of a specific shape, being a combination of stalagmites and conical stalactites, but in the opposite arrangement than in the case of stalagnates. As a result of the supply of mineralized water, stalagmites are formed on the nodes of the mesh. Lower down, stalactites are formed due to the downward flow of solution (Fig. 5a). Taking into account the shape and forming process of such forms, the name **stalagmitite** can be proposed for them. These are analogous forms, although more massive and better developed than the sinters shown by Smith (2023) on the protective mesh in Harry Woods Cave (Eastern Australia). A similar dripstone was also observed in the adit in Sowina, where it developed on a steel structural element of the door frame of a former explosives storage facility.

In the adit in Marcinków, flat, concentric structures of a few centimetres in diameter were encountered, being lamellar crystalline accumulations, formed below stalactites in a transitional environment, which can be described as semi-aquatic, i.e., on the floor covered with a thin, 1–2-centimetre layer of water (Fig. 5b). Morphologically they can be compared to splash rings (Hill & Forti, 1997), or rather to raft **splash cups** mentioned by (see Smith 2023b), however they differ from them in size, structure and mechanism of formation.

A unique kind of a **flowstone** with rimstone dam has been observed in Młoty. An isolated structure, located in the axial part of one of the excavations, was fed from below – from under the layer of ferrous precipitates (Fig. 5c). In terms of direction of transport of the building material, it mimics a mud volcano, however, taking into account the known forms of speleothems, they partially resemble the geysermites (see: Hill and Forti 1997).

The latest discovery is the occurrence of enigmatic forms in an unnamed adit in Złoty Stok, opened for research in 2024. They are of different sizes, have different height-to-diameter proportions, the best developed of them are morphologically similar to stalagmites, although they have significantly different features. Their shape can be described as **tubular** or **chimney-like**, the interior is empty, and the holes at the top are often funnel-shaped (Fig. 5d). The height-to-width proportions are about 3:1 to 4:1 for structures growing on the floor and up to 9:1 for those occurring on the sidewalls. These structures are built of a soft (sometimes slightly brittle on the surface) manganese oxide, dark gray or brownish, with a very loose structure, the density of which in an air-dry state is only 0.35 g/cm^3.

In terms of form, these dripstones are similar to unusual gypsum speleothems described in Covadura cave (Spain – see: Hill and Forti 1997). But it should be emphasized that there are no traces of the supply of mineral material from the roof or the upper part of the sidewalls. So specific way of formation of Spanish stalagmites cannot be adapted here, nor can these dripstones be considered as conulites. Similar but ferruginous forms, defined as extremely singular, were found in Zoloushka Cave in Ukraine (Kotula et al. 2019), their creation was linked to the life activity of funguslike microorganisms. Perhaps the genesis of tubular stalagmites from Złoty Stok may be similar, this problem is currently being studied.

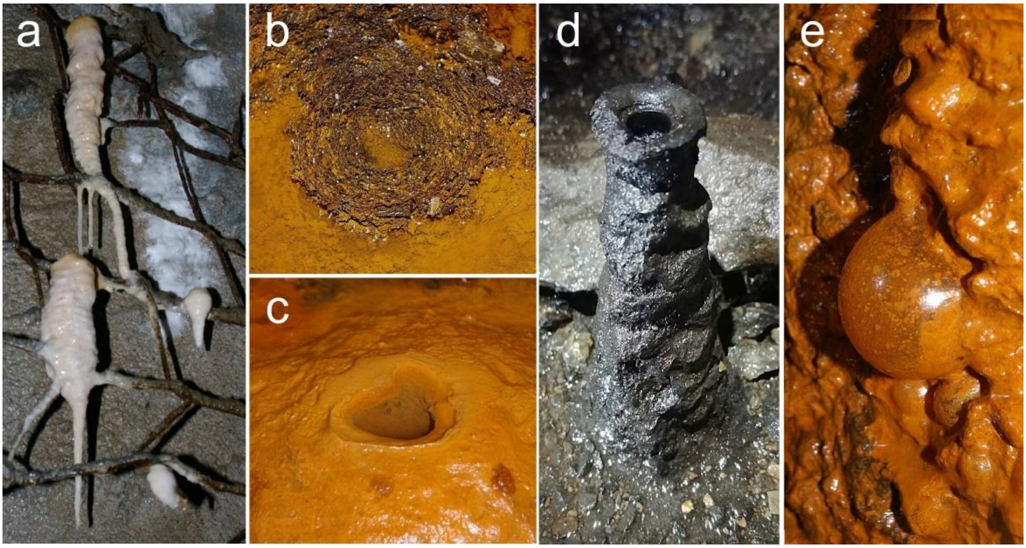

Fig. 5. Examples of untypical dripstones: a – stalagmitites on the steel support mesh, b – concentric, crystalline splash cup (7 cm in diameter), c – flowstone accumulation fed from below (diameter of rimstone dam – 23 cm), d – chimney-form stalagmite-like accumulation; e – three centimeters in size bubble structure on gelly flowstone wall cover (a, c, e – Młoty, b – Marcinków, d – Złoty Stok)

