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International Journal of Speleology

Official Journal of Union Internationale de Spéléologie

Speleogenesis in a lens of metamorphosed limestone and ankerite: Ochtiná Aragonite Cave, Slovakia

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Abstract: The Ochtiná Aragonite Cave (Western Carpathians) represents a unique natural phenomenon. It originated under particular lithological and hydrogeological conditions of the Ochtiná Karst in which several isolated lenses of Paleozoic crystalline limestone, partly metasomatically altered to ankerite, are enclosed by phyllites. Meteoric water seepage through non-carbonate rocks dissolved limestone and caused the oxidation of ankerite to Fe oxyhydroxides. Carbon dioxide produced during ankerite oxidation enhanced limestone dissolution. The maze cave consists of parallel fault-controlled linear passages and chambers interconnected by transverse horizontal passages. Phreatic and epiphreatic solution morphologies resulted from slowly moving or standing water. These include flat ceilings (Laugdecken), facets, lateral notches, convection ceiling cupola-shaped depressions, and spongework-like hollows. Flat ceilings were developed in several altitude positions, each of them probably closely below the slightly oscillated water table. Primary phreatic cupola-shaped depressions, truncated by flat ceilings, represent relics of the oldest cavities (pre-Quaternary? to Early Pleistocene). Inward-sloping smooth facets were not developed only in passages with flat ceilings, but also in the passages and halls with a vaulted ceiling. The asymmetrical shape of cusped depressions above the facets were documented in detail by a high-resolution cave topography with terrestrial laser scanning and digital photogrammetry. Middle–Late Pleistocene accumulation phases, identified by magnetostratigraphy of cave sediments and U-series dating of speleothems, are associated with phreatic and later epiphreatic development. The deposition on the bottom bedrock began before 1.8 Ma. The Brunhes/Matuyama boundary (0.773 Ma) and Jaramillo magnetozone (0.990–1.071 Ma) were recorded in the profile in the Oválna chodba Passage. Slow depositional rate (~0.09 cm/kyr) calculated from magnetostratigraphy resulted from slow water movement in confined conditions in marbles completely enclosed by phyllites and no direct relation to the surface. Only occasionally turbid water was loaded in extremely fine-grained infiltration material and autochthonous Fe oxyhydroxides. The depositional rate in Mn-rich layer was much slower (~0.03 cm/kyr). Additional U-series dating confirmed that old aragonite generations (with ages about 500–450 ka and 143–121 ka) were partly corroded by repeated floods during Late Pleistocene humid episodes. Aragonite younger than 13.5 ka is not corroded.

Keywords: Cave morphology, LiDAR, magnetostratigraphy, ankerite, speleogenesis

Received 20 June 2021; Revised 26 October 2021; Accepted 5 November 2021

Citation: Bella, P., Bosák, P., Pruner, P., Hercman, H., Pukanská, K., Bartoš, K., Gaál, L., Haviarová, D., Tomčík, P., Kdýr, Š., 2022. Speleogenesis in a lens of metamorphosed limestone and ankerite: Ochtiná Aragonite Cave, Slovakia. *International Journal of Speleology*, 51(1), 13-28. <https://doi.org/10.5038/1827-806X.51.1.2397>

INTRODUCTION

The Ochtiná Aragonite Cave ("Ochtinská aragonitová jaskyňa" in Slovak, OAC) belongs to the UNESCO World Heritage List within the Property No. 725:

"Caves of Aggtelek Karst and Slovak Karst". OAC, along with other smaller cavities were discovered in the Kapusta Adit in 1954 during iron ore exploration. The cave opened to public in 1972, after an artificial tunnel was excavated between 1966 and 1967.

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The OAC is formed in the lens of limestone, part of which was metasomatically altered to ankerite, $\text{Ca}(\text{Fe}^{2+}, \text{Mg})(\text{CO}_3)_2$. According to Droppa (1957), the cave originated by the limestone dissolution and chemical weathering of the ankerite by meteoric waters infiltrating along steep faults when cavities were completely flooded, and outflow conduits were blocked by flushed Fe oxyhydroxides. While Droppa (1957) suggested the OAC developed during the Holocene, Kubíny (1959) linked its genesis with Pleistocene glacial periods. Homza et al. (1970) concluded that cave spaces were formed by Tertiary and Quaternary ankerite weathering and flushing of Fe oxyhydroxides. Complicated OAC morphology with numerous irregular larger and smaller spherical cavities led Nicod (1976) and Choppy (1994) to advocate for hydrothermal origin. However, no diagnostic minerals were detected in OAC (Čilek et al., 1998; Bosák et al., 2002). Gaál (1996) and Hurai et al. (2002) noted that the hydrothermal processes occurred in a deeper part of limestone complex only during Early to Late Cretaceous.

Gaál and Ženiš (1986), as well as Gaál (1996) suggested that iron oxidation in ankerite by meteoric waters was responsible for origin of the OAC and that the morphology of cavities is controlled by the shape of original ankerite bodies within limestone lenses. Modern cave morphologies resulted from the later dissolution of limestone walls. Similarly, Ščuka et al. (1988), Rajman et al. (1990, 1993), as well as Bosák et al. (2002) considered that the limestone dissolution was enhanced by CO_2 released from decomposition

of siderite/ankerite. Siderite $\text{Fe}(\text{CO}_3)$ and pyrite (FeS_2) were found in the Hrádok Massif (e.g., Mišík, 1953; Bystrický & Fusán, 1954), but not directly in the OAC.

Phreatic and epiphreatic solution morphologies (solution flat ceiling, inward-sloping smooth facets, cupola-shaped depressions, and others) originated in slowly moving or standing water (Bella, 1998, 2004; Bella et al., 2000; Bosák et al., 2002). Ford and Williams (2007) presented the OAC as an excellent example of "notch caves" originating from lateral corrosion along the standing water table in the lens of metamorphosed limestone enclosed by phyllites.

Complementary multidisciplinary research aiming at refining the origin and development of the OAC was conducted since 2013. New knowledge and data obtained from a high-resolution documentation of cave topography and morphology, high-resolution magnetostratigraphy of cave sediments, and additional U-series speleothem dating are presented here to explain the genesis of the OAC.

LOCATION AND SETTINGS

The OAC is located in the Ochtná Karst on the north-western slope of Hrádok Hill (809 m above sea level; asl) in the eastern part of Revúcka vrchovina Highland (Slovenské rudohorie Mountains, central-southern Slovakia; Fig. 1A, B). The artificial tunnel entrance to the OAC is at 642 m asl. The cave is about 300 m long (Ševčík & Kantor, 1956) with a vertical relief of 33 m (Pukanská et al., 2020).

