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Intensely lithified paleokarst deposits in Okno Cave, Demänovská Valley (Slovakia)

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Abstract: Lithified paleokarst turbidite deposits in Okno Cave, Demänovská Valley occur in cavities intersected by the main relict fluvial passages of the cave. The deposits show a degree of diagenesis not normally associated with lithified cave sediments with the development of spar-lined voids and diagenetic chalcedony. This indicates a period of post-depositional burial before their exposure in the walls of the present cave. The deposits indicate the existence of an ancient period of cave development and filling after the folding of the limestone but before the incision of the Demänovská Valley. This is likely to have taken place in the Paleocene.

Key words: Paleokarst, caves intersecting paleokarst, Demänovská Valley, Okno Cave.

Introduction

While much paleokarst has been reported from the Triassic limestones of Slovakia (Činčura 1992, 1993, 1998; Činčura & Köhler 1995; Činčura & Šucha 1992), there have been few reports of paleokarst deposits as remnants in caves or exposed in and intersected by the walls of caves. Novotný & Tulis (2002) described Paleogene sandstones and conglomerates in Skalné Okno Cave in the Slovenský raj (Slovak Paradise) National Park. The deposits described here appear to be the first examples reported from Slovakia of paleokarst turbidite sediments filling ancient caves that have been intersected by more modern caves.

Setting

Location

The Demänovská Valley is one of a number of north-south trending valleys cutting through the Nízke Tatry Mountains (Low Tatras) in central Slovakia. An extensive system of largely fluvial caves, the Demänovská Caves, is developed in the limestone towards the northern end of the valley 10 kilometers south of the regional city of Liptovský Mikuláš. The caves include the show caves Demänovská Cave of Liberty and Demänovská Ice Cave.

Geomorphological setting

The Demänovská Valley was excavated through the E-W trending Nízke Tatry Mountains (Western Carpathians) by the Demänovka River flowing north towards the Liptovská kotlina Basin (Fig. 1). The entrance to Okno Cave is located high in the eastern side of Demänovská Valley, some 150 meters above the active bed of the Demänovka River at an elevation of 916 meters above sea level (Fig. 2).

Droppa (1966) recognised that Okno Cave represented the highest and oldest, ninth level, in his sequence of cave development in Demänovská Valley. He gave no definite age for this level due to "lack of sufficient evidence", but suggested a Pliocene age because of "the degree of weathering of the fluvial gravel" (Droppa 1966, p. 191). Orvošová (2005) suggested that the incision of the adjacent Jánska Valley (Fig. 1), which is incised through the same limestone as Demänovská Valley, also occurred in the Pliocene.

Geological setting

In the Demänovská Valley area, Mesozoic marine sediments dipping to the north and northeast on the Krížna Nappe overlie the "crystalline core" of the Low Tatra Mountains (Fig. 3). Okno Cave is developed in the Triassic Gutenstein Limestone. Biely (1992) indicated that strata near the cave dip 30 degrees to the northeast. The limestone at the cave entrance is massive with beds 1 m or more thick. East of the cave entrance the limestone dips at 30° towards 064°. Granites and crystalline metamorphic rocks crop out to the south of the limestone, while to the northeast the limestone is overlain by Jurassic marls and sandstones.

Okno Cave

Okno (Window) Cave, with a plan length of 930 meters, is principally composed of former stream passages, extending in an arc for some 600 meters south

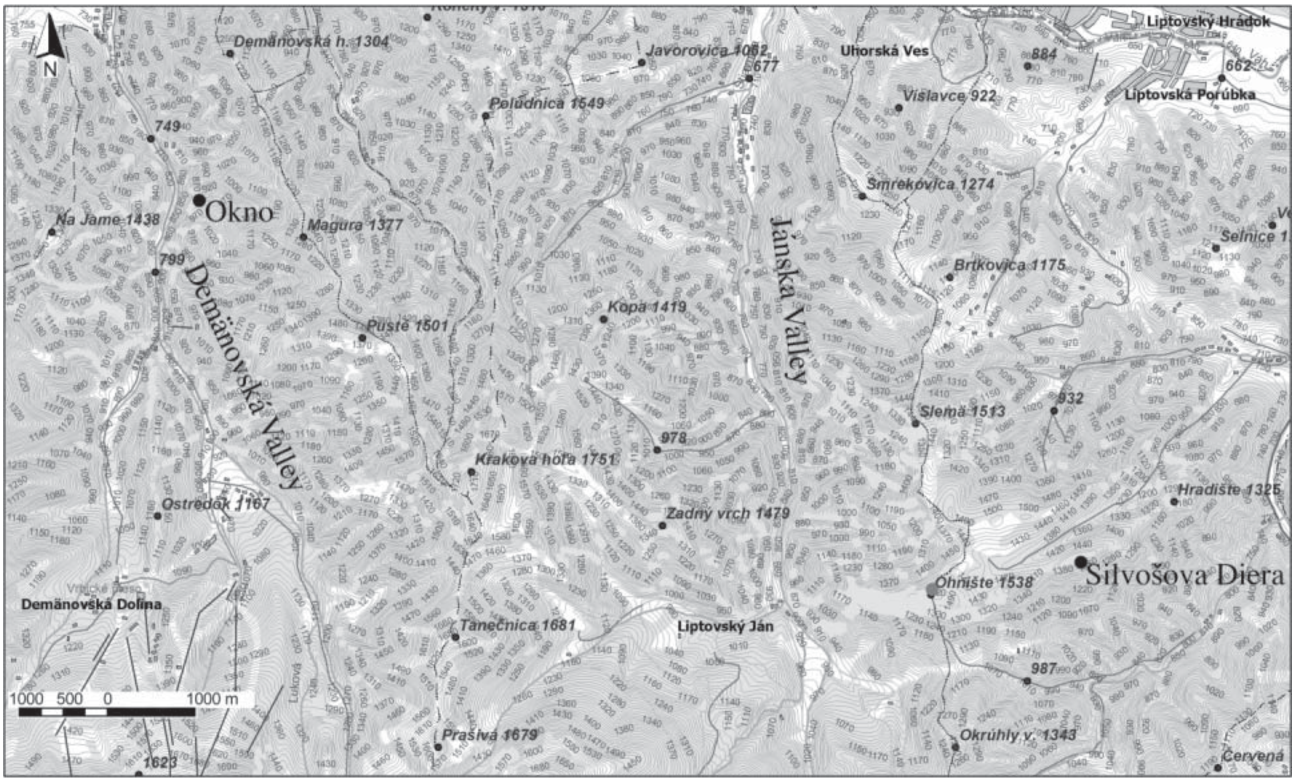

Fig. 1. Location map by P. Gažík generated from the Správa slovenských jaskýň, GIS system.

Fig. 2. View of the Demänovská Valley looking to the South from high on the eastern bank. The arrow indicates the location of the entrance to Okno Cave. Photo P. Bella.

from its entrance (Fig. 4). The cave is almost horizontal in long-section. In detail the northern and southern sections of the cave are structurally-guided rooms, while the centre section is meandering, although still probably structurally-guided in plan.

A fluvial origin for the main passages is supported by the presence of well-developed scallops in the walls of Sieň Smútočnej Vŕby indicating a northerly flow ("5" in Fig. 4, Fig. 5A). Fluvial action is also indicated by large deposits of strongly cemented clastic sediments composed of coarse sand and rounded cobbles ("6" in Fig. 4, Fig. 5B).

In addition to the dominant fluvial elements, the cave ceiling intersects a number of elliptical cupolas ("4" and "7" in Fig. 4, Fig. 5C). These are oriented obliquely to the fluvial passages and appear to be guided by a different set of vertical joints (striking N-S and E-W) to those that guide the fluvial passages (striking generally NW-SE and NE-SW). Marušin (2003) noted that NW-SE and NE-SW trending structures guided the development of the Demänovská Cave system as a whole.