Pisoids were found only in three research sites, they differ in size, internal structure and type of surface. In the Main Adit of the former Wolność mine in Kowary, they formed in subaquatic conditions, in a miniature rimstone dam with a cross-section of about 4 cm, in a structure called "cave pearl cup". Several pearls found there had a clearly ellipsoidal form, their lengths ranged from 0.4 to 1 cm.

Interesting are pisoids in the eastern penstock in Młoty (Zagożdżon 2019). They developed on an area of about 0.5 m^2, in transitional water conditions – calcite crusts grow on rock fragments lying on the floor of the excavation, under the zone of more intensive water drip from the roof, however, water does not accumulate here, it does not create any reservoir. The sizes of pisoids range from 1 to 3.5 cm, they have both clearly spherical and rounded or more irregular forms, depending on the thickness of the carbonate coating.

Another type of pisoids were found in one of the mine-laying corridors of the Kłodzko Fortress (Zagożdżon 2019). These are isometric bodies of about 1 cm in diameter, highly porous with a very irregular, cauliflower-like surface. They can be described as intergrowths of rosette-shaped crystals brushes with diameters of 1.55–2.15 mm. In the cross-section, it is clearly visible that these are the crowns of dendritic mineral aggregates about 4–5 mm long.

A few **vesicular** dripstone forms were observed in Młoty. They are almost perfectly hemispherical, semi-transparent, confusingly similar to a soap bubble (Fig. 5e). We could classified them as cave balloons (Hill and Forti 1997), but they don't occur in the cave and consist of iron oxides. They are the result of very slow degassing of the porous, soft mass, what occurs as the weight of the dripstone cover increases with the sedimentation on top.

In the Sudety there are also two examples of dripstones composed of unusual material. First of them are small **conical stalactites** which developed in Hellmuth Stollen in Sowina. They are the result of corrosion (in subaquatic conditions) of steel elements of the skeleton of shelves in the underground warehouse (Fig. 6a). They show a clearly zoned and exceptionally highly porous, dendritic structure (Fig. 6b). These dripstones consist mainly of iron oxides, but their mineral composition is probably variable, similarly to the case described by Malinowski et al. (2010) from the Wieliczka Salt Mine.

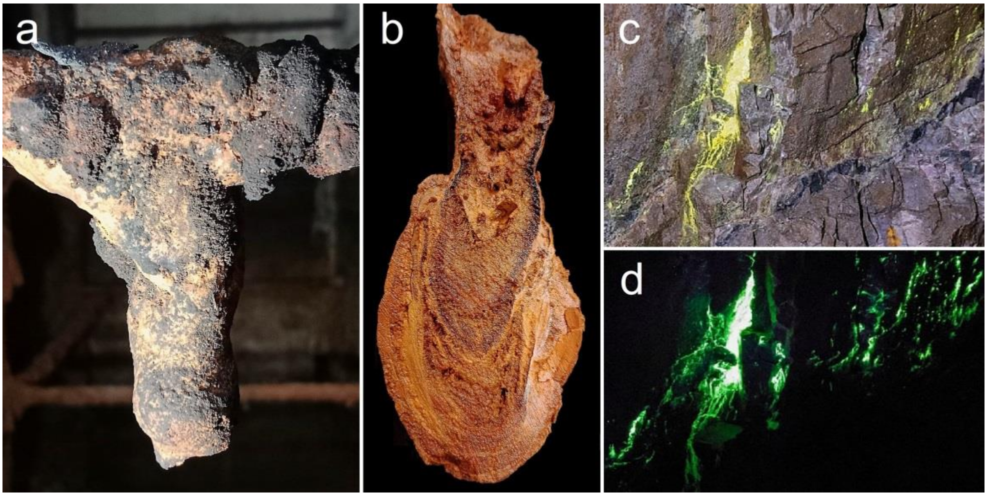

Fig. 6. Dripstones composed of unusual substances: stalagmites resulting from decomposition of steel elements in Sowina (a – external view in the tunnel, b – cross-section; both about 8 cm long) and flowstones of secondary U minerals in Podgórze mine (c – in visible light, d – under UV light; Photo: Antczak 2024)

A unique type of hypogeothems are small flowstones and encrustation of **secondary uranyl minerals** in adit no. 19 of the Podgórze mine in Kowary. Bright yellow accumulations have been initially described as uranospinite with traces of metauranospinite (Siuda et al. 2008) and later as mainly uranospinite, nováčekite-II and natrouranospinite (Syczewski et al. 2022).