Fig. 1. Location of the Ochtná Aragonite Cave and the geological settings of the Hrádok Massif. A) Hrádok Massif from the Štítnik River Valley (Photo by P. Bella); B) Map of the vicinity of the cave (topography: <https://zbgis.sk/geodesy.sk/mkzbgis/sk/>); C) Geological cross-section sketch (modified from Gaál, 2004). 1. Drnava Formation, graphitic and sericitic-graphitic phyllites, 2. Crystalline limestone (marbles), 3. Rožňava Formation (ankerite, weathered ankerite), 4. Metamorphosed quartz greywacke and sandstone, 5. Metamorphosed quartz conglomerate.

The OAC is formed in Lower Devonian crystalline limestone (marble) and ankerite of the Drnava Formation (Lower Paleozoic; Gelnica Group/Gemic Unit) at the contact zone of Veporic and Gemic units. Three carbonate lenses in the Hrádok Hill are completely or almost surrounded by graphitic and sericitic-graphitic phyllites rich in sulfides in places (Bystrický & Fusán, 1954; Bajaník et al., 1983; Gaál, 2004; Fig. 1C). They are ~50 m in thickness with a total length of 800 m and general inclination of 40°–45° SE (Ševčík & Kantor, 1956). The Drnava Formation is unconformably overlain by weakly metamorphosed quartz greywacke and sandstone, and quartz conglomerate of the Rožňava Formation (Permian; Gočaltovo Group/Gemic Unit). Conglomerates build the present highest part of the Hrádok Hill (e.g., Bystrický & Fusán, 1954; Bajaník et al., 1983; Gaál, 2004; Grecula et al., 2009; Fig. 1C).

The Drnava Formation underwent low-pressure metamorphism in greenschist facies probably in Viséan–Namurian/Serpukhovian (Carboniferous) and folding/faulting at the end of the Variscan Orogeny (e.g., Fusán, 1957; Grecula, 1982; Sassi & Vozárová, 1987; Vozárová & Vozár, 1988). Hydrothermal fluids ascended along steep faults leaching Paleozoic metabasalts (Grecula, 1982) when Fe (Mn)-rich fluids concentrated their mineral load in limestone lenses. Because Ca was metasomatically depleted, a part of limestone was altered to ankerite (e.g., Mišík, 1953; Bystrický & Fusán, 1954). Hurai et al. (2002) assumed crystallization of quartz–ankerite–sulfidic ores from basinal brines were expelled during Early to Middle Cretaceous compression at the closure of the Meliata Ocean. Only some Variscan faults were rejuvenated during the Alpine Orogeny and cleavage in marble originated (Gaál, 2004).

Nearly 56% of the OAC is developed in marble. Marble lenses are generally NE–SW-trending and strata dip is steeper in the southern part of the cave (60°–85°) than in the northern one (30°–50°). The ESE–WNW-trending Alpine cleavage oblique to Variscan faults is evident (Gaál, 2004). The ankerite is exposed on over 43% of cave walls, mostly along the NE–SW-trending faults that dip 70°–80° NW (Gaál, 2004). They, as a part of the Hrádok fault zone (see Potočný et al., 2020), are associated with Alpine fault rejuvenation. Faults represent principal infiltration paths of meteoric waters into the cave.

Fe oxyhydroxides originated by ankerite oxidation and form several cm-thick covers of ankerite bodies, mainly along faults. Fe oxyhydroxides have rusty- or light-brown color and consists of cryptocrystalline goethite, partly with increased Mg contents (e.g., Ševčík & Kantor, 1956), and water content of ~40% (Čilek et al., 1998; Bosák et al., 2002). Quartz veins up to 30 cm thick cut ankerite bodies and protrude from Fe oxyhydroxides on the weathered surface of ankerite (Ševčík & Kantor, 1956).

Recent groundwater penetrates along bedding in marble lenses dipping in direction of north-eastern slope of the Hrádok Hill, where several springs in the Banská dolina Valley are situated 100 m lower than the OAC (Droppa, 1957). The north-western

slope is drained by the Ochtinský potok Brook. The OAC water likely reaches the surface in the spring at 613 m asl located north-east of the Kapusta Adit mouth (Ševčík & Kantor, 1956; Droppa, 1957). Chemical composition of spring water is similar to cave groundwater (Rajman et al., 1990), i.e., mostly alkaline, moderately mineralized, with a temperature from 7.2 to 8.5°C. In seepage as well as lake waters, the Ca–Mg–HCO₃[–] type is chemically dominant. Both are characterized by low sulfate concentrations up to 34–43 mg/L (Peško, 2002; Haviarová & Peško, 2004; unpublished analyses from 2017 and 2018). The water table in cave lakes is ~23 m higher than in the spring situated 480 m away.

METHODOLOGY

Terrestrial laser scanning, digital photogrammetry, and geomorphological research

The survey of the cave performed by terrestrial laser scanning (TLS) and digital close-range photogrammetry (DCRP) resulted in high-resolution topography and morphology of the OAC (for details see Pukanská et al., 2020). More than 121 million points from 54 survey stations were measured with a compact all-in-one full panoramic pulse laser scanner Leica ScanStation C10. The spatial resolution of 20 × 20 mm of the final point cloud was achieved. New cave map, sections, and the 3D model using these surveying technologies were created from the resulting point clouds, processed in computer-aided design software – Microstation V8i and Leica Cloudworks. We used a triangular mesh generation method by Poisson Surface Reconstruction algorithm (Bolitho et al., 2007) to create the 3D MESH model, where surfaces are represented as a polygonal mesh. Some specific morphologies (cusped depressions and below-lying smooth facets on the lower parts of cave walls) were mapped with the Structure-from-Motion (SfM) method of DCRP using digital camera DSLR Pentax K-5 with Pentax SMC DA 15 mm lens and processed in Agisoft PhotoScan Professional Edition software. TLS and SfM were performed and processed in the Institute of Geodesy, Cartography and GIS, Faculty of Mining, Ecology, Process Control and Geotechnologies of the Technical University in Košice, Slovakia.

Basic morphometric data on cave morphology and some selected specific solution morphologies (flat ceiling, facets) were generated. An inventory of solutional morphologies enabled to infer former speleogenetic processes (following the studies of Lange, 1962, 1963; Curl, 1966; Reinboth, 1971; Kempe et al., 1975).

Paleomagnetic analysis

Sediment profile in the eastern part of the Oválna chodba Passage (pilot samples distant 10–12 cm; Bosák et al., 2002) was revised (Fig. 2). High-resolution (for details see Bosák et al., 2003; Zupan Hajna et al., 2008) re-sampling of 40 samples in 2013 covered a 62-cm thick profile with 2 to 4 cm resolution. Furthermore, 14 parallel samples (marked A, B) were

taken at 4, 10, 17, 24, 31, 41, and 55 cm below the profile's top to control statistics of paleomagnetic parameters (Fig. 2B). Paleomagnetic analyses were performed and processed in the Department of Paleomagnetism, Institute of Geology of the Czech Academy of Sciences in Průhonice by methodology described by Zupan Hajna et al. (2008) or Bella et al. (2019).