The paleokarst deposits occur in a wall pocket, a small NE-SW trending passage and a small E-W trending passage that appear to be morphologically more related to the cupolas than to the fluvial passages.

Deposits

In addition to field observations, samples were collected and examined as polished blocks and in thin section under a polarising stereomicroscope and a petrographic microscope. A sample of the fluvial sandstone from Location 6 (Sk11) was also thin sectioned and examined for comparison.

Deposit 1

This deposit is located in an alcove in the southwestern wall of Okno Cave, about 25 m from the entrance

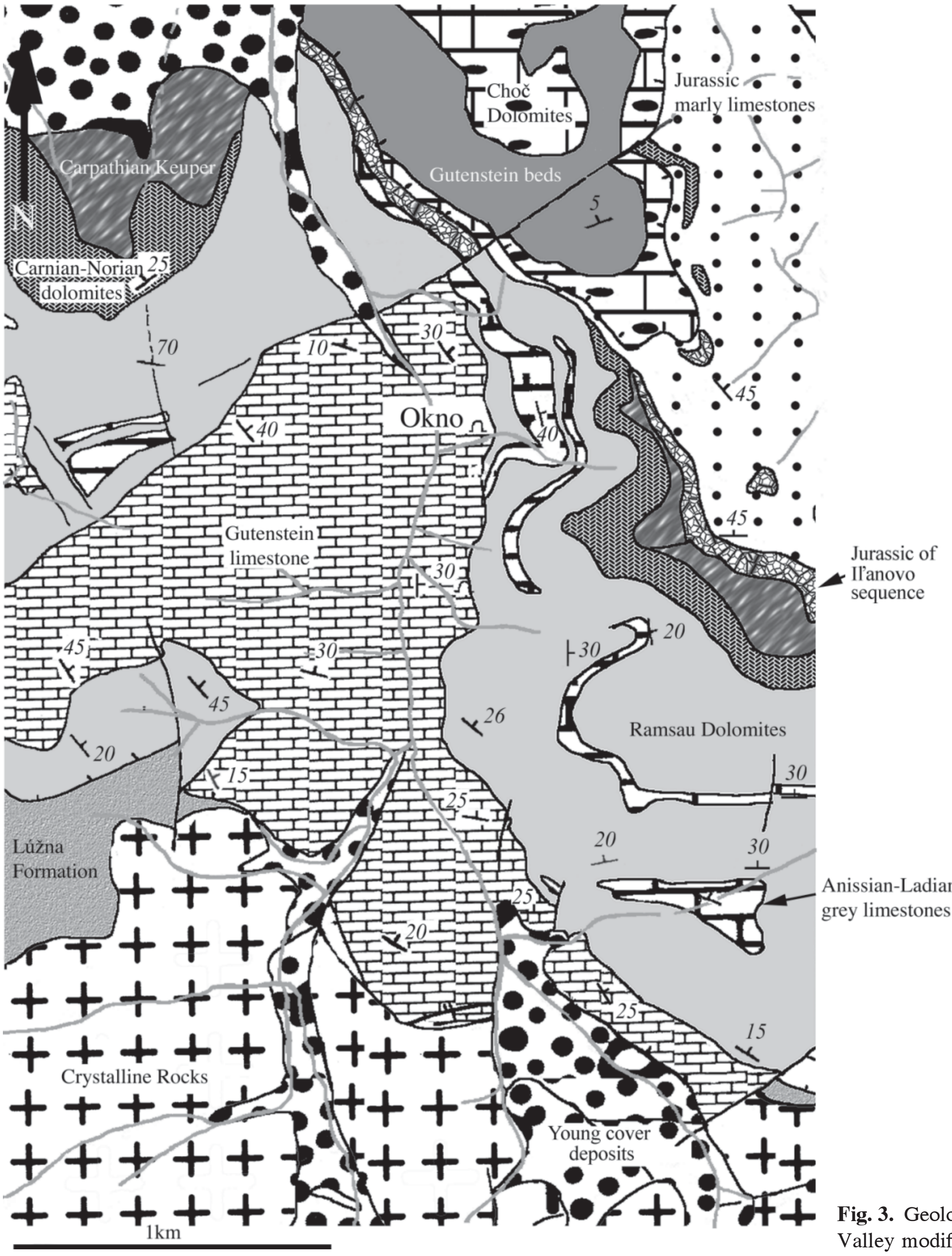

Fig. 3. Geological map of the Demänovská Valley modified after Biely (1992).

("1" in Fig. 4). It partly fills the remnant of a cupola-shaped cavity 2.5 m high (Fig. 6A). The upper third of the cavity is dome shaped. Below the dome, there is a distinct notch in the southern wall where the cavity reaches its greatest width of 1.5 meters. In the northern wall, a less distinct notch forms the top of a well-developed inward-sloping plane in the wall, similar to the *facetten* of Kempe (1975). The top of the deposit just fills the notch (Fig. 6B).

The deposit is 1.3 m thick at its broken (eroded) outer edge and consists of three units, an upper dark laminated unit, 250 mm thick (Sk6), a middle brown unit, 600 mm thick (Sk7) and a lower brown sandy unit, 450 mm thick (Sk8). The upper surface of the deposit, partly covered by a thin veneer of flowstone, dips to the north-northeast (24° towards 028°). The strata in the top unit also dip to the centre of the cavity, forming distinct dish-shaped bedding (Fig. 6B). On the southern side of the deposit, the layers of the middle unit are folded, dipping to the south (Fig. 6C).

Dark laminated unit, Sk6

The thin section of the dark laminated unit (Sk6) shows very finely laminated grey-brown lime mudstone with some pyrolusite dendrites. It consists almost entirely of calcite with poorly developed laminations. Micro faults displace some laminae (Fig. 8A).

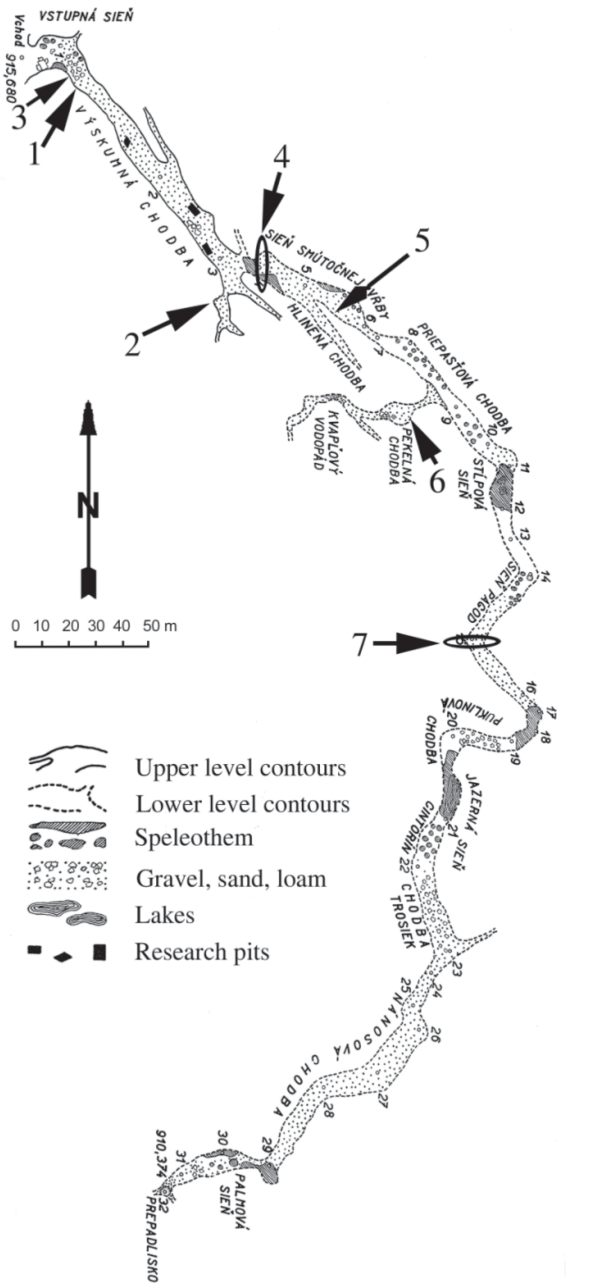

Fig. 4. Okno Cave, modified after Droppa (1953) showing location of features described in text. **1** — Paleokarst deposit 1, **2** — Paleokarst deposit 2, **3** — Paleokarst deposit 3, **4** — Elliptical cupola with N-S orientation just inside cave gate, **5** — Scallops in Sieň Smútočnej Vŕby, **6** — Fluvial sediments in Pekelná Chodba, **7** — Elliptical cupola with E-W orientation.