They develop on the walls of the workings, below small cracks that supply mineralized solutions (Fig. 6c) (Antczak 2024). The dripstones are thin, reaching a maximum of 3 mm. They take the form of irregular covers, with an area up to 1 m^2 or narrow strips along the paths of solutions flowing down the rock surface. The areas of occurrence of these dripstones is more visible when observed under UV light (Fig. 6d), what is the biggest attraction of the underground tourist route organized in the Podgórze mine.

4. DISCUSSION

Referring to the terminology presented in chapter 1, a number of occurrences of caltemites *sensu* Smith (2015 – "derived from man-made structures") can be identified in the Sudety Mts., e.g., in Kowary and Sowina (former mines), or in Kłodzko and Młoty (other underground facilities). However, the carbonate dripstones formed from natural material (e.g., Wapienna Adit, Daisy Adit) were also observed. In terms of structural characteristics, these are virtually identical to speleothems, so one might ask whether the term caltemite is truly appropriate for them. The term minothem, proposed by Carbone et al. (2016), also raises doubts. According to these authors, it should be applied to dripstones in any man-made underground environment, but it is indeed misleading for structures not related in any way to mining, such as the former military facilities in Kłodzko and Osówka (or the cellars and underground garages not discussed here). It therefore seems reasonable to propose rather the term anthropothem as univocally covering dripstones in all man-made underground structures.

The commonness of dripstones and their diversity is noteworthy, depending on the structure of the rock mass, the type of base on which they are formed, the composition of the building material and the processes causing their formation. A full analysis of these relationships goes beyond the scope of this study, but key issues can be identified (see Table 1).

Table 1. Basic data on anthropothems in selected sites in Sudety Mts.
(scale of occurrence: + small, ++ medium, +++ large)

Observation sites	Scale of occur rence	Main natural and anthropogenic factors of formation	Chemical composition	Origin of material
Ciechanowice – Wapienna Adit	++	– marble lens in greenstone schists complex – numerous faults of different scale	Ca carbonates	– natural
Kłodzko	+	– lime binding materials in the surface infrastructure of the fortress	Ca carbonates	– mortars
Wałbrzych – Daisy Adit	++	– local occurrence of carbonate rock (oncoids conglomerate) in polymictic clastic formation	Ca carbonates	– natural
Kowary – Freiheit-	+	– small concentrations of calcium carbonate (marbles in silicate	Ca carbonates	– natural – mortars

Table 1 continued

Wolność		metamorphic complex) – concrete support of the excavations in some zones		
Boguszów- -Gorce	+	– fractured rhyodacitic subvolcanic intrusion – fault – full brick and mortar protective casing	Ca carbonates, Fe oxides	– mortars (Ca) – natural (Fe)
Młoty	+++	– large faults – intensive inflows of highly mineralized waters – full mortar protective casing, injections of limestone materials to strengthen the casing	Ca carbonates, Fe oxides	– mortars, cement lait-ance (Ca) – natural (Fe)
Sowina	++	– Carboniferous productive series (mainly sandstones), hard coal seam – full brick and mortar protective casing with many steel elements	Ca carbonates, Fe oxides	– mortars (Ca) – natural and steel (Fe)
Krobica	+++	– metal ore deposit – long-term stagnation of highly mineralized water in the entire adit space	Fe oxides	– natural
Wieściszowice	+	– mica schist complex heavily mineralized with pyrite (old pyrite deposit)	Fe oxides	– natural
Złoty Stok – Ochre Adit	+++	– metal ore deposit – long-term stagnation of highly mineralized water in the entire adit space	Fe oxides	– natural
Marcinków	+++	– strongly tectonized schist massif – polymetallic ore deposit – intensive inflows of highly mineralized waters	Fe, Mn oxides, Cu sulphides	– natural
Złoty Stok – new adit	++	– tectonized blastomylonite schist and gneiss massif – inflow of mineralized shallow circulation waters	Mn oxides	– natural
Kowary – Podgórze mine	+	– strongly tectonized schist and gneiss massif – uranium ore deposit	uranyl minerals	– natural
Osówka	+	– fractured gneiss complex – intensive inflows of highly mineralized shallow circulation water – natural ventilation	water ice	– natural

Most of the studied sites are located in metamorphic massifs, several in sedimentary complexes, and one in a rhyodacitic laccolith body. However, the lithology of the rock mass only in some cases has a decisive influence on the conditions and intensity of dripstones formation. This is particularly true for calthemites, which originate from natural materials, and in one case, small iron oxide dripstones occurrence is a result of the presence of dispersed pyrite in the coal seam. Other anthropothems, however, result from the activation of locally occurring mineralization or activation of the binding materials components.