Sediments were sampled in non-magnetic plastic boxes oriented in situ. Unconsolidated samples were demagnetized by an alternating field up to 100 mT in 13 steps on the LDA-3A apparatus (AGICO, Ltd.) or the Superconducting Rock Magnetometer (755 4K SRM). The isothermal remanent magnetization (IRM) and the saturation isothermal remanent magnetization (SIRM) were determined using the pulsed magnetometer MMPM, where the field takes

values from 10 to 1,000 mT. The characteristic remanent magnetization (ChRM) of each sample was determined by subjecting its demagnetization results to the principal component analysis technique of Kirschvink (1980) and the computer program Remasoft 3 (Chadima & Hroudá, 2006). The mean directions of the respective remanence components relative to the horizontal position of the rocks were calculated using the Fisher's (1953) statistics. The interpreted polarities of the geomagnetic field were correlated with normal and reverse magnetozones of the GPTS geomagnetic scale (Cande & Kent, 1995), and calibrated using the ages of Cohen & Gibbard (2019). The NRM magnitude and the interpretation of magnetic polarity record depend on the concentration and type of magnetic minerals in sediment.

Fig. 2. Sedimentary profile in the Oválna chodba with paleomagnetic samples: A) general view; B) detail of sampling profile with paleomagnetic cubes (Photos by P. Bella).

U-series dating

Following the U-series dating of aragonite and calcite speleothems by D.C. Ford (in Rajman et al., 1990, 1993) and Bosák et al. (2002), two additional samples were collected to reconstruct development phases of the cave. Recrystallized flowstone preserved in the small ceiling cavity at the eastern edge of the Oválna chodba is truncated

by a solution flat ceiling (OCH-4; 646.5 m asl; Figs. 4 and 5). The sample was taken to verify previous U-Th isotopic data and age of samples JOA 1 and JOA 2 (Bosák et al.; 2002). The second sample (OCH-5; 646.7 m asl) is from a kidney-shaped aragonite precipitated on the ceiling of the Hviezdna sieň Hall (Figs. 4 and 5) whose surface was later corroded by floodwater.

Fig. 3. Position of samples for U-series dating. A) Recrystallized flowstone (OCH4-A) truncated by a flat ceiling at the eastern edge of Oválna chodba; B) Corroded aragonite (OCH5-A) on the ceiling of the Hviezdna sieň (for sample positions see Fig. 4) (Photos by P. Bella).

Both samples were analyzed by the $^{230}\text{Th}/^{234}\text{U}$ method at the U-series Laboratory of the Institute of Geological Sciences of the Polish Academy of Sciences (Warsaw, Poland). The ICP-MS method was used for uranium (U) and thorium (Th) isotope analyses. Chemical separation of U and Th from the carbonate matrix was carried out in the institute following the method described by Hellstrom (2003). Measurements were performed on a double-focusing sector-field ICP MS (Element 2, Thermo-Finngan MAT) in the Department of Geological Processes, Institute of Geology of the Czech Academy of Science, Prague, Czech Republic. The measurement results were corrected for counting background and chemical blank. U-series ages were iteratively calculated from the $^{230}\text{Th}/^{234}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios. All uncertainties, except those associated with decay constants were considered when assessing age uncertainties using error propagation rules.

RESULTS

High-resolution cave topography and morphology

The OAC is a subhorizontal maze developed at a ground area of about 30×35 m limited by the dimensions of marble lens. The cave consists of two morphologically different parts (Fig. 4A): 1) high linear fissure passages and elongated halls with ceiling

fissures controlled by steep parallel NE–SW-trending tectonic lines in the western cave segment (Vstupná sieň Hall – Puklinová chodba Passage – Mramorová sieň Hall); in the central part (Mliečna cesta Hall), and in the eastern one (Hlboký dóm Chamber) and 2) transverse lower flat-roofed and vaulted passages interconnecting morphologies of the first type (Oválna chodba, Ježovitá chodba, Čarovná chodba, and Priepastovitá chodba passages).

The central part of the cave is mostly horizontal with openings of looped conduits descending below the floor level in places (Priepastovitá chodba and Ježovitá chodba). Numerous higher cupola-shaped depressions and enlarged ceiling fissures reach upwards from a generally horizontal ceiling, which is wider than the floor. The peripheral eastern and western cave segments are tectonically controlled in a larger extend, therefore a vertical span of their uppermost and lowermost points is greater (up to 33 m) than in the central part of the cave. The topmost point is situated in the highest part of fissure passage connecting the Vstupná sieň and the Mramorová sieň. Lakes, with oscillating water table, occur in the lowest depressions at the opposite edges of the cave. The area of cave ground plan is $1,335 \text{ m}^2$, the inner surface area of underground spaces is $7,064 \text{ m}^2$, and their volume reaches $4,424 \text{ m}^3$.

Fig. 4. Ochtná Aragonite Cave. A) 3D visualization (▲ – studied sedimentary profile for the paleomagnetic analysis, ■ – sampling sites of U-series dating); B) Side projection (W–E) and altitudes of flat ceilings.

Medium- and small-scale solution morphologies, mainly horizontal flat ceilings (Laugdecken after Biese, 1931), inward-sloping smooth facets (Facetten, planes of repose), ceiling cupola-shaped and smaller spherical depressions, wall notches, as well as spongework-like hollows are typical features of the cave. Flat ceilings occur at several altitude levels: 647.50–647.65 m (the western niche in the Puklinová chodba, the western edge of Oválna chodba), 647.0–647.25 m (the central part of Oválna chodba), 646.45–646.55 m (the eastern edge of Oválna chodba, Aragonitová záhrada Passage), and 646.30–646.35 m (Ježovitá chodba) – mostly in segments of transverse passages with continuously exposed marble in the eastern half of the OAC (Figs. 4 and 5A). The height difference between the lowest and highest flat ceilings is 1.35 m. Flat ceilings consist of several individual fully horizontal surfaces (up to 12.8 m²) interrupted by slightly rugged quasi horizontal surfaces (with bedrock protrusions up to 10–15 cm), wherein a height difference among fully horizontal surfaces is 10 to 25 cm. If we connect quasi-horizontal

and fully horizontal surfaces, the “generalized” surface of the flat ceiling in the Oválna chodba reaches 34.9 m² with the greatest at its eastern edge width (up to 5.5 m). The largest “generalized” segment of flat ceiling (52 m²) occurs in the Ježovitá chodba and is 3.5–4.5 m wide. Also, fully horizontal surfaces are sporadically interrupted by small bedrock pyramidal and comb-shaped pendants.

Transverse passages with flat ceilings associated with solution facets are characterized by triangular cross-sections (Laughöhle profile after Biese, 1931 – Oválna chodba) or trapezoidal cross-sections (Ježovitá chodba and Priepasťovitá chodba; Fig. 6A, B). In detail, flat ceilings are not directly connected here to inward-sloping smooth facets with a sharp angle. The upper parts of cave walls between flat ceilings and facets are represented by overhanging rounded segments with cusped depressions. Morphostratigraphically, flat ceiling at 646.3 m asl truncates older cupola-shaped and smaller spherical depressions (mostly in the Ježovitá chodba; Fig. 6C).