Apart from calcite, there are a few elongate brown biotite grains present and under high power rare, very fine quartz grains are resolved. The quartz grains undergo undulate extinction and some have well-developed crystal faces.

Middle, brown unit, Sk7

The middle brown unit (Sk7) is a finely graded carbonate siltstone/sandstone with cyclic laminae. Major laminae are approximately 5 mm thick and graded. Minor laminae are approximately 0.5 mm thick, finer grained and darker (tan coloured). Bedding is cross-cut by solution voids, some open and some filled with spar (Fig. 8B).

The siltstone is almost completely composed of calcite. Non-carbonate grains consist of some elongate brown biotite grains aligned parallel to bedding, and rare, angular, quartz grains that show little sign of transport. Lines of partially interconnected voids traverse the sample, mostly running obliquely across bedding. Some follow micro faults.

Brown sandy unit, Sk8

The brown sandy unit (Sk8) is coarser grained than the other two units and consists of interbedded very coarse and finer sands (Fig. 8C). Some liesegang banding is developed.

The unit is composed of large angular to subangular clasts up to 1 mm in a fine brown carbonate matrix (Fig. 8D). The large clasts include: calcite crystal fragments, polycrystalline calcite aggregates, limestone lithoclasts, slate lithic fragments, silicic volcaniclastic fragments and quartz. The striking characteristics of this unit are its poor sorting, the variety and immaturity of the larger clasts and the presence of matrix, rather than carbonate cement between the clasts.

Deposit 2

This deposit in located in a side tube off a north-south trending branch from the southern end of Výskumná chodba ("2" in Fig. 4). The tube containing the deposit has an unusual triangular profile, modified by two distinct notches, and is 1.6 m wide at its base (Fig. 7A). The deposit is situated 100 mm below a flowstone false floor. The upper surface of the flowstone is 100 mm below the top (apex) of the tube (Fig. 7B).

The deposit dips to south and has a maximum thickness of 130 mm at its southern side. It is fine-grained and strongly indurated. The upper third of the deposit consists of a single bed with visible laminations (Sk14), while the lower third consists of four thinner beds. Sample Sk10 was collected from the lowest bed on the northern side of the deposit and sample Sk14 comes from the centre of the uppermost bed, as indicated in Fig. 7B.

Massive mudstone unit, Sk10

In hand specimen, the lower third of Sk10 is a finely laminated light tan mudstone, while the upper two thirds are massive grey-brown mudstone. In thin section, rhythmic bands, 2 mm thick, of fine and finer carbonate mud, intersected by a flame structure of slightly coarser carbonate silt (Fig. 8E) become apparent. This mudstone is almost entirely composed of calcite, with rare grains of biotite and quartz resolved at 500×.

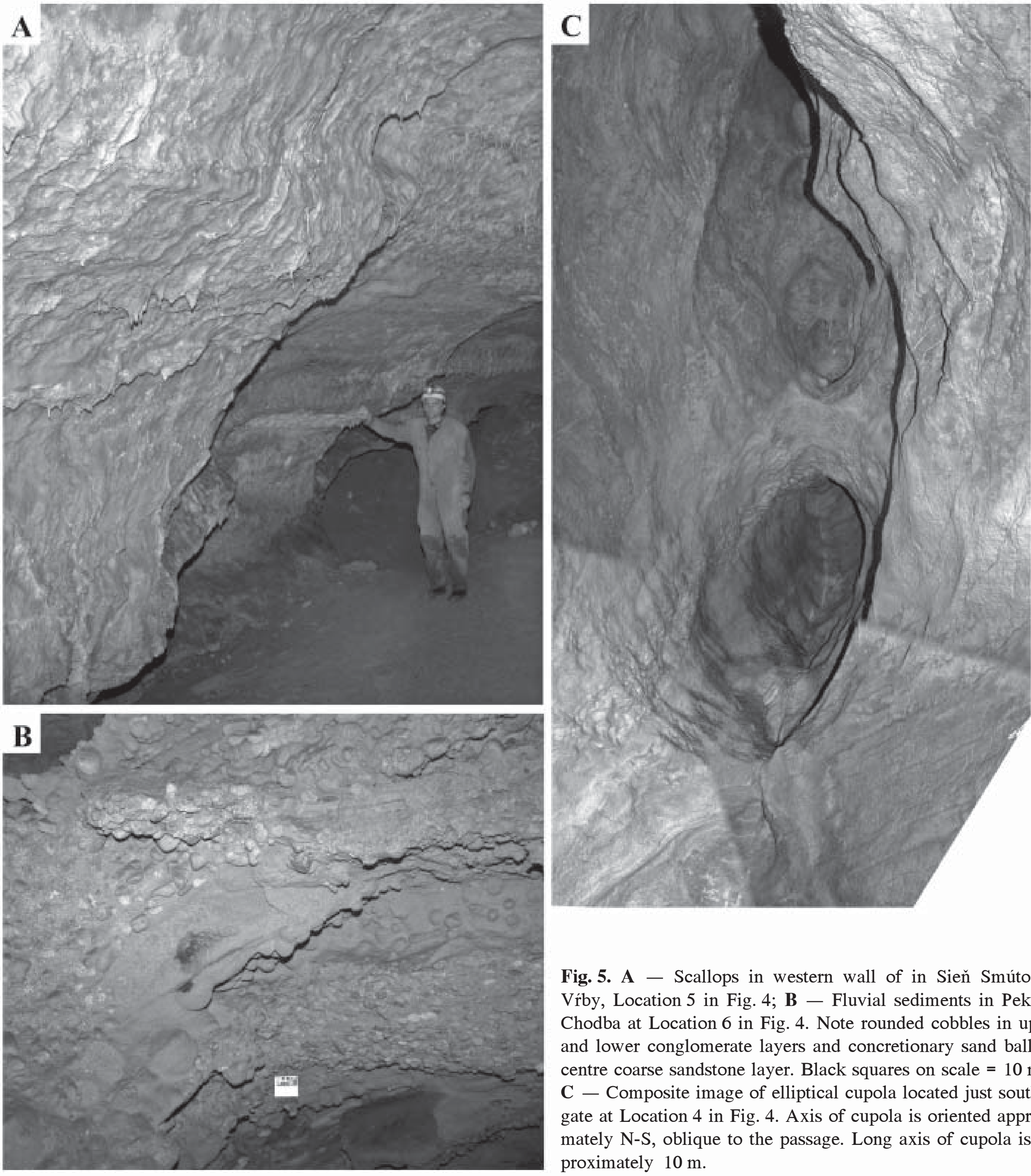

Fig. 5. A — Scallops in western wall of in Sieň Smútočnej Vŕby, Location 5 in Fig. 4; **B** — Fluvial sediments in Pekelná Chodba at Location 6 in Fig. 4. Note rounded cobbles in upper and lower conglomerate layers and concretionary sand balls in centre coarse sandstone layer. Black squares on scale = 10 mm; **C** — Composite image of elliptical cupola located just south of gate at Location 4 in Fig. 4. Axis of cupola is oriented approximately N-S, oblique to the passage. Long axis of cupola is approximately 10 m.

