The Late Cretaceous conditions of the Gombasek beds sedimentation (Silica nappe, Western Carpathians)

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The Silica nappe forms the rear paleoalpine nappe structure of the Alpine orogeny in the Central Western Carpathians. The main period of the nappe formation relates to a spatial convergence from the south to the north. During the Early to Late Cretaceous, the position of this nappe as well as its structural core elasticity reflect an uplift of the Silica nappe pile and consequently its weathering and karstification. After that, inner karst structures were injected by concentrated aqueous solutions from which Fe, Mn (±Ni) nodules and crusts have been precipitated. This stage of nodules/crusts deposition reflects anoxic conditions. Ongoing bulging of the Silica nappe caused an increase of the karstification rate and locally also its connection to the surface. Implicitly conditions for the clastic sedimentation were formed and deposition of the Gombasek beds was initiated. The Late Cretaceous paleoclimate could be characterised by small temperature variations during the year and only seasonal rainfalls what is also indicated from the composition of the Gombasek beds reflecting quiet water conditions with recurrent sediment inflows. Limestone clasts incorporated to the upper part of analysed sedimentary record most likely relate to the tectonic activity increase during Late Cretaceous thrusting.

Key words*: Late Cretaceous, Karstification, Nodules, Gombasek Beds, Silica Nappe, Slovak Karst*

Introduction

The Late Cretaceous evolution in the Western Carpathians relates to significant nappe shortening tectonics and therefore sedimentary record underfeeding at their realm. Crustal shortening of Variscan and Gemeric basement formed décollements of Mesozoic sedimentary sequences. The Mesozoic strata were separated to the individual crustal segment which were passively transported as large - scale nappes toward the north (Andrusov, 1936; Plašienka et al., 1997). Progressive nappe over-thrusting from the south to the north was finished by the latest, the Silica nappe sheet. In the same time, the exhumation of Veporic and Gemeric basement superunits have been completed (Kráľ, 1977; Plašienka et al., 1999, 2007; Janák, 2001) and therefore weathering of sedimentary sequences started. In consequence of mentioned conditions, wetterstein limestones on the top of Silica nappe were intensively karstified. Narrow fissure caves were created at the top of the Silica nappe pile, and they were filled by the Gombasek beds. These sediments are well preserved for example in the Gombasek Quarry located in the southern margin of the Plešivec Karst, as a part of the Silica nappe Slovak Karst. The sediments were dated to Late Cretaceous age from palynomorphs (Mello and Snopková, 1973; Cílek and Svobodová, 1999; Dašková et al., 2011).

Conditions of karstification and sedimentation could be related to paleoalpine climate. For the Late Cretaceous period, high annual average temperatures and only small temperature variations during the year are typical. Annual rainfall was evidently high, but precipitation was concentrated in the summer monsoon, while the winter monsoon season was dry (Činčura, 2002). These climatic conditions, alternating wet and dry periods (Zhang and Karathanasis 1997; Gasparatos et al., 2005), could explain covering of the karst surfer by Fe-Mn crusts and nodules. The Fe-Mn modules are discrete bodies formed under alternating oxidising and reducing periods. Subrounded morphological features are formed by the processes of reduction, translocation and oxidation of Fe-Mn (Gasparatos, 2012).

This study is focused on some petrographic and sedimentological features of the Gombasek beds, which could be important for the understanding of the climatic conditions, tectonic activity and palaeogeography during Late Cretaceous age.

Geological overview

The southern margin of the Central Western Carpathians is built by basement complex of the Gemeric Superunit composed of the low-grade Lower Paleozoic volcano-sedimentary formations intruded by Permian to

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Early Triassic S-type granites (Uher and Broska, 1996; Poller et al., 2002). The basement does not have sedimentary cover as a result of their erosion during Jurrasic age. It was tectonically overthtrusted by Bôrka and Silica nappes from the south. The study area is located in the Silica nappe where massive wetterstein limestones dominate (Fig. 1). Their complicated tectonic structure related to the overthrusting of the nappe bodies caused incorporation of other younger sediments into the gross structure of the rock massif. The sediments preserved in the studied quarry are mostly in the form of irregular layers and lenses.