Fig. 5. Occurrence of solution flat ceilings (A) and inward-sloping smooth facets (B). Altitudinal positions of solution flat ceilings: blue 646.30 to 646.35 m asl, green 646.45 to 646.55 m asl, yellow 647.00 to 647.25 m asl, and red 647.50 to 647.65 m asl.

Fig. 6. Passages with a solution flat ceiling and facets. A) Ježovitá chodba; B) Oválna chodba. Cupola-shaped spherical depression truncated by a flat ceiling; C) Ježovitá chodba. Asymmetrical cusped depressions on the cave wall above solution facets; D) Srdce Hrádku Passage (Photo by P. Bella, right).

Facets as solution inward-inclined smooth wall surfaces generally maintain a slope of $\sim 40^\circ\text{--}45^\circ$, independent of an inclination of marble bedding planes or lamination, which is in accordance with Lange (1963; Figs. 6A–D). Facets developed not only in flat-roofed passages, but also in vaulted (horizontal or inclined) passages and chambers (Fig. 5B), mostly only in the lower parts of bedrock walls (lower halves). The length of the inclined surface of the facets is typically 2–2.5 m, rarely to 4.2 m. The length of the inclined surface of the facets decreases depending on the reduction of the height and width dimensions of passages. The upper edges of facets are not linear at one height level, and they are not separated from upper-lying morphologies by wall water table notches. Facets truncate looped phreatic conduits on the walls or floor of passages in places (Priepasťovitá chodba and Ježovitá chodba).

Numerous cusped depressions occur on cave walls above facets, mainly in chambers and wider passages. Their length and width reach dimensions of mostly 5 to 10 cm. They are predominantly asymmetrical, with a shallower part oriented downwards to their lower edge (Fig. 6D). This feature was also documented in a high-resolution cave morphology, result of the TLS and digital photogrammetry (see Pukanská et al., 2020). Such cusped depressions resemble large asymmetrical scallops; therefore, they might be considered as former flow direction indicators.

The water table notch, about 0.4 m high (646.6–647.0 m asl) and 0.21 m deep, extends along the south-eastern wall of the Mramorová sieň. The notch corresponds to altitudes of flat ceilings in the Oválna chodba and Aragonitová záhrada. Flat ceiling in the Ježovitá chodba is situated 0.3 m below. Higher-lying notches in the ceiling of enlarged fault with tectonic breccia along the south-eastern edge of the Mramorová sieň are at 648.5 m asl. The water table notch on the northern wall of the Hlboký dóm is at 643.20–643.55 m asl, i.e., lower than all flat ceilings, and about 6.5 m above the water table of the present lake at the chamber bottom (the north-eastern edge of the cave).

High-resolution magnetostratigraphy of sediments

Re-sampled profile in the Oválna chodba (Fig. 2) consists of layered fine-grained sediments deposited on marble bedrock between two opposite inward-sloping smooth facets (detailed descriptions in Čílek et al., 1998 and Bosák et al., 2002). Sediments represent continuous condensed deposit of infiltration load with no distinct internal hiatuses. The profile top is truncated by younger erosion in vadose conditions.

Successive demagnetization by alternating fields (AF) allowed to derive reliable data of paleomagnetic directions and to determine polarity of magnetic field at the time of deposition, although samples showed low NRM. Mean values of magnetic parameters and standard deviations for pilot 5 samples (1999) and 27 additional samples (2013) are summarized in Table 1. Mean paleomagnetic D and I values (Table 2) in group with R polarity (1999) show high dispersion (α_{95}) in comparison with R-polarized samples of 2013 group

due to low number of samples (n) and in group with R polarity (2013) show higher dispersion than the group with N polarity due to lower NRM values in the lower part of profile.

Table 1. Magnetic parameters and standard deviations for all samples in Oválna chodba (NRM: natural remanent magnetization; MS: magnetic susceptibility).

Ochtiná Aragonite Cave	NRM [mA/m]	MS [SI*10 ⁻⁶]
Values	0.42–72.58	35–1,999
Mean value	20.333	446.8
Standard deviation	20.551	441.6
Number of samples	32	32

Table 2. Mean paleomagnetic directions for all samples in Oválna chodba (N: normal polarity; R: reverse polarity; D, I: declination, inclination of the remanent magnetization; α_{95} : semi-vertical angle of the cone of confidence calculated according to Fischer (1953) at the 95% probability level; K: precision parameter; n: number of analyzed samples).

Polarity	Mean paleomagnetic directions		α_{95} [°]	K	n
	D [°]	I [°]			
N	354.28	54.03	5.55	63.58	10
R	172.69	-46.41	7.86	11.76	17

Low differences in the NRM and MS values is characteristic for control samples at seven levels from 2013 (Fig. 2), but different contents of magnetic minerals at the same level is indicated (e.g., sample OA41). Interpreted polarities at identical levels correspond; the primary magnetization component C and the polarity was not determined only in one sample (OA04B). Examples of subsequent AF demagnetization of samples with N and R polarities from different profile levels are shown in Figure 7A. The stereographic projections of interpreted paleomagnetic directions of the RM are illustrated in Figure 7B for N-polarized (2013) and R-polarized (1999 and 2013) samples.

According to the IRM, magnetite is carrier of the magnetization in all samples accompanied by other magnetically harder mineral (hematite; examples in Fig. 7A). The low value of the anisotropy of low-field magnetic susceptibility (AMS) was measured in all samples (Fig. 7C). The dominant direction of magnetic lineation is NE–SW with very low inclination to NW. Anisotropy shape T has slightly oblate and elongated shape.

Sediments in the upper part of profile showed N magnetic polarity, which Bosák et al. (2002) interpreted as the Brunhes chron (C1n; <0.773 Ma; ages according to Cohen & Gibbard, 2019). The N/R boundary (Brunhes/Matuyama chron boundary, B/M; Bosák et al. 2002) was more precise determined in 2013 sampling at 13 cm below the profile's top (between samples OA12 and OA14, with precision of ± 1 cm; Fig. 8). Sampling in 1999 was interpreted as N/R boundary between samples OCH1 (~ 5 cm) and OCH2 (~ 18 cm; Bosák et al., 2002). Sediments at relative levels of 14–53 cm (OA14 to OA53; 2013) show mostly R magnetic polarity (deposition during Matuyama Chron; Bosák et al., 2002). The newly

detected short N-polarized magnetic zone is situated 33 cm below the top of the profile (OA33). Samples at profile's base (OA55 to OA60) showed unclear polarity, therefore the stratigraphic interpretation

is not fully clear. Paleosecular variations are evident between samples OA01 and OA12 (N polarity), as well as between samples OA36 and OA45 (R polarity).