Laminated mudstone unit, Sk14

In hand specimen, Sk14 is grey mud with tan laminae 1 mm thick or less. There are numerous irregular secondary cavities up to 2.5 mm across, some forming small branching networks. In thin section, very fine layers and silty layers up to 4 mm thick are resolved. The layers are curved, forming convolute bedding (Fig. 8F). The fine layers are almost entirely calcite with rare quartz and biotite grains. Quartz and biotite are just slightly more abundant in the coarser layers. Some of cavities are lined with fine spar that penetrates into the rock mass as sparry veins.

Deposit 3

Deposit 3 is located in a side tube off the southwestern wall of Okno Cave, 4.5 meters northwest of Deposit 1 ("3" in Fig. 4). Here an approximately E-W trending passage (axis 104°) extends to the west from the wall of the main passage. This passage is 2.3 m high. It has a hemispherical ceiling with walls that start off vertical, then slope to the northeast and then become vertical again near the cave floor (Fig. 7C). The deposit consists of three separate remnants of lithified sediment, one at floor level and the other two forming false floors across the tube.

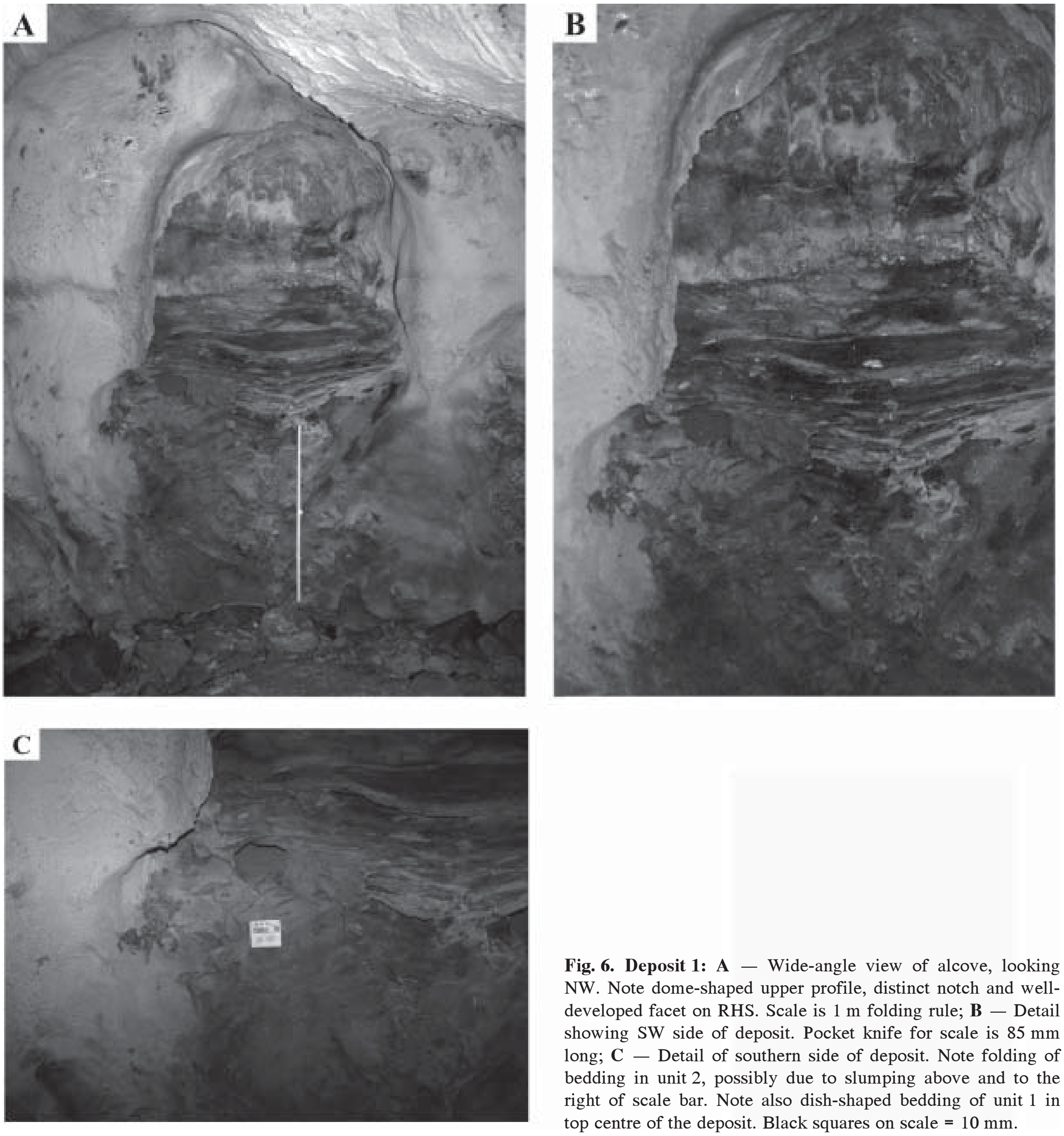

Fig. 6. Deposit 1: A — Wide-angle view of alcove, looking NW. Note dome-shaped upper profile, distinct notch and well-developed facet on RHS. Scale is 1 m folding rule; **B** — Detail showing SW side of deposit. Pocket knife for scale is 85 mm long; **C** — Detail of southern side of deposit. Note folding of bedding in unit 2, possibly due to slumping above and to the right of scale bar. Note also dish-shaped bedding of unit 1 in top centre of the deposit. Black squares on scale = 10 mm.

Basal rough unit, Sk15

The lowest, rough unit (Sk15) is 100 mm thick. It has a rough surface texture in the field, suggesting that it is coarse grained. In hand specimen, the rock surface appears finely pitted and some elongate black grains are visible. The bulk of the rock appears to be a homogeneous grey mudstone with a flaky surface texture, similar to that seen on quartzites.

Three samples were collected from the basal rough unit: Sk15A from the top third of the unit, Sk15B from the middle third and Sk15C from the bottom third.

Sk15A (Top)

The top third of the basal rough unit (Sk15A) is a fine sparite with poorly-defined graded beds, 10 mm thick. It consists almost entirely of blocky spar grains (Fig. 9A). Under high power, the spar is resolved as blocky rhombs and rhomb fragments. The non-carbonate component consists of a few aligned biotite flakes, tiny rare elongate quartz grains and extremely rare muscovite flakes. A line of secondary cavities extends across the sample. These cavities are approximately 1 mm long and poorly rectangular in shape.