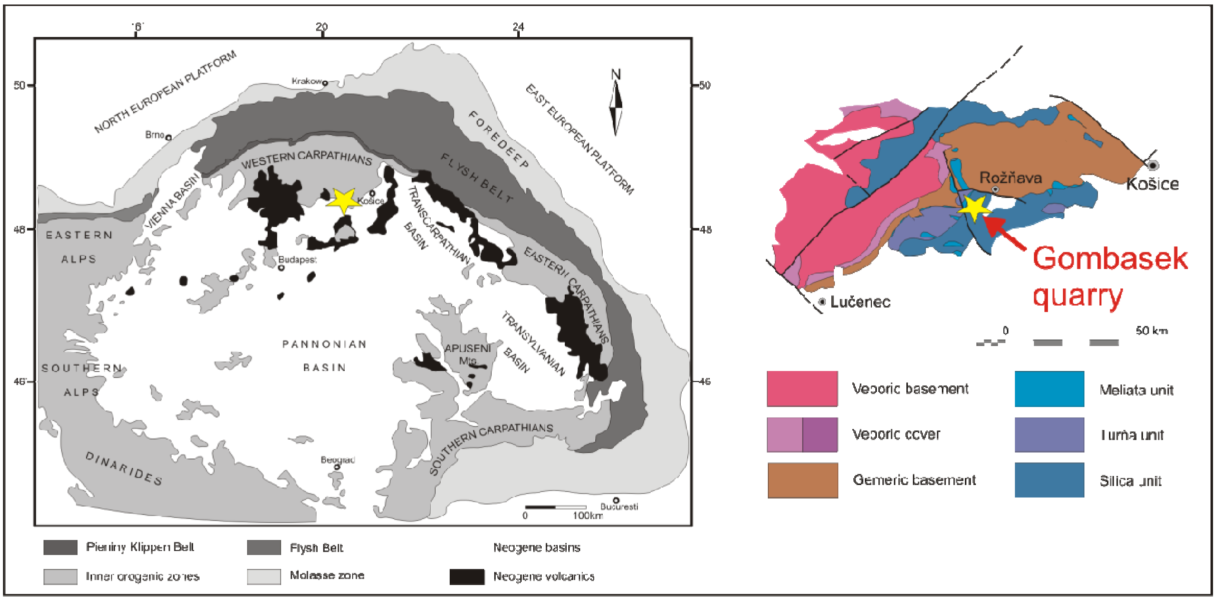


Fig. 1. Main geological units distribution in the Central Europe (Kováč et al., 1998) and position of the Gombasek quarry in the Western Carpathians (Biely et al., 1996).

The essential part of Gombasek quarry deposits consists of massive, white and whitish-gray limestones with high fossils content (Bystrický, 1964; Mello, 1974; Kochanová et al. 1975; Mello et al., 1997), known as a wetterstein limestones. Regarding their extension and thickness, they represent the most important limestones in the framework of the Triassic carbonate platform. Their karstification liability is evident mainly from the near-surface positions where some karst forms like grikes, sinks, vertical and successively mineralized fissures evolved. Intensive weathering is also indicated by the occurrence of red coatings fringing structural discontinuities of the limestone.

The limestone analysed in the study area is medium- to thick-bedded. In general, the bedding is of the NE-SW direction with weak, monoclinal 10°- 20° dip towards the NW (Sasvári et al., 2006). Bedding planes were tectonically deformed. Based on the structural as well as the stratigraphic records from the studied deposits, it is possible to state that actual thickness of the limestone complex in the Gombasek quarry does not correspond to the "original" thickness. This was most likely caused by tectonic processes resulting in the space shortening, generation of the duplex structure and following tectonic "accumulation" of the entire sedimentary complex.

Sediment fill of described limestone is represented by Gombasek beds (Mello et al., 1997) consisting of dark shales and sandstones. The sediments are known from the Gombasek quarry, where they are exposed in the form of lenses or irregular layers. Their occurrence is most frequent in the basal part of the quarry, where it is also the thickest. The altitude difference between individual occurrences is from 10 to 30 m, however, higher upward, the difference is up to 150 m. In the near-surface positions of the quarry, also Quaternary sediments are preserved. They consist mainly of weathered products represented by red and ocherous claystones containing irregularly scattered clasts of wetterstein limestone.

Methodology

The main aim of the presented study was a characterization of sandstones of Gombasek beds as well as the ferruginous crusts and nodules covering limestones in the contact zone with these beds. Detailed mapping of structural and sedimentological features of the Gombasek beds was realised in the Gombasek quarry. Mineral composition was investigated using reflected light microscopy and scanning electron microscopy SEM-EDS analyses were performed using the FEI QUANTA 200F microscope coupled with an energy dispersive spectrometer (EDAX) at the Department of Mineralogy, Petrography and Geochemistry, AGH – University of Science and Technology, Kraków. Some areas of the samples were studied in SE (secondary electrons) and BSE (backscattered secondary electrons) mode, first without any coating and later after coating with approximately 20nm of carbon. These procedures allowed to compare the quality of images and to cross-check the results. Acceleration was set at 15 keV. The environment used was the one of water vapour at a pressure of 100 Pa.

Sedimentary characteristics

The Gombasek beds consist of a rhythmical alternation of the sandstone to siltstone and mudstone beds and represent filling of the karst caverns formed as a result of the limestone karstification occurred in the Late Cretaceous. The characteristic feature of the mentioned karst caverns is the presence of the ferruginous crust on the walls, i.e. in the contact zone between sandstone and limestone (Fig. 10, 11).

Coarser-grained beds of light grey and light to reddish-brown colour could be, based on their grain-size, identified as an unimodal moderately well sorted **very fine-grained sandstones** to **coarse-grained siltstones** (Fig. 2). Most common are the beds where the silt and sand particles ratio is almost 1:1 but sporadically beds of the fine-grained sandstone characterised by normal gradation were identified too. In general, the thickness of these beds reaches from a few millimetres to about 20 cm and can be characterised by sharp bases. However, occasionally, also up to 100 cm thick sandstone beds are preserved.

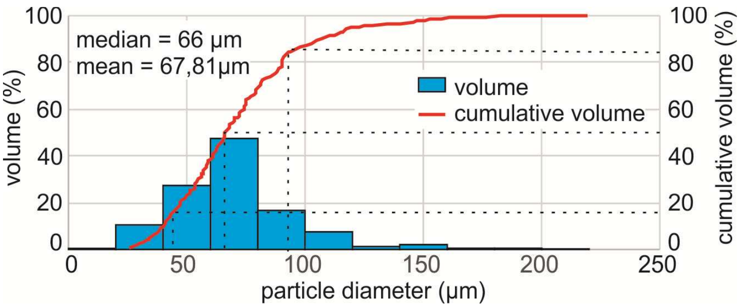


Fig. 2. Histogram of the particle diameter changes with the cumulative frequency curve of the representative sandstone sample. The histogram is of unimodal distribution what indicates the relative high structural maturity of the sand. Also, it is apparent that based on the grain size, predominate grains of 60-80 (48%) and 40-60 μm size (27,8%) indicating coarse-grained siltstone to fine-grained sandstone. With respect to the cumulative frequency curve was defined the sorting coefficient (based on the Folk, 1968) indicating moderately well sorting of the sample.