Fig. 7. Examples of the AF demagnetization of samples (A), directions of C-components of remanence (B), and the AMS (C). A up: Sample OA08, normal paleomagnetic polarity; A middle: Sample OA41A reverse paleomagnetic polarity; A down: Sample OA43 reverse paleomagnetic polarity: left circles – a stereographic projection of the natural remanent magnetization, middle – Zijderveld diagram, right boxes – a graph of normalized values of the remanent magnetic moments versus demagnetizing fields; M – modulus of the remanent magnetic moment of a sample subjected to AF demagnetization (mT); B – direction of ChRM components of remanence of samples with normal and reverse polarity; stereographic projection, open (full) small circles represent projection onto the lower (upper) hemisphere. The mean direction calculated according to Fisher (1953) is marked by a crossed circle, the confidence circle at the 95% probability level is circumscribed around the mean direction.

Fig. 8. Principal magnetic and magnetostratigraphy parameters. M: natural remanent magnetization, Susc: magnetic susceptibility, D: declination, I: inclination; paleomagnetic profile: profile A = samples from 1999, profile B = samples from 2013.

Radiometric ages of speleothems

Results of U-series analyses of two samples are presented in Table 3. These, along with other published data (Bosák et al., 2002) are used to reconstruct the development phases of the cave. They are characterized by relatively high $^{230}\text{Th}/^{232}\text{Th}$ activity ratio (>300). For the mass spectrometry the threshold value of $^{230}\text{Th}/^{232}\text{Th}$ ratio for “clean samples” is commonly considered at values 200–300 (Hellstrom, 2006) so for analyzed samples “detrital correction” was not applicable.

Sample OCH4-A (flowstone truncated by a flat ceiling at the eastern edge of Oválna chodba; Fig.

3A) has an anomalous $^{230}\text{Th}/^{234}\text{U}$ activity ratio (>1), indicator of an open system. Also, samples JOA 1 and JOA 2 (aragonite recrystallized to calcite) taken from the same flowstone in 1997, had $^{230}\text{Th}/^{234}\text{U}$ ratio higher than 1 (about 1.4; Bosák et al., 2002). All three samples have low U contents (0.650, 2.544, and 3.553 ppm), whereas sample OCH5-A (aragonite) has higher U content (11.390 ppm). It suggests uranium leaching from samples JOA 1, JOA 2, and OCH-4 during later processes. Aragonite on the ceiling of the Hviezdna sieň (OCH5-A; Fig. 3B) is dated to 143.2 ± 0.6 ka. Its surface was partly corroded during subsequent floods.

Table 3. New U-Th isotopic data used for speleothem dating.

Method	Sample	U [ppm]	$^{234}\text{U}/^{238}\text{U}$ AR	$^{230}\text{Th}/^{234}\text{U}$ AR	$^{230}\text{Th}/^{232}\text{Th}$ AR	Age [ka BP]	Initial $^{234}\text{U}/^{238}\text{U}$ AR
ICP-MS	OCH4-A	2.544±0.005	1.033±0.002	1.729±0.004	3035±8		
	OCH5-A	11.39±0.02	1.324±0.002	0.761±0.002	13315±43	143.2±0.06	1.4835±0.0023

ICP-MS U-series: calculations use the decay constant of Jaffey et al. (1971) for ^{238}U , Cheng et al. (2013) for ^{234}U and ^{230}Th , and Holden (1990) for ^{232}Th . Ages do not include uncertainties associated with decay constants. AR: activity ratio. Error margins quoted are 2 σ deviations for ICP-MS data. Note: For sample OCH4-A age was not calculated due to U leaching; sample OCH5-A was partly corroded during floods.

INTERPRETATION AND DISCUSSION

CO₂ release during the oxidation of ankerite

Meteoric waters infiltrating along steep faults caused the dissolution of marble and the weathering (oxidation) of ankerite to Fe oxyhydroxides. However, marble was dissolved to a greater extent due to the CO₂ release during ankerite oxidation, i.e., by comparable process described by Kempe (1975, 1998, 2009) in siderite.

Ankerite is sparingly soluble in water. In the presence of water and CO₂, its dissolution is much faster because the corresponding bicarbonates are formed, which are soluble in water:

Oxygen, present in water, oxidizes ferrous bicarbonate $\text{Fe}(\text{HCO}_3)_2$ to ferric hydroxide, $\text{Fe}(\text{OH})_3$ according to equation 5:

The products of this reaction are ferric hydroxide, a reddish-brown colloidal substance (goethite, Fig. 9) and a large amount of released CO₂, which further contributes to the karstification process represented by the dissolution of surrounding carbonate rocks.

Ankerite contains about 2 wt% manganese (II), therefore stoichiometric species of $\text{CaMn}(\text{CO}_3)_2$ is present. In the presence of water and CO₂, this compound will break down (see Equation 6 and 7) and form the soluble manganese (II) bicarbonate, which in the presence of oxygen forms dark brown hydrated manganese (III) oxide (Eq. 8). This latter reaction produces CO₂ that further dissolves limestone:

If more oxygen is available, the oxidation continues to black hydrated manganese (IV) dioxide:

Fig. 9. Crystalline limestone, ankerite, and goethite in Aragonitová záhřada (Photo by P. Bella).

Mn-rich black layer occurs inside brown clays (a mixture of goethite and clay minerals) in the sediments in the Oválna chodba (Fig. 2) and in the artificial trench of tourist path in the western part of Čarovná chodba. The black layer is composed of several bands of hydrated manganese dioxide with abundant intercalations of white allophane and redeposited Fe oxyhydroxides. Allophane was produced in the acidic environment, probably associated with weathering of sulfides (pyrite) in the surrounding rocks (Čilek et al., 1998; Bosák et al., 2002). Equivalent sedimentary profile with Fe and Mg oxyhydroxides, as well as allophane is also exposed in the artificial trench of tourist path in the western part of Čarovná Passage.

Rajman et al. (1990, 1993) previously considered that, in addition to the oxidation of ankerite/siderite, also sulfide (pyrite) mineralization in surrounding rocks may have influenced hydrochemical properties of waters seeping into the OAC. However, the absence of gypsum suggests that this cave formed mainly due to the oxidation of ankerite bodies and the dissolution of the surrounding marble supported by CO₂, which is released during the oxidation of these calcium-ferrous and ferrous carbonates (Bosák et al., 2002). This corresponds to the current chemical composition of waters in the cave that have low calcium and magnesium mineralization (Rajman et al., 1990; Peško, 2002; Haviarová & Peško, 2004). Very acidic (pH 1.9 to 3) and strongly mineralized chloride-sulfate waters with a slightly increased temperature (11.7°C) are recently drained only through the Alžbeta Adit (analyzed by V. Vosáhlo in 1955; see Korpeľ & Kotras, 1957 and Rajman et al., 1990), located southwest of the OAC at the end of the Ochtinský potok Valley.