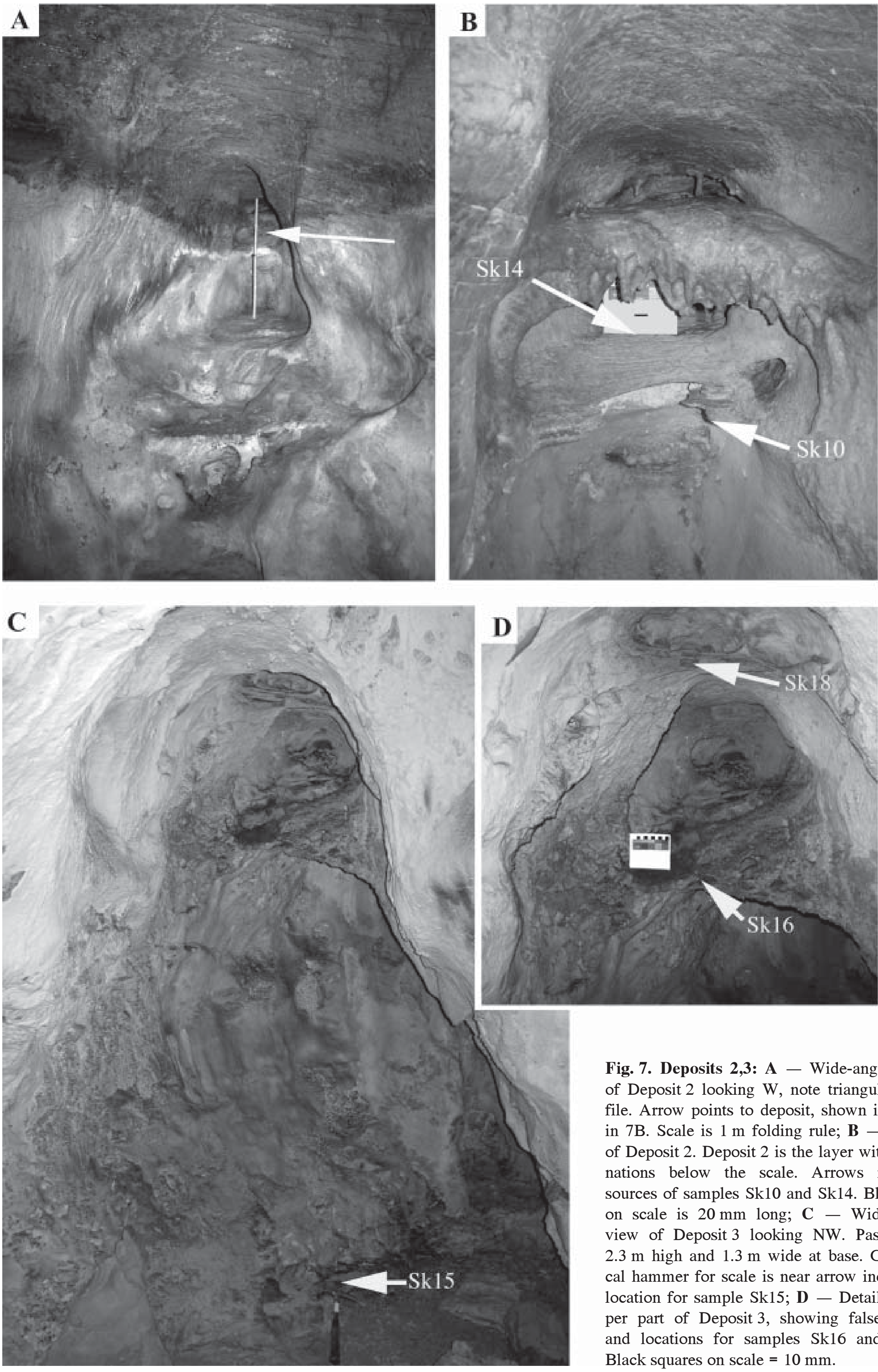

Fig. 7. Deposits 2,3: A — Wide-angle view of Deposit 2 looking W, note triangular profile. Arrow points to deposit, shown in detail in 7B. Scale is 1 m folding rule; **B** — Detail of Deposit 2. Deposit 2 is the layer with laminations below the scale. Arrows indicate sources of samples Sk10 and Sk14. Black bar on scale is 20 mm long; **C** — Wide-angle view of Deposit 3 looking NW. Passage is 2.3 m high and 1.3 m wide at base. Geological hammer for scale is near arrow indicating location for sample Sk15; **D** — Detail of upper part of Deposit 3, showing false floors and locations for samples Sk16 and Sk18. Black squares on scale = 10 mm.

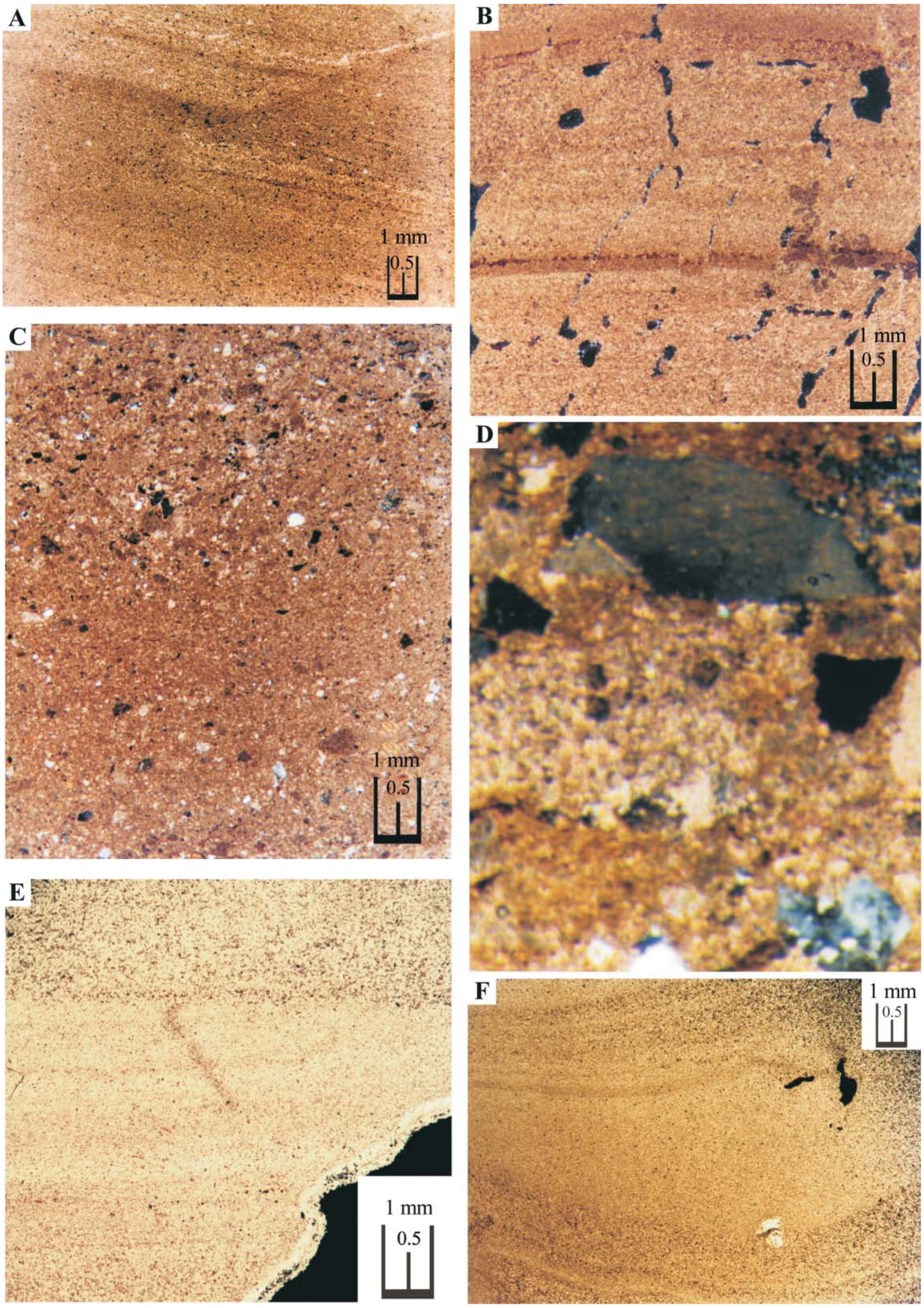

Fig. 8. Thin sections: **A** — Deposit 1, dark laminated unit, SK6, Crossed Nicols, 6.4×. Note grading and fault; **B** — Deposit 1, middle brown unit Sk7, Crossed Nicols, 6.4×. Note graded laminae, aligned voids and dendrites on fine mud layer; **C** — Deposit 1, brown sandy unit Sk8, Crossed Nicols, 6.4×. Note large angular clasts and the variety of clasts: calcite crystal fragments, composite calcite grains, quartz, lithic fragments, biotite slivers, poor sorting and grading; **D** — Deposit 1, brown sandy unit Sk8, Crossed Nicols, 40×. Note large angular quartz grains, lithic clasts and matrix support; **E** — Deposit 2, lower unit Sk10, Crossed Nicols, 6.4×. Note coarse carbonate lamina at top and fine carbonate lamina at bottom; **F** — Deposit 2, upper unit Sk14, Crossed Nicols, 6.4×. Note convolute bedding and irregular cavities.