Siltstone and sandstone beds are relatively resistant, allowing the identification of some stratifications in their structure. Predominating structures are current ripples and parallel lamination which are in some beds highlighted by the presence of the thin organic and/or mud drapes (Fig. 3). Some of the described beds sporadically contain angular fragments of the limestone, which most likely reflect disruption of the creaky top of the cavern (Fig. 4). **Mudstones** are of dark grey to black colour and form beds of thickness similar to sandstones. These beds are less resistant to weathering what result in their higher disintegration.

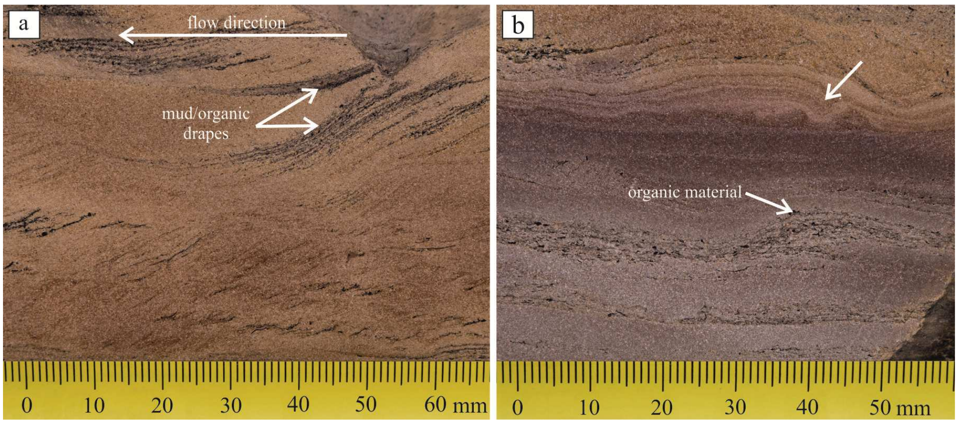


Fig. 3. Typical sedimentary structures observed in the studied sandstones. a – Current ripple structure, which reflects the deposition during lower flow regime. Organic and/or mud drapes indicated that the flow regime typical by ripples formation was episodically followed by quiet depositional conditions. The direction of the flow was from the right to the left as can be seen from the preserved lee side of the ripples. b - Parallel lamination as a result of the variations in the grain size of deposited sediment between very fine sand to silt or clay visible also as colour changes (the finer sediment shows the darker colour). Organic material content, as well as the low grain size of the sediment, indicate deposition by settling out from suspension. Indications of starting ripple formations and/or small-scale convolution (see arrow) could reflect disruption of quiet depositional conditions by the new input of sediment. This is also indicated by a relatively abrupt change in the grain size (from muddy to sandy).

Described grain size, as well as other features of Gombasek beds, indicate that these sediments were deposited during relatively quiet water conditions punctuated by recurrent intervals of new sediment inflows. Sediment inflows are documented by beds of laminated and rippled siltstones to sandstones. Organic and/or mud drapes, which could be designated in some beds, confirm that phases of sediment deposition from the current were overridden by more quiet phases, during which the sediment was settled out from suspension. This type of depositional environment is also indicated by the presence of mudstone beds deposited by the same way.

Presented process of deposition could occur in karst environment (limestones) where various cavities were formed and represent depositional environment for the inflowing sediments. Regarding the genetic character of these basins, it is probable that some of them could be un-closed and interconnected. Marschalko and Mello (1993) interpreted described Gombasek beds as low-density turbidites formed in such settings.

During the Gombasek beds deposition (Santonian and Campanian), the studied area was not constantly flooded (Gaál and Bella, 2005) but most likely it was episodically flooded. As a result, the local sedimentary basins would rather be interpreted as small lakes (Cílek and Svobodová, 1999) with quiet depositional regimes, which were occasionally disrupted by new sediment inflows.