Origin of solution facets and above-lying cusped depressions

The OAC is a key locality to study the origin of solution facets on limestone walls. According to Lange (1963), these specific solution rock shapes (referred as “planes of repose”) developed during sedimentation of fine-grained particles of insoluble matter on the floor and inward-inclined parts of cave walls, which protect the bedrock from further dissolution (see also Goodman, 1964). Reinboth (1968, 1971) suggests the formation and enlargement of Facetten (solution facets) from upwards at an angle of 45°. He linked their development with the formation of the flat ceiling. However, there is no sharp angle in the corner between them, but an overhanging wall with solution pits. Further, he stated that facets developed because fluid near the ceiling/water table dissolves soluble rock more rapidly than in lower parts of the cavity. According to Gripp (1913), Kempe (1970, 1972), and Kempe et al. (1975), Facetten are created by descending (under-)saturated water.

Gripp (1913), Reinboth (1992), and Kempe (1996a) explained the origin of Facetten in flat-roofed passages with a triangular cross-section in gypsum caves. However, solution facets in the OAC are not associated only with a flat ceiling. They may occur in phreatic conduits with oval or vaulted ceiling without any re-shaping by later processes. They were also

noticed around chambers without flat ceilings, in small wall niches even in several height positions in the same passage or chamber. In flat-roofed passages of the OAC, the corner between solution facets and flat ceiling is represented by overhanging wall with solution hollows or cusped depressions.

Cusped depressions and lower-lying inward-sloping smooth solution facets (Fig. 6) show that these morphologically different and sharply bounded wall-rock shapes originated by limestone dissolution under different conditions. Asymmetrical cusped depressions indicate their development by downward slowly moving water, whereas smooth facets are covered by a protective coating accumulated from suspended Fe oxyhydroxides (Fig. 6D). In phreatic conduits with stagnant or almost stagnant water, natural water convection resulted from the density difference between solutions at limestone walls and in the bulk of water body. While water at the dissolving surface moves downward (an increase in solution density along exposed limestone surfaces), within the bulk fluid is opposite motion – upward (Curl, 1966; see also Gripp, 1913). In the transverse passages of the OAC, the bedrock floor and flat ceilings are not controlled and dissected by central vertical fracture as assumed by models of Grip and Kempe. It is more likely that solution facets in the OAC were probably developed by limestone dissolution under conditions of slowly downward moving water, possibly accompanied by deposition of insoluble fine-grained particles (*sensu* Lange, 1963, 1968).

Origin of solution flat ceilings

The origin of a horizontal ceiling along the water table was described by Gripp (1913), but in gypsum caves. Lange (1962) stated that when the water table remains nearly constant, solution planed ceilings in limestone caves can be developed along the surface of a cave lake (by so-called “ceiling planation”). The formation of flat ceilings in caves in connection with external or internal erosion base was also discussed by Cocean (1975, 1979).

In the OAC, solution flat ceilings occurring at different elevations are associated with solution inward-sloping smooth facets, i.e., they were developed in the flat-roofed passages, but with no sharp angle between facets and flat ceiling. Therefore, flat ceilings were probably formed closely below the slightly oscillating water table (as assumed by Reinboth, 1968, 1971 and Kempe et al., 1975; see also Gechter et al., 2008). The wider horizontal wall notch in the Mramorová sieň (Fig. 4B) that occur at the same altitude as the flat ceiling in the Ježovitá chodba, indicates a slight water table oscillation during its formation. Solution experiments with salt models by Reinboth (1992) showed that the solution at the Laugdecke is about twice faster than the solution at a vertical wall and about three times faster than on upward-facing surface. Flat ceilings seem to develop if the solution is fast, i.e., in low-saturated water (Kempe, 1996a). Undersaturated groundwater moving through the fractured insoluble rocks from the surrounding area penetrates the karstified marble lens. Since this water has a lower density, it is

concentrated in the upper part of the water column. In several places, small bedrock pyramidal and comb-shaped pendants protrude downwards from the flat ceilings, which have not been completely removed by the lateral enlargement/corrosion of the ceiling.

Magnetostratigraphy and morphogenetic implications

Magnetostratigraphy (both on pilot samples and high-resolution) proved N magnetic polarity in the upper part of profile. It is interpreted as the Brunhes chron (C1n; <0.773 Ma). The N/R boundary (C1n/C1r) is linked to the B/M chron boundary already by Bosák et al. (2002). R-polarized sediments below the N/R boundary represent the Matuyama chron. The newly detected short N-polarized magnetic zone inside the R-polarized Matuyama chron at 33 cm below the top of the profile (OA33) is interpreted here as the Jaramillo event (C1r.1n, 0.990–1.071 Ma). To support this interpretation, we compared mean paleomagnetic directions (D, I) from the Oválna chodba with the segment of identical age in the Domica Cave, which is situated only ~30 km to SSE (Bella et al., 2019; Table 4). The newly calculated counter-clockwise paleorotation (CCW) values both for N- and R-polarity segments are nearly identical in

both sediment segments. R-polarities in the Domica Cave have larger dispersion, but still within α_{95}° values. Higher CCW rotations in R-polarized segment than in N-polarized one generally correspond to published data for Pannonian–Carpathian domain (Krs & Pruner, 1999; Márton et al., 2015). Domica data show higher CCW values also due to fact, that evaluated R-polarized segment below the B/M boundary is longer than in the OAC. Mean paleomagnetic directions and the CCW values both in the Domica Cave and in the OAC strongly support our magnetostratigraphy interpretation for sediments in the Oválna chodba. Short-lasting N excursions below the B/M boundary (i.e., Kamikatsura at ~0.885 Ma, Santa Rosa at ~0.932 Ma, cf. Gibbard and Cohen, 2019) hardly can be recorded in this type of phreatic clays and size of sampling boxes. Samples at profile base (OA55 to OA60) showed unclear polarity, therefore the stratigraphic interpretation is not fully clear; they might even represent the transition to Olduvai subzone (C2n, 1.780 to 1.925 Ma). The sedimentary profile is truncated by erosion in the vadose zone and unconformably covered by flowstone (~177 ka – sample JOA3; Pruner et al., 2000; Bosák et al., 2002) constraining the youngest possible age of Oválna chodba sediments.

Table 4. Mean paleomagnetic directions and rotations (present declination value of 2° is included in the CCW calculation).

Cave	n	Polarity	Mean paleomagnetic directions		α_{95}°	CCW [°]
			D [°]	I [°]		
Ochtiná	9	N	355.91	52.23	5.14	6.09
Domica	51	N	355.44	56.26	3.61	6.56
Ochtiná	23	R	172.51	-47.81	8.39	9.49
Domica	59	R	166.93	-47.24	4.27	15.07

The calculated and estimated/interpolated depositional rates of individual segments of profile in Oválna chodba are based on dated paleomagnetic boundaries (from the B/M boundary at 0.773 Ma; up to Jaramillo base at 1.071 Ma) and continuous deposition without any hiatuses (Table 5). Top of Jaramillo (0.990 Ma) subzone is roughly equal to upper boundary of Mn-rich horizon with asbolane/allophane. The values for upper part (to Jaramillo top) and profile base (below Jaramillo base) are slightly below 0.09 cm/kyr (Table 5). Mn-rich layer indicates even lower depositional rates (slightly below 0.03 cm/kyr).