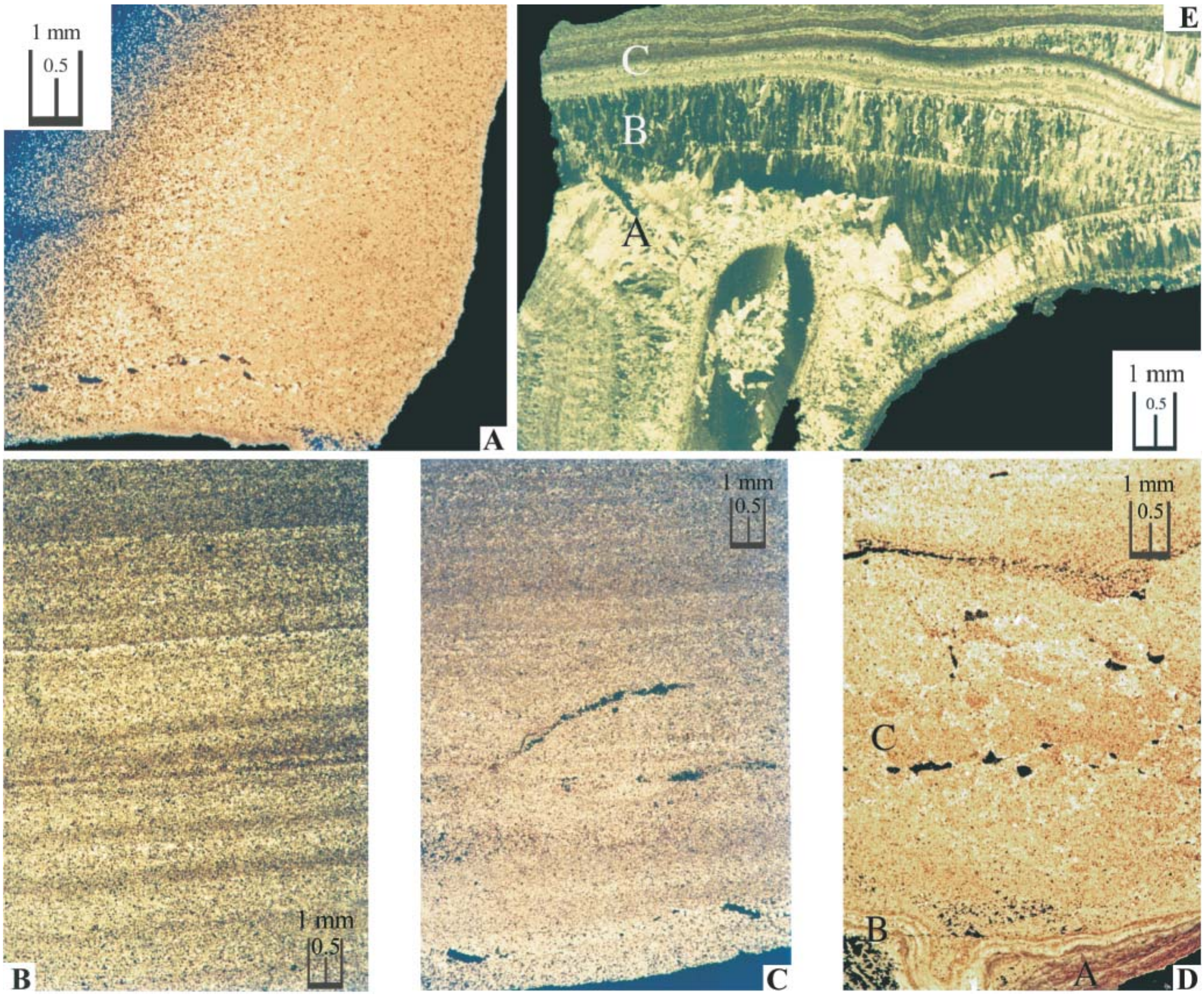

Fig. 9. Thin sections: **A** — Deposit 3, lower unit Sk15A, Crossed Nicols, 6.4×. Note poorly defined laminae and line of voids close to bottom of image; **B** — Deposit 3, lower unit Sk15B, Crossed Nicols, 6.4×. Note distinct laminae; **C** — Deposit 3, lower unit Sk15C, Crossed Nicols, 6.4×. Note laminae coarser at bottom of sample and voids; **D** — Deposit 3, middle unit Sk16, Crossed Nicols, 6.4×. Note newer dripstone layers at bottom of image "A", older dripstone structure "B", mottled micrite with voids in centre of image "C" and poor lamination at top of image; **E** — Deposit 3, upper unit Sk18A, Crossed Nicols, 6.4×. Note section through straw a bottom of image "A", then flowstone layers "B" and interlaminated mudstone and flowstone at top "C".

Sk15B (Middle)

The middle third of the basal rough unit (Sk15B) is a coarser sparite with distinct laminae 3 mm thick, some of which are graded (Fig. 9B). The spar has a granitic texture, consisting of a mosaic of intergrown angular grains. Well-formed calcite rhombs are absent. The non-carbonate component is more prominent than in Sk15A. In addition to aligned small biotite flakes, fine slivers of quartz and rare muscovite flakes, there are also subangular quartz grains up to 0.25 mm and a few biotite flakes up to 0.5 mm.

Sk15C (Bottom)

The lower third of the basal rough unit (Sk15C) is a slightly coarser version of the overlying Sk15B. It has some thicker laminae, up to 4 mm thick and a 3 mm thick distinctly coarse lamina at its base (Fig. 9C). Under high power the spar grains are coarser and less well sorted than in Sk15B, consisting of rhombs of various sizes and smaller calcite fragments. A few small, square, opaque rusty grains, apparently limonite pseudomorphs after pyrite are scattered through the sample.

The non-carbonate component of Sk15C consists of angular grains of quartz with undulose extinction, aligned biotite flakes, and rare small flakes of muscovite. Rare, small, apparently diagenetic, patches of chalcedony are visible at high power between the spar grains. Elongate secondary spar-lined cavities, 3 mm long × 0.5 mm wide, are developed in the lower coarse lamina.

Middle dark unit, Sk16

The middle, dark unit (Sk16) is 30 mm thick (Fig. 7D) and forms a false floor. It is dark grey and massive and contains many small cavities up to 2 mm across and one