The influence of disjunctive tectonics is crucial – the presence of intense jointing, (Boguszów-Gorce, Osówka), fracturing zones (e.g., Marcinków), and faults (Ciechanowice, Podgórze, Młoty). These structures enable intensive migration of water (solutions), which facilitates the mass formation of dripstones. In extreme cases, water completely filling the excavations and stagnating for a long time has resulted in the formation of complete flowstone covers on the walls and roof (Krobica, Złoty Stok – Ochre Adit).

In terms of origin, the mineral material composing the studied anthropothemes is of two types: natural (from the leaching of rocks and minerals present in the rock mass) and anthropogenic (formed from the degradation of building materials). The first group is more chemically diverse. It includes primarily calcium carbonate, as in calthemites in the Daisy Adit (derived from limestone), and in Ciechanowice and Freiheit-Wolność mine in Kowary (from marble). In addition, these are iron oxides and hydroxides (as in Ochre Adit or Wieściszowice), manganese oxide (new adit in Złoty Stok), copper sulfates (Marcinków), uranyl minerals (Podgórze mine), and water (Osówka). Anthropogenic material is almost exclusively calcium carbonate leached from building mortars and concrete, but two sources of this substance can be identified. In most cases, it is leached from the protective casing of the roofs and walls of underground structures, as in Młoty, Sowina, and Boguszów-Gorce. In Kłodzko, however, at least some of it comes from the fortress constructions located on the surface. In Sowina, ferrous dripstones were formed from anthropogenic material deriving from the corrosion of steel elements of the equipment.

In this context, the phenomenon of superposition of dripstones of different chemical compositions observed in Młoty is worth mentioning, for it is the result of the overlap of natural factors and human activity.

6. CONCLUSIONS

The underground anthropogenic facilities in Sudety Mts. together constitute an extensive and very diverse environment for the formation of dripstone structures. In the studied objects mainly carbonate (calcite) dripstones occur – typical caltemites, formed as a result of leaching and precipitation of lime components of binding materials, and dripstones formed from calcium carbonate naturally occurring in the rock mass. Anthropothems characteristic for AMD environments are also common. They often occur locally, but in several objects they form *en masse*, when the intense mineralization in the rock mass occurs (historic metal ore deposits) and the circulation of aqueous solutions is facilitated along tectonic zones. They are mostly composed of iron oxides and hydroxides, less frequently iron and copper sulphates and others. In addition, organic-mineral and ice dripstones were observed. In terms of their mineral composition, flowstones composed of secondary uranium minerals should be mentioned as unique, while in terms of genesis, the ferrous stalactites formed from structural steel are noteworthy.

The most common forms, both in the case of carbonate dripstones and AMD, are straw stalactites and flowstones. However, a number of rare forms have also been presented, also those not described in the literature so far. Among the carbonate speleothems, these are pisoids, including those formed in conditions specified as semi-aquatic, and combinations of stalagmites and stalactites, here called stalagmitites. In AMD environments, these were specific, crystalline splash-cups formed in semi-aquatic conditions, bubble (balloon) structures formed as a result of degassing of soft flowstone accumulations, and an isolated rimstone fed from below, in some extent similar to a geysermite. Enigmatic tubular forms have been found in the adit in Złoty Stok, they are currently being studied and will be the subject of the next publication.

The wide variety of conditions of dripstone's formation in man-made underground objects and the mineral material that builds them suggests the need to enrich or modify the terminology. Hence, it was proposed to introduce the terms hypogeothem (covering all dripstones formed in underground environments, or in objects having any natural or artificial vault) and anthropothem (to describe those hypogeothems that were formed with any human involvement).

Dripstones are an interesting subject of research with both cognitive and practical significance. In the analyzed sites, they are a complex result of the superposition of various geological and sometimes biological factors, as well as human activity. Their presence can aid in locating mineralization zones deep within the rock mass, as well as geological discontinuities and linear defects in building structures. It can be concluded that anthropothemes, compared to speleothems, are currently relatively poorly understood, and the Sudety Mts. represent a good model area for further research.

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