The prevailing NE–SW direction of magnetic lineation from AMS measurements indicates uniform direction of water flow during the accumulation of sediments, i.e., from the Hlboký dóm through the Oválna chodba to the Mliečna cesta. The low depositional rate of clays and silty clays above and below Mn-rich zone resulted from very slow water movement in confined conditions in marbles completely enclosed by phyllites and with no direct relation to the surface. Only occasionally turbid water seeped through crystalline rocks was loaded in extremely fine-grained infiltration material, autochthonous Fe oxyhydroxides and negligible coarser-sized allogenic input (see in Bosák et al., 2002). Much slower depositional rate of Mn-rich layers probably resulted from slow chemical reactions and precipitation on Mn-bearing minerals (although also

mixed with input of infiltration load). Calculated and estimated data from Table 5 might indicate that the deposition in the Oválna chodba profile started not sooner than ~1.8 Ma ago. The unclear paleomagnetic polarity of basal samples (OA55A–B to OA60) and N–R polarity of sample OA55 might support this calculation. These samples could represent the top of the Olduvai magnetic subzone (C2n, 1.780–1.925 Ma), if depositional rates below Jaramillo base were not higher than presented in Table 5. The age of flowstone covering the sediments is ~177 ka (Bosák et al., 2002), therefore described sediments were eroded in fully vadose conditions between <630 and >177 ka (Table 5) by multiple oscillating and mowing groundwater in the lower parts of the OAC, similar to the present hydrological situation.

The prevailing NE–SW direction of magnetic lineation from AMS measurements indicates uniform direction of water flow during the accumulation of sediments, i.e., from the Hlboký dóm through the Oválna chodba to the Mliečna cesta.

Updated reconstruction of an origin and development of the cave

The OAC began to develop under confined phreatic conditions in marble completely enclosed by phyllites. Mostly fault-controlled infiltration of oxygenated water from surface through phyllites and other

metamorphic rocks caused oxidation of ankerite to Fe oxyhydroxides accompanied by CO₂ release. Dating of sediments indicates that the beginnings of cave formation can be placed in Pliocene–Early Pleistocene (Tables 5 and 6). The primary cavities were enlarged by the dissolution of marble around bodies of decomposed ankerite. Following their gradual enlargement, horizontal passages developed, through which the fissure parts of the cave formed along parallel faults (Mramorová sieň – Vstupná sieň, Mliečna cesta, and Hlboký dóm) were interconnected. Irregular niches and cupola-shaped depressions are remnants of older cavities, which were formed by marble dissolution under conditions

of very slow density-driven convectional cellular water circulation when water body operated probably close to the saturation (see Kempe, 1996b).

Fine-grained infiltration sediments and suspended Fe oxyhydroxides were deposited on the floor and bedrock walls inclined to ~45°. Because these materials are poorly permeable to impermeable, their presence prevented the dissolution of the underlying marble surfaces. Therefore, the corrosion occurred only on the exposed (uncovered) parts of marble walls and ceilings. Inward-sloping smooth bedrock surfaces enlarged from the bottom up and were covered with a protective coating accumulated from suspended Fe oxyhydroxides (see Lange, 1963).

Table 5. Calculated and estimated/interpolated depositional rates and duration of deposition of individual segments in the Oválna chodba.

Profile segment	Vertical distance [cm]	Age [Ma] [§]	Period		Depositional rate [cm/kyr]
			[Myr]	[Ma]	
Profile top – Brunhes base	13	>0.177 – <0.773	≤0.145*	≤0.630 – 0.773*	0.088*
Matuyama top – Jaramillo top	19	0.773 – 0.990	0.217	0.773 – 0.990	0.088
Jaramillo top – Jaramillo base	2	0.990 – 1.071	0.81	0.990 – 1.071	0.028
Jaramillo base – base of Mn-rich layer	16	>1.071	~0.570*	1.071 – ~1.640*	0.028*
lower clay	12	–	≤0.180*	1.640 – ≤1.820*	0.088*

[§]paleomagnetic boundaries (Gibbard & Cohen, 1999) and U-series dating (Bosák et al., 2002);

*estimated/interpolated values refer to identical sediment environment as in calculated segments.

Sediments studied in the lower part of the Oválna chodba began to accumulate on its bottom bedrock in fully phreatic conditions in confined aquifer before 1.071 Ma, most probably not later than 1.8 Ma ago (Early Pleistocene, Table 5); the formation of this passage must have ended in this time. Layers with allophane, product of sulfide weathering, started to deposit at ~1.6 Ma and ceased their accumulation roughly at 0.990 Ma (the end of the Jaramillo magnetic subzone; Table 5). The flowstone covering the sediments dated to ~177 ka, deposited already in vadose conditions.

Epiphreatic horizontal wall notches have formed along the slightly oscillating and long-lasting stagnation groundwater table and flat ceilings (Laugdecken) closely below it. Primary phreatic cavities were substantially enlarged. Many irregular cupola-shaped depressions and spongework-like hollows are relics of primary phreatic morphologies and are still preserved above flat ceilings and on sides of main passages.

Remnants of corroded aragonite in some cupola-shaped depressions were truncated by younger horizontal flat ceilings. They date the evolution of flat ceiling at 646.5 m asl in the short passage between the Oválna chodba and Hlboký dóm. Flat ceiling cut the older ceiling cavity between ~450 and >177 ka (Bosák et al., 2002), i.e., after partial erosion of fine-grained sediments. Thus, sediments in the Oválna chodba were eroded between ~680 and >450 ka by periodic and multiple groundwater table oscillations. Solution of inward-sloping smooth bedrock surfaces (facets) developed during the major enlargement phase/phases of passages and chambers and they truncate looped conduits (Bella, 2004).

The dated aragonite with a corroded surface at 646.7 m asl (sample OCH5-A) suggests that the cave was once again flooded up to its ceiling after 143 ka. This is documented by the thin Fe oxyhydroxides coating accumulated on the 177 ka old flowstone in the Oválna chodba. Also, corrosion vugs in aragonite (138–121 ka old – samples 90/Och2A and 90/Och2B) contain allogenic admixture of mica and quartz (Bosák et al., 2002). The lower part of cupola-shaped depressions truncated by a flat ceiling were flooded even later as the perimeter of depressions is coated by thin accumulations of Fe oxyhydroxides. The upper part of cupolas served as “air traps” and do not contain allogenic coatings but are instead decorated with white aragonite formations (e.g., in the Ježovitá chodba). Younger aragonite generations with ages ≤14 ka (samples 90/Och1 and 95/Och1A; Bosák et al., 2002) are not corroded, meaning that later oscillations of groundwater floods were less ample. At present, the lake water table in OAC's lower part oscillates within 3–4 m, depending on the amount of surface precipitation.