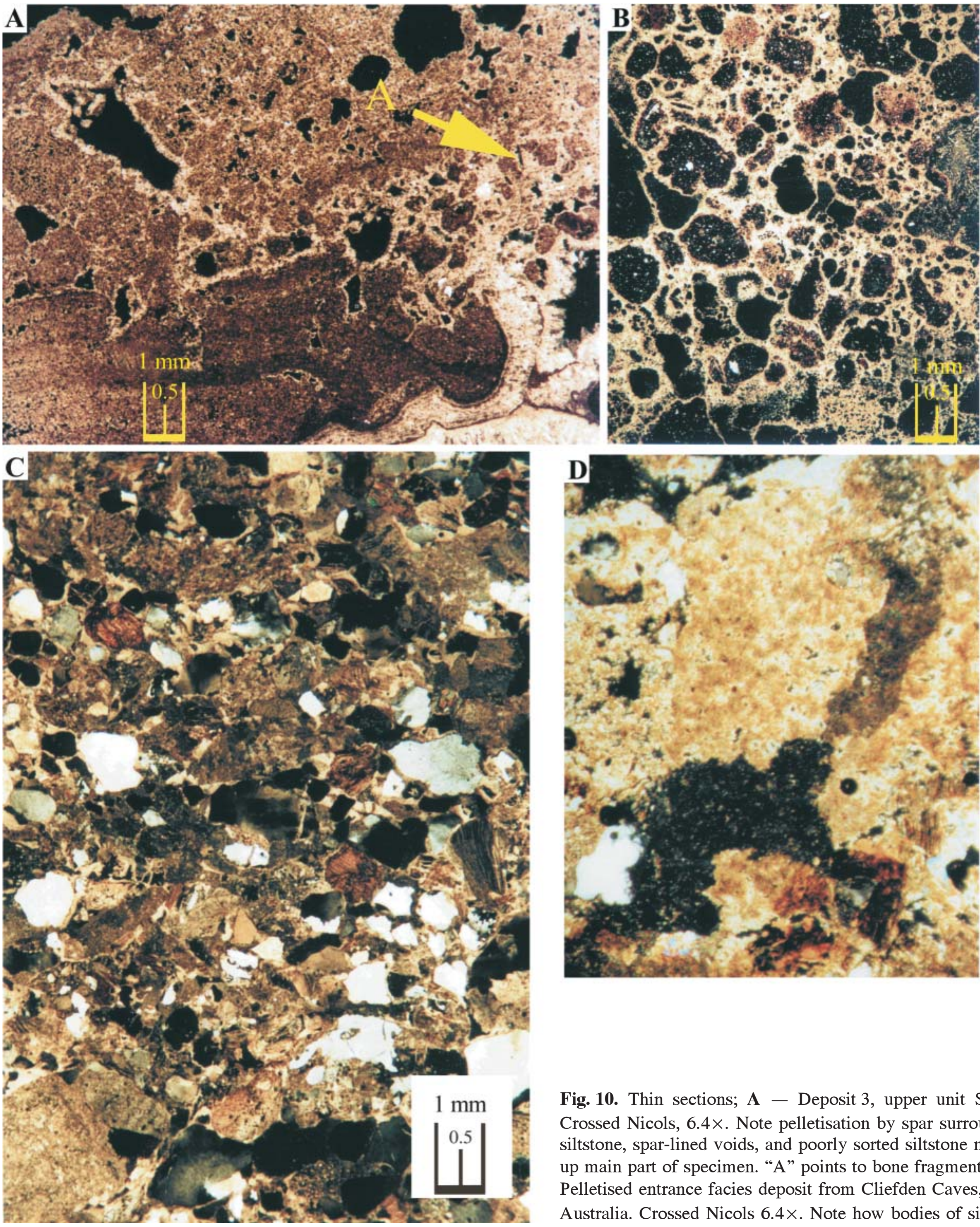

Fig. 10. Thin sections; **A** — Deposit 3, upper unit Sk18B, Crossed Nicols, 6.4×. Note pelletisation by spar surrounding siltstone, spar-lined voids, and poorly sorted siltstone making up main part of specimen. "A" points to bone fragment; **B** — Pelletised entrance facies deposit from Cliefden Caves, NSW Australia. Crossed Nicols 6.4×. Note how bodies of siltstone are completely surrounded by invading spar resulting in pellets of siltstone in a sea of spar; **C** — Coarse fluvial sandstone, Sk11, from Location 6 in Fig. 5, Crossed Nicols, 6.4×. Note angularity of clasts and presence of very immature clasts, such as books of biotite; **D** — Coarse fluvial sandstone Sk11, Crossed Nicols, 50×, showing zoned spar cement. Note how the cement goes to extinction in irregularly shaped zones (dark patch extending from left to right in frame).

larger cavity 13 mm across. Tiny golden sparking grains are visible on broken surfaces. Under a stereomicroscope these are seen to be the faces of biotite and muscovite flakes. The middle dark unit is overlain by a thin laminated unit that proved impossible to sample.

A finely-laminated layer of dripstone, that may be very recent in origin, covers the bottom 1–2 mm of the specimen ("A" in Fig. 9D). On the left side between the dripstone and the specimen proper, there is a layer of dripstone that appears to be part of the original sequence ("B" in

Fig. 9D). The main component of the sample appears to fill irregularities in the surface of this dripstone.

The bulk of the specimen is a poorly-sorted wacke with a mottled appearance ("C" in Fig. 9D). Larger grains include calcite crystal fragments and less-common quartz grains with undulose extinction in a fine brown matrix. Biotite and muscovite flakes, mostly seen end-on, show no preferred orientation. At 200×, the matrix resolves as angular calcite grains of varying size along with some biotite flakes, muscovite flakes and angular quartz grains. Secondary spar-lined cavities, up to 4 mm × 1mm, form in chains across the specimen, linked by nascent sparry veins.

Upper porous unit, Sk18

The upper false floor (Sk18, Fig. 7D) consists of a thin layer of flowstone varying in thickness from 5–10 mm (Sk18A) overlying remnants of a fine light brown siltstone penetrated by many irregular voids up to 10 mm, some of which are spar-lined (Sk18B). As with Sk16, tiny golden sparking grains are visible on broken surfaces of Sk18B, similarly, under a stereomicroscope these are seen to be the faces of biotite and muscovite flakes. The temporal relationship between the flowstone and the rest of the deposit in unclear.

Flowstone, Sk18A

This sample consists of dripstone layers underlying thin layers of mudstone interbedded with flowstone (Fig. 9E). The base of a small stalactite, with a monocrystalline straw centre, dominates the lower left-hand side of the specimen ("A" in Fig. 9E). This grows on an older flowstone layer ("B" in Fig. 9E).

In the top of the specimen ("C" in Fig. 9E) mud layers occur, interbedded with dripstone. The mud layers contain small, mostly elongate, grains of quartz, biotite and muscovite in a matrix of very fine brown micrite.

Porous siltstone Sk18B

At a gross scale, Sk18B appears to consist of rounded clumps (almost pellets) of poorly sorted brown siltstone, separated by interconnecting zones of spar (Fig. 10A). The pellets and the intact areas of siltstone, consist of murky brown partially-recrystallized micrite containing scattered grains of quartz and biotite flakes.

The spar zones are interspersed with cavities up to 2 mm across lined with large spar crystals, some up to 1.5 mm long. A few large clasts are interspersed within the spar zones including angular and rounded quartz up to 0.5 mm, biotite flakes up to 0.5 mm, and one elongate bone fragment also approximately 0.5 mm long.

Sk18B shows many of the characteristics that Osborne (1978) attributed to the progressive cementation of entrance facies deposits: the gradual removal of mud by percolating vadose water and its replacement by spar. This frequently results in the separation of the initial porous silty matrix into pellet-like zones. While the overall texture of Sk18B is similar to the sediment described by Osborne (1978) shown in Fig. 10B, the mudstone within the pellets in Sk18B is significantly more cemented than that in the Australian sample, which is quite porous. The spar crystals surrounding the pellets are larger and more euhedral in Sk18B than those in the Australian sample.

Coarse fluvial sandstone (Sk11)

The fluvial sandstone from location 6 is coarser, significantly less mature and has distinctly different cement to the paleokarst deposits (Fig. 10C,D). It consists of rectangular to subangular grains, up to 3 mm in size, of quartz with undulose extinction, polycrystalline quartz, weathered K feldspar, gneissic and schistose lithoclasts, books of biotite and a few limonitic opaques. While most of the grains are subangular, some quartz and lithic grains are subrounded. The fabric is grain supported. Between the grains, there is white, massive spar cement that goes to extinction in zones (Fig. 10D). This coarse spar cement is distinctly different from the matrix found in the coarser units of the paleokarst sequences (e.g. Sk8 and Sk16) or the cement in the entrance facies (Sk18B).

Discussion

Genesis of the paleocaves

The simplest interpretation of the cavities containing these deposits is that they are dip-tubes formed by an early phase of meteoric speleogenesis that was guided by a different set of joints to those that guide the modern cave.

The cavities containing the deposits have a number of unusual features, which suggest they are not dip-tubes and may have a different origin. The facet in the cavity containing Deposit 1 and the triangular shape of the tube at Deposit 2 are not typical of phreatic dip-tubes. Taken together with the large cupolas, which share the same orientation, these features suggest that it is worth investigating the possibility of a hypogene origin for the ancient cave containing the paleokarst deposits and for other high-level caves in the Demänovská Valley.