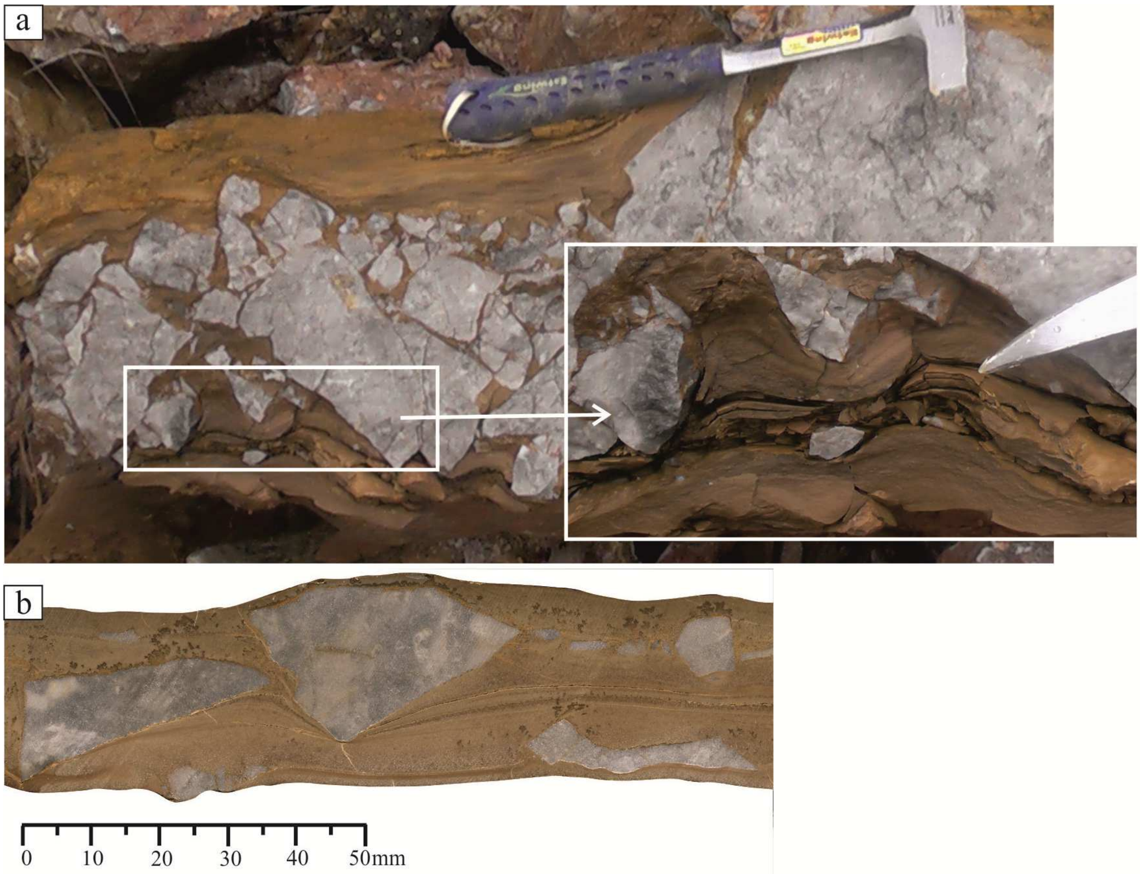


Fig. 4. Parallel laminated sandstone with the angular fragments of limestone. a – Clasts of limestone represent the collapse of the top of the cavern. Convolute bedding evolved under the clasts layer indicate that underlying beds were saturated by water, which was pushed up after clasts impact, i.e. sedimentation occurred in the water environment. b – In comparison to samples with the organic / mud drapes the velocity of the depositional flow was a little bit higher what allow the alignment of the limestone clasts parallel to flow direction. On the tops of described clasts could be distinguished thin corrosion surface (see arrows), which could indicate that rate of sediment supply was too low to cover clasts immediately. Therefore, there was a time for limestone corrosion.

In the analysed sediments, signs of the Mn mineralisation were also distinguished. These could be preserved as the manganese aggregate on the bedding planes of the sandstone beds (Fig. 5) and in this case could be interpreted as of syngenetic character, reflecting percolation of the mineral solution through the sediment during its deposition. Other forms are Mn dendrites, which accompanied calcite veins (Fig. 5) and therefore are interpreted as of epigenetic character.

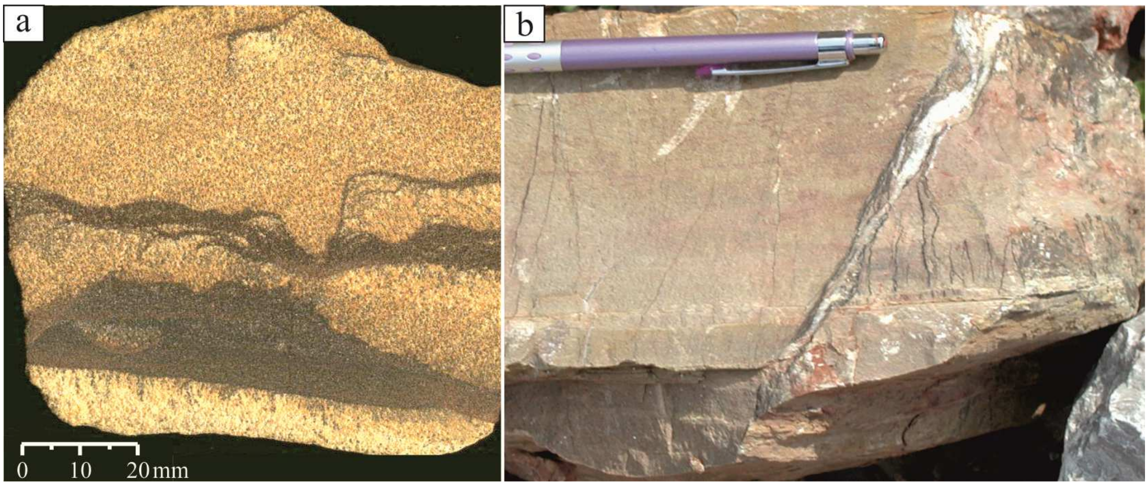
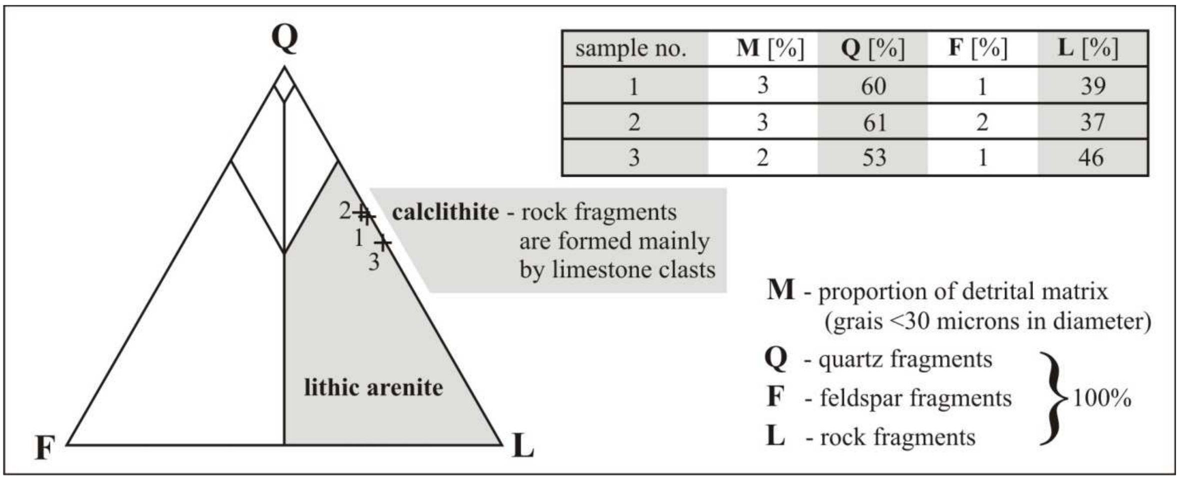


Fig. 5. Sandstone beds with visible syn-depositional (a) or post-depositional (b) Mn mineralisation.

Petrography of psammitic rocks from Gombasek beds

Sandstones from Gombasek beds are formed by compositionally and texturally different laminae. Textural differences are caused by slight changes in granularity (Fig. 7a, b). Compositional changes are caused by moderate varieties in the volume of quartz or carbonate clasts in laminae (Fig. 7a, b). Quartz fragments are more abundant in the most cases. Other compositional differences result from the presence of the carbonised plant material (Fig. 8d). This material is substantial in some parts of the sandstone, and is almost missing in other parts. Laminae with the abundant organic material are typically dark coloured (Fig. 3). The presence of iron oxides is characteristic of some laminae, where they are connected exclusively with carbonate material (Fig. 8a, b, c; 9c). These laminae have reddish-brown colour (Fig. 3).

Petrographically studied samples of psammitic rocks from Gombasek beds can be classified as **arenites** according to the proportion of detrital matrix. Following the modal composition of sand-sized particles, the sandstones belong to **lithic arenites** (Fig. 6). Sandstones can be named as **calclithites** because a substantial part of lithic fragments is represented by limestones (Fig. 6). Psammitic rocks are composed mainly of arenaceous fraction grains, amount of which varies from 82 to 87 %. The volume of structurally different fine-grained matrix varies from 2 to 3 %. The amount of cement varies from 7 to 13 % of the rock. Sand-sized detrital grains are formed especially by quartz (47 – 52 %) and rock fragments (31 – 40 %). Sand-sized feldspar grains are less common (0 – 2 %). In terms of textural maturity, the studied sandstones have a little matrix, moderate to good sorting and subangular to rounded grains. They are texturally mature.



sample no.	M [%]	Q [%]	F [%]	L [%]
1	3	60	1	39
2	3	61	2	37
3	2	53	1	46

Fig. 6. Position of studied sandstones in classification diagram of siliciclastic arenaceous sedimentary rocks according to composition (Pettijohn et al., 1987).

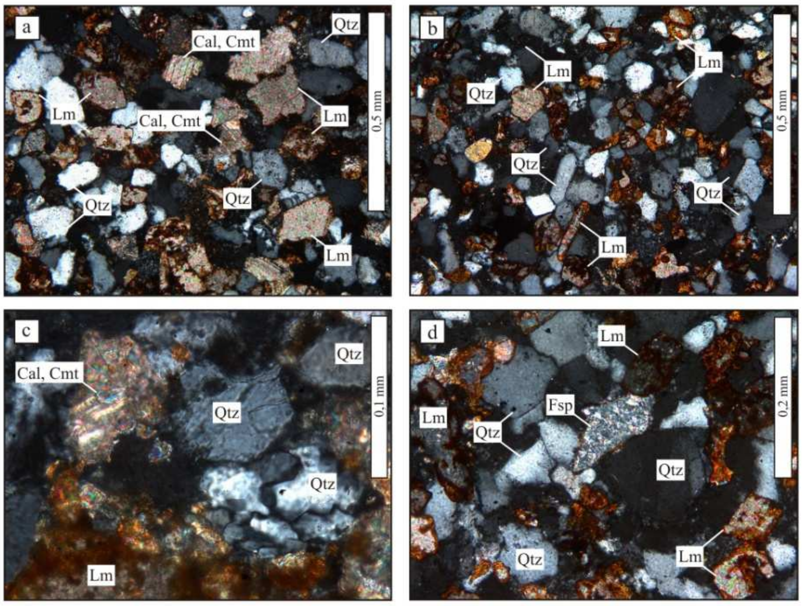


Fig. 7. Photomicrographs of psammitic rocks from Gombasek beds, crossed polarised light; a – part of the sandstone lamina with relatively bigger clastic grains and with relatively higher content of carbonate grains comparing to average grain size; b – part of the sandstone lamina with relatively smaller fragments and lower volume of carbonate grains comparing to average grain size; c – monocrystalline subangular quartz fragments (centre and upper right) and more rare polycrystalline subangular quartz grain (lower right) with undulose extinction of subgrais; d – fragments of angular sericitised feldspar grains (centre) are rare; Cal - Calcite, Cmt – Cement, Fsp – Feldspar, Lm – Limestone, Qtz – Quartz.

Quartz fragments are mainly monocrystalline. The volume of nonundulatory quartz grains and those with apparent undulosity is approximately the same. Fragments with strong undulose extinction are not frequent. Relatively minor part of quartz fragments is polycrystalline. Sometimes they have oriented and elongated subgrains with sutured grain boundaries. They represent fragments of the stretched metamorphic quartz (Fig. 7c). Studied sandstones are very-fine grained that could be the reason of relatively low content of polycrystalline quartz grains. The very-fine quartz particles are probably the subgrains or fragments of the original polycrystalline grains. The roundness of the quartz fragments ranges from subangular to subrounded (Fig. 7a-d).

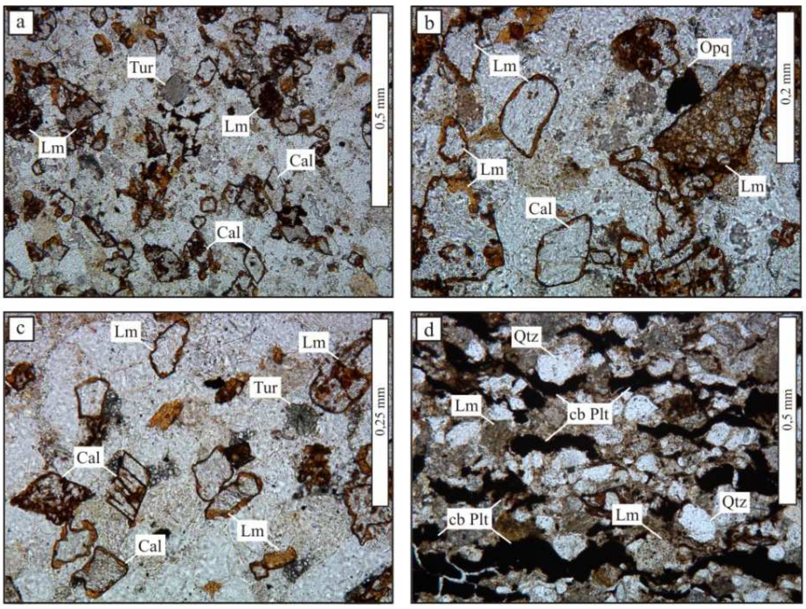


Fig. 8. Photomicrographs of psammitic rocks from Gombasek beds, plane polarised light; a – sandstone contains two types of carbonate fragments, major are limestone fragments, less frequent are calcite rhombohedral grains (lower right), clastic grains of tourmaline are present rarely; b – most of the limestone fragments are mud-grade limestones, detrital origin is visible in some clastic grains (left side); c – detrital carbonate grains are coated with a thin brown rim of iron oxide, in some grains iron oxide penetrate internal parts of carbonate grains; d – some laminae contain abundant volume of carbonized plant remnants which are oriented parallel to lamination, carbonized plant material is deformed due to process of sediment compaction; Cal - Calcite, cb Plt – carbonized Plant, Lm – Limestone, Qtz – Quartz, Tur – Tourmaline.

Lithic fragments are formed mainly by carbonate rocks. Clasts of siliceous rocks are present rarely. Carbonate grains are formed by different kinds of limestone (Fig. 8a-c). Sometimes calcite crystal fragments occur. In most cases, limestone clasts can be classified as lime-mudstones formed mainly by micrite crystals. Less frequent are grains of lime-grainstones with grains supported with little matrix. The roundness of the limestone grains can be characterised as subrounded to rounded. The original rhombohedral idiomorphic to hypidiomorphic shape is visible in many calcite fragments with well-marked cleavage. Unlike the quartz grains, the thin reddish-brown rim of iron oxide is typical of detrital carbonate fragments (Fig. 8a–c). Iron oxide also penetrates internal parts of some limestone grains. In calcite crystal fragments, iron oxide penetrates their cleavage planes (Fig. 8c).

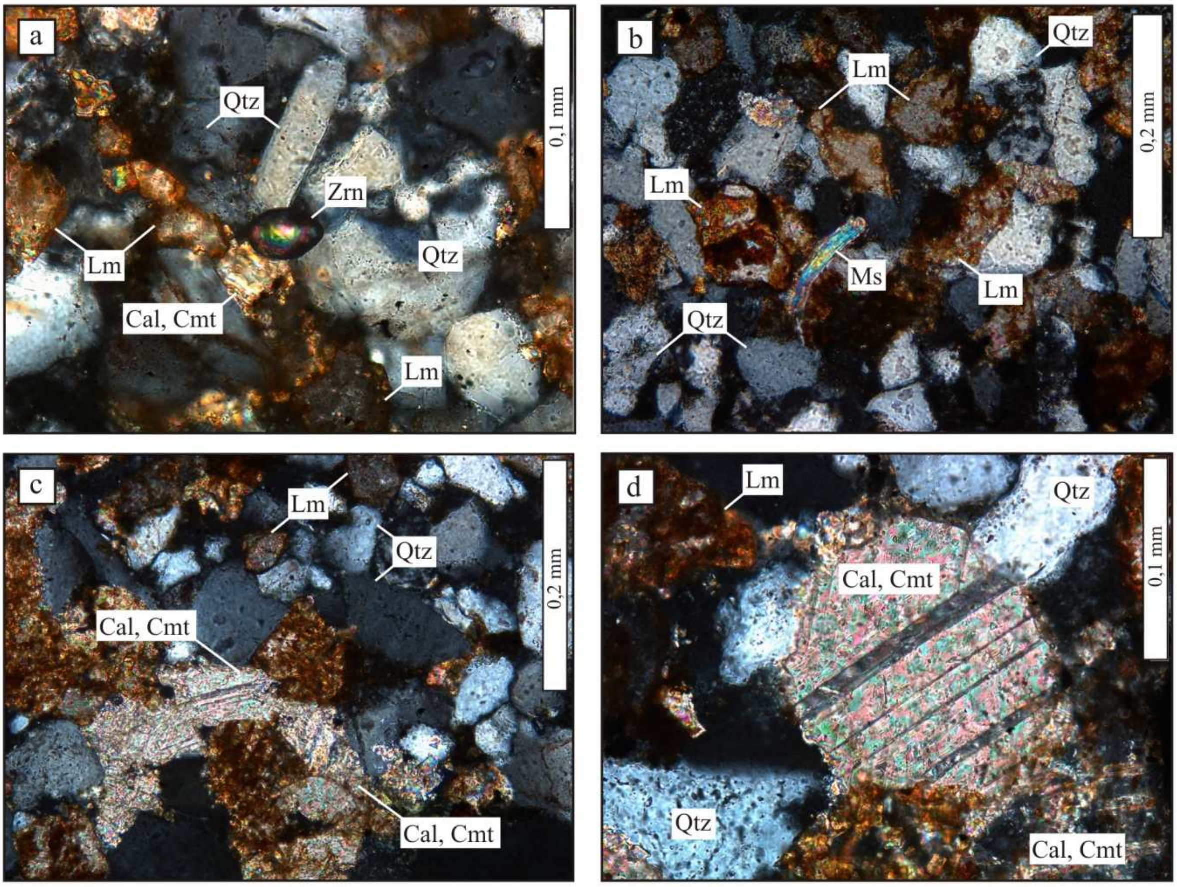


Fig. 9. Photomicrographs of psammitic rocks from Gombasek beds, crossed polarised light; a – common accessory minerals of sandstones are rounded zircon grains; b – relatively rare are crystals of white mica; c – cement of the sandstones is formed by calcite, some parts of calcite cement crystals are penetrated or rimmed by iron oxides analogous to clastic carbonate fragments; d – newly formed crystal of calcite cement with typical lamellar twining, grain is not coated with iron oxides; Cal - Calcite, Cmt – Cement, Lm – Limestone, Ms – Muscovite, Qtz – Quartz, Zrn – Zircon.

Feldspar fragments are very rare in the studied sandstones (Fig. 7d). Low feldspar content is caused by their instability in sedimentary conditions. The process of feldspar chemical weathering may be rapid, producing clay minerals and mica. Alteration of feldspar fragments was more intensive in tropic and humid climate that was typical of the Late Cretaceous period during the Gombasek beds formation (Mello and Snopková, 1973; Cílek & Svobodová, 1999; Gaál, 2008). The content of feldspar fragments in psammitic siliciclastic rock also depends on its granularity. The very-fine size of feldspar clasts supports their rapid chemical breakdown.

A common constituent of studied psammitic rocks are the remnants of carbonised plants. These opaque carbon substances appear in the rock rather locally. They can form a substantial part of particular sandstone laminae (Fig. 8d), and their size does not exceed 1 mm. Carbonised plant remnants of longitudinal shape are oriented parallel to lamination of the sedimentary rock. They are strongly deformed by the more competent surrounding clastic material, and in many cases, they are disintegrated by the process of sediment compaction.

Zircon (Fig. 9a), monazite and rutile are common accessory minerals in studied rocks. Relatively rare accessory mineral is tourmaline (Fig. 9b). The granitoid rocks of Slovak Ore Mts are probably the source of these accessory minerals (Gaál, 2008). Quartz fragments together with the accessory minerals were deposited in limestone plain of Slovak Karst, where they stuck in the seasonally flooded karst cavities with redox conditions of sedimentation.

Spaces among sandstone fragments are infilled by matrix material locally. Matrix is penetrated by iron oxide and it has aleuritic to pelitic character in terms of granularity. Studied psammitic rocks are carbonate-cemented. Cement is formed by very-fine crystalline calcite (Fig. 9c, d) of microsparite to sparite size. Crystals are irregular in shape and xenomorphic. Lamellar twining is typical of cement calcite grains (Fig. 9d). In the sandstone, cement fills spaces among the clastic grains. Part of the calcite cement is coated or penetrated by iron oxides analogous to carbonate clastic grains. Probably younger generation of cement is formed by light calcite crystals without iron oxides (Fig. 9c, d).

Nodules microanalytical study

Gombasek beds analysed in this study were deposited in the karst cavern formed in the wetterstein limestone. The bottom and the walls of this cavern were covered by symmetrical to asymmetrical concentric and/or cylindrical forms of the Fe-Mn (±Ni) clusters and/or nodules (Fig.10 b, c). Limestone surface *does not indicate* either any degree of karstification nor weathering. However, it was covered by irregular accumulations of a Fe-Mn mineralisation presented mainly as crusts, clusters and nodules (Fig. 10 a) pyrite clusters (Fig. 11 a, b) or very rarely as a macroscopic pyrite grains (Fig. 11 c). The size of idiomorphic pyrite grains is up to 1 cm. The nodules are rusty, dark grey with metal shine with size up to 3 - 4 cm. Relations between pyrite and nodules are not clear.

Microanalytical study of presented nodules confirmed the high concentration of Fe and Mn oxides and hydroxides (confirmed by X-ray diffractometry), occasionally in the form of very fine crystalline hematite but mostly as an amorphous goethite. Goethite was identified in forms typical for an oxi-hydroxides, i.e. “palisades” and fan-shaped aggregates of elongated, needle-like crystals, up to a few tens of μm long (Fig.12 a). Cryptocrystalline masses, botryoidal accumulations (Fig.12 a, b, c), and sheaf-like aggregates (Fig.12 c) were common as well. Hematite habits and shapes were also variable, but small (up to a few μm in size) spherical particles, botryoidal and globular aggregates prevail (Fig. 12 d,g). Ordinary impurities, mainly Si, Al, Ca and in some cases P, Mg, Mn, Ti, K, diversify chemistry of these oxides. Variable phase contrast seen in BSE images suggests inconstant water content in iron oxides.

Manganese oxides were also quite often encountered in the samples studied. They form aggregates of lamellar or sheeted crystallites (Fig.12 f), suggesting layer-type crystal structure. Chemical composition of the Mn oxides is also variable; typical admixtures are Ca, K, Fe, Al, Mg and Si. Occasionally, significant amounts of nickel (over 1 wt.%) were measured in these minerals (Fig.12 h).

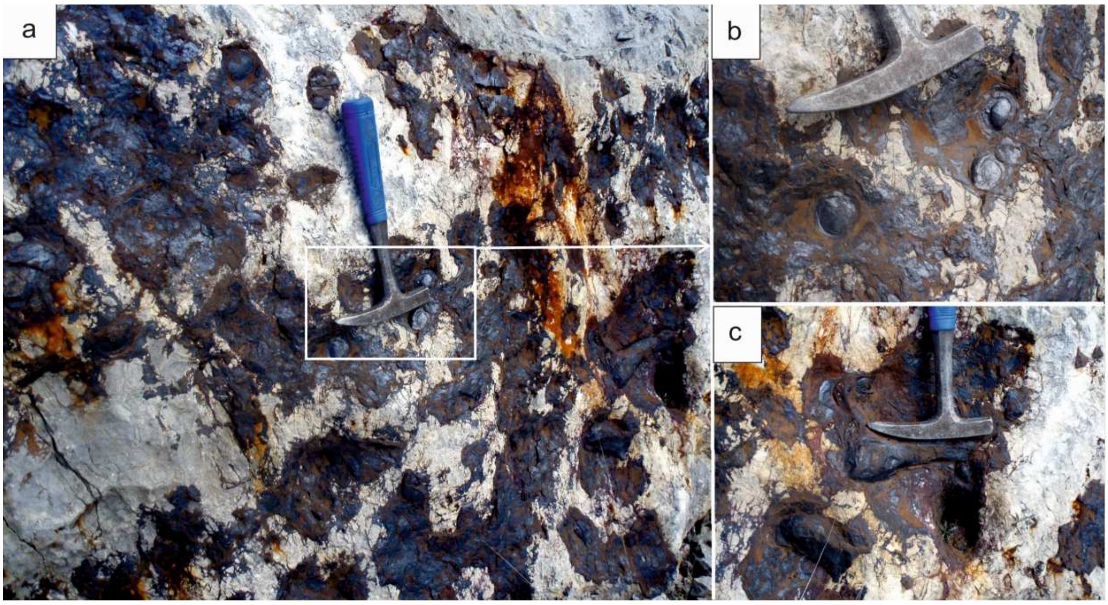


Fig. 10. Fe, Mn, (±Ni) crusts, clusters and nodules preserved on the surface of a limestone cavern. a- nonintegrated areal nodules distribution b- symmetrical concentric forms, c – asymmetrical cylindrical forms.

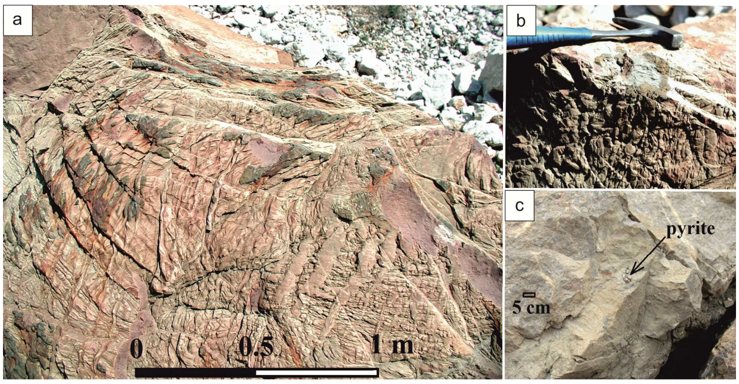


Fig. 11. a- irregular distribution of pyrite crust on carbonate surfaces b- a cross-section of pyrite crust in two perpendicular cross-sections, c- pyrite druse on faulted surface.