The aragonite generation that is ~121 ka corresponds to MIS 5e, whereas the one of ~13.5 ka corresponds to the Allerød oscillation, nearly at the end of the last glacial period (MIS 2). The youngest generation of aragonite is still forming (MIS 1; Čílek et al., 1998; Bosák et al., 2002).

Type of speleogenesis

Water that has derived its aggressiveness from sources unrelated to surface, i.e., from depths (Palmer 1991, 2007, 2011; Ford & Williams, 2007), represents one of the basic criteria to distinguish hypogenic caves. Kempe (2009) and Kempe et al.

(2016) classified caves formed by processes driven by CO₂ released during ankerite/siderite oxidation at depth, as hypogenic, defining a specific subtype of non-ascending hypogenic speleogenesis. However, according to Webb (2020), such caves are termed supergene, because generation of the acidity is due to near-surface oxidation and they are the result

of shallow meteoric waters circulation and not by ascending waters, where the source is at depth beneath the cave. Following these inconsistent definitions, the OAC may be rather classified as a supergene cave, since it was not formed by waters ascending from the depth and the aggressiveness of waters was derived from near-surface source.

Table 6. Main development phases of the Ochtná Aragonite Cave (updated from Bosák et al., 2002; see also Figure 10).

Development phases	Cave morphology and sediments	Period
Initial phreatic	Individual primary phreatic cavities originated along parallel steep fractures	Late Tertiary – Early Pleistocene
Phreatic	Enlargement of primary cavities to larger voids and conduits, their interconnection through transverse conduits, formation of solution facets, and ceiling cupola-shaped depressions and spongework-like hollows	
Epiphreatic – vadose	Formation of the upper solution flat ceiling (Oválna chodba) closely below the “stabilized” water table, ongoing formation of solution facets and phreatic cavities and conduits in the lower lying, still flooded part of the cave, the highest parts of the steep fissures above the groundwater table began to be sculpted by seeping meteoric water	Early Pleistocene
	Sediment accumulation started (in the Oválna chodba)	<1.8 Ma
	Allophane deposition in the middle part of the sedimentary profile (allophane was produced in the acidic environment, probably associated with sulfide weathering)	≤0.9 – ~1.6 Ma
	Water table drop below middle part of the Oválna chodba	Middle Pleistocene
	Erosion of sediments	<630 – ~500 ka
	Precipitation of the oldest dated generation of aragonite in cavities above the water table (kidney-shaped forms), recrystallization of aragonite to calcite	~500 – ~450 ka
	formation of the lower-lying solution flat ceilings (Ježovitá chodba) and wall notches (Mramorová sieň and adjacent cave parts) closely below the repeatedly “stabilized” water table, final formation of solution facets and phreatic cavities and conduits in the lower-lying, still flooded part of the cave, ongoing enlargement of the highest parts of the steep fissures above the groundwater table by meteoric water	~450 – >177 ka
	Precipitation of flowstone on eroded surface of redeposited Fe oxyhydroxides (e.g., Oválna chodba)	177 ka
	Precipitation of the second aragonite generation (kidney-shaped forms), only partly recrystallized to calcite	143 – 121 ka
	Water table oscillations and repeated floods of the lower-lying cave parts (up to the ceiling level of the Hviezdna sieň), formation of wall notch in the Hlboký dóm along the stabilized water table (approximately at the position of the floor of transverse corridors), the surface of the older aragonite generations was corroded by floodwater (corrosion vugs in 138–121 ka old speleothems contain mica and quartz)	Late Pleistocene
	Precipitation of the third aragonite generation (acicular and spiral forms)	~13.5 ka
	Precipitation of the youngest aragonite generation (“frostwork” in the sense of Hill & Forti, 1995), water table oscillations to a height of 3–4 m and repeated floods on the accumulation floor of the lowest-lying cave parts (flat floor of Vstupná sieň, inclined floor of the Hlboký dóm)	Holocene – Recent

Fig. 10. Simplified sketch of the Ochtná Aragonite Cave development. WT: groundwater table; for details see Table 6.

CONCLUSIONS

The OAC is a one of the most representative examples of a cave formed in a lens of crystalline limestone and ankerite completely enclosed by phyllites. Its origin was controlled by several parallel steep faults along which meteoric water percolated underground. The ankerite was oxidized to various Fe and Mn oxyhydroxides producing CO₂ that in turn enhanced dissolution of marble. Many cupola-shaped depressions and irregular sponge-work-like hollows of phreatic origin contrast with solution flat ceilings formed at multiple elevations just below the former stabilized, but slightly oscillated groundwater table during its interrupted descent. Flat ceilings occur mainly in transverse horizontal passages that interconnect parallel fault-controlled passages and halls. Older cupola-shaped depressions are truncated by flat ceilings. Inward-sloping smooth solution facets were probably developed by the limestone dissolution under conditions of slowly moving or stagnant water, possibly assisted by the sedimentation of insoluble fine-grained rock particles, i.e., they represent so-called the “planes of repose”. Their smooth surfaces, inclined at an angle of about 45°, are covered by thin Fe oxyhydroxides coatings. Inward-sloping smooth facets occur in the flat-roofed passages, as well as in the passages and halls with a vaulted ceiling. Cave sediments deposited from slow moving water in confined phreatic conditions. Jaramillo magnetozone (0.990–1.071 Ma) and the Brunhes/Matuyama boundary (0.773 Ma) were recorded in the Oválna chodba profile. The slow depositional rates (~0.09 cm/kyr, and ~0.03 cm/kyr in Mn-rich horizon) calculated from magnetostratigraphy, correspond to depositional environment under confined phreatic conditions. Transition from phreatic to epiphreatic and vadose zones occurred 630 to 500–450 ka. Older generation of aragonite formations (with ages ~500–450 ka and 143–121 ka) were corroded during older repeated floods. Aragonite formations younger than 13.5 kyr are not corroded because the last repeated floods oscillate only in the lower parts of the cave.

ACKNOWLEDGEMENTS

This work was supported by the grants VEGA No. 1/0146/19 and KEGA No. 004TUKE-4/2019, and institutional financing of the Czech Academy of Sciences, Institute of Geology (no. RVO67985831) and the State Nature Conservancy of the Slovak Republic, Slovak Caves Administration. Thanks to Stanislav Šlechta, Štefan Rákay jr., Leoš Zamborský and Peter Gažík for assistance with field works and measurements. Many thanks to reviewers and the editor for their useful comments and suggestions.

Authorship statement: PBE and PBO designed and directed the study; LG studied the cave geology and PBE the cave morphology; KP and KB performed the terrestrial laser scanning, digital photogrammetry and 3D visualization of the cave; PP, PBO and ŠK performed the paleomagnetic analysis of cave sediments and

its interpretation; HH performed the U-Th dating of speleothems; DH analyzed the chemistry of cave waters; PT interpreted the chemogenesis; PBE and PBO reconstructed an origin and development of the cave. PBE and PBO wrote the paper with input from all authors.

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