Environment of deposition

With the exception of the upper unit in Deposit 3, the lithified sediments in Deposits 1, 2 and 3 are upward fining sequences. The three units from Deposit 1, the two units from Deposit 2 and the lower unit from Deposit 3 have sedimentary features characteristic of cave turbidites (Osborne 1983, 1984). They are fine distal laminates, graded-bedded units and proximal poorly-sorted sandy units. The coarser organized and disorganized conglomerate facies are not present. The middle unit from Deposit 3 (Sk16) is most likely a proximal turbidite, formed by relatively fine-grained sediment slumping into the phreas from an entrance facies talus cone, i.e. the fine-grained equivalent of a disorganized conglomerate.

The upper unit from Deposit 3 (Sk18) consists of speleothem and a mottled, porous, poorly sorted siltstone containing large quartz grains and a bone fragment. Sk18 is most likely a lithified entrance facies deposit, deposited and cemented in the vadose zone.

Turbidity currents in caves result from slumping of material into a low-energy phreatic cave environment. The presence of coarse allochthonous grains indicates a surface source, with the sediment entering the cave via an entrance facies cone that slumped into the ponded water. The folding in the middle unit of Deposit 1 is consistent with slumping in a phreatic environment.

Previous reports of cave turbidites have been from non-fluvial caves. Marine turbidites (caymanites) have been reported from modern and ancient flank-margin caves (Korpás 2002) and freshwater turbidites from low energy maze caves (Osborne 1983). Turbidites have not been reported among the sediments found in the presently active parts of Demänovská Caves, nor are they likely to have been deposited under the fluvial conditions indicated by the morphology and sediments found in Okno Cave proper. The turbidites indicate that the Okno paleocave had a low energy phreatic environment quite different from that of both "modern" Okno Cave and the modern Demänovská Cave system. The paleokarst turbidites formed in still phreatic lakes like those found in modern low energy phreatic caves, many of which have or are suspected to have a hypogene origin (see Klimchouk 2007).

Provenance of the sediment

The larger clasts in the brown sandy unit (Sk8) include both autochthonous (single crystal and polycrystalline calcite fragments) and allochthonous (quartz, biotite and lithic) grains. The coarse calcite fragments are derived from either the disintegration of speleothem and/or hydrothermal calcite. The allochthonous grains are similar to the more mature clasts in the coarse fluvial sandstone (Sk11).

The only significant non-carbonate grains in the finer-grained turbidite lithologies are quartz, muscovite and biotite. The micas are in the form of plates, seen end-on in thin section as elongate grains. With the exception of the bone fragment, the non-carbonate grains in the entrance facies are similar in composition to those in the turbidites.

The composition and shape of the non-carbonate grains are consistent with a siliceous tectonized plutonic or dynamic metamorphic origin. The maturity of the grains, even in the entrance facies, suggests a significant amount of transport, presumably on the surface before deposition in the caves. Alternatively, the mature non-carbonate grains in the paleokarst deposits could be reworked grains derived from older rock units.

The maturity of the non-carbonate grains from the paleokarst deposits contrasts with the low maturity and angularity of the clasts in the coarse fluvial sandstone (Sk11), which is likely to be derived directly from the crystalline core of the Low Tatras. The lack of feldspar among the coarse fractions and the lack of clay in the fine fractions would seem, however, to rule out such an origin for the paleokarst deposits. Feldspar is not only present in the coarse fluvial sandstone but feldspar and clays are also common components of modern fluvial sediments in the Demänovská Caves (J. Psotka, Pers. Comm.).

Diagenesis

In all of the turbiditic specimens (Sk6, Sk7, Sk8, Sk10, Sk14 and Sk15), the micrite of the lime mudstone matrix has undergone neomorphism to form irregular grains of microspar. They frequently surround relict patches of micrite as described by Bathurst (1975).

Spar-lined voids and nascent sparry veins occur in most of the paleokarst sediments. These are largely unrelated to the depositional fabric of the rocks. In the terminology of Choquette & Pray (1970), these voids are "not fabric selective mesopores".

The neomorphic texture of the matrices, the presence of spar-lined voids, the development of nascent sparry veins and the presence of diagenetic chalcedony all indicate a degree of diagenesis not normally seen in lithified cave sediments. The contrast between the lithified entrance facies (Sk18B) and the Australian example (Fig. 10A,B), suggest that Sk18B may have also undergone a higher than normal degree of diagenesis. There is no evidence for unusual diagenesis in the coarse fluvial sandstone (Sk11). This suggests a period of burial before the excavation of the present fluvial cave and the deposition of the fluvial sandstones and conglomerates.

Constraints on the age of the paleocaves and deposits

The deposition of the paleokarst sediments is at a gross level constrained in time between a minimum age set by the excavation of Demänovská Valley and a maximum age set by the tectonic processes that resulted in the dip of the enclosing limestone beds.

The limestone beds are inclined as the front of the Krížna Nappe, produced by north-south compression at approximately 85 Ma during the Cretaceous (Biely & Bezák 1997). This means that the turbidite paleokarst deposits and the cavities they occupy can be no older than Late Cretaceous in age.

The difference in maturity between the non-carbonate clastics in the paleokarst deposits and those in the fluvial sediments suggest that the non-carbonate grains in the paleokarst deposits entered the paleocaves at a time when the crystalline core of the mountains was largely covered. The paleocaves were close to the surface at this time and contained phreatic lakes where turbidites were deposited, and airspace, perhaps due to a falling water table, where flowstone and dripstone were deposited.

The diagenesis of the deposits suggests that a phase of subsidence followed. The paleocaves, and the sediments in them, were buried and exposed to circulating pore water. Burial was most likely caused by deposition of the Central Carpathian Paleogene Basin of Gross et al. (1984).

Uplift and erosion during the Pliocene (Kadlec et al. 2004) initiated the modern phase of cave development and incision by the Demänovka River. Okno Cave and its fluvial sediments formed early in this phase, intersecting the paleocaves and paleokarst deposits.

The paleocaves and paleokarst deposits can be no older than 85 Ma, and no younger than 2 Ma, and given their burial history are most likely to have formed in the Paleogene or Late Cretaceous. This suggests a correlation with the Paleoalpine paleokarst period of Činčura & Köhler (1995) with the paleokarst deposits in Okno Cave representing an underground equivalent of the surface paleokarst features Činčura & Köhler describe.

Orvošová et al. (2004) described hydrothermal paleokarst calcite from Silvošova Diera Cave, a small cave located at an elevation of 1446 m some 10.8 km southeast of Okno Cave (Fig. 1). They proposed that this calcite was a product of hydrothermal karstification in pre-Pliocene, most likely Paleogene times. Alternatively, if the paleocaves containing the deposits are hypogenic they could have formed at the same time as Silvošova Diera Cave, which has similar age constraints (Orvošová et al. 2004; Orvošová 2005).

In either case, the constraints on cave development, the difference in provenance between the deposits and more recent relict sediments and the evidence for burial indicate that the sediments are most likely Paleocene in age.

Conclusions

The strongly lithified paleokarst deposits in Okno Cave were deposited under low energy phreatic conditions, quite different from the depositional environment found in the active parts of the Demänovská Cave system today or indicated during the evolution of "modern" Okno Cave. The depositional environment had sufficient connection to the surface to allow the entry of relatively mature allochthonous grains from a granitic source.

After deposition, the paleokarst deposits were subject to significant diagenesis, most likely due to burial of the karst landscape under Paleogene basinal sediments. The paleokarst deposits are probably Paleogene or Late Cretaceous in age and are likely to correlate with the Paleoalpine paleokarst period of Činčura & Köhler (1995).

There are some features of the sediments, and the cavities they fill, which are suggestive of hypogene karstification. This requires further investigation.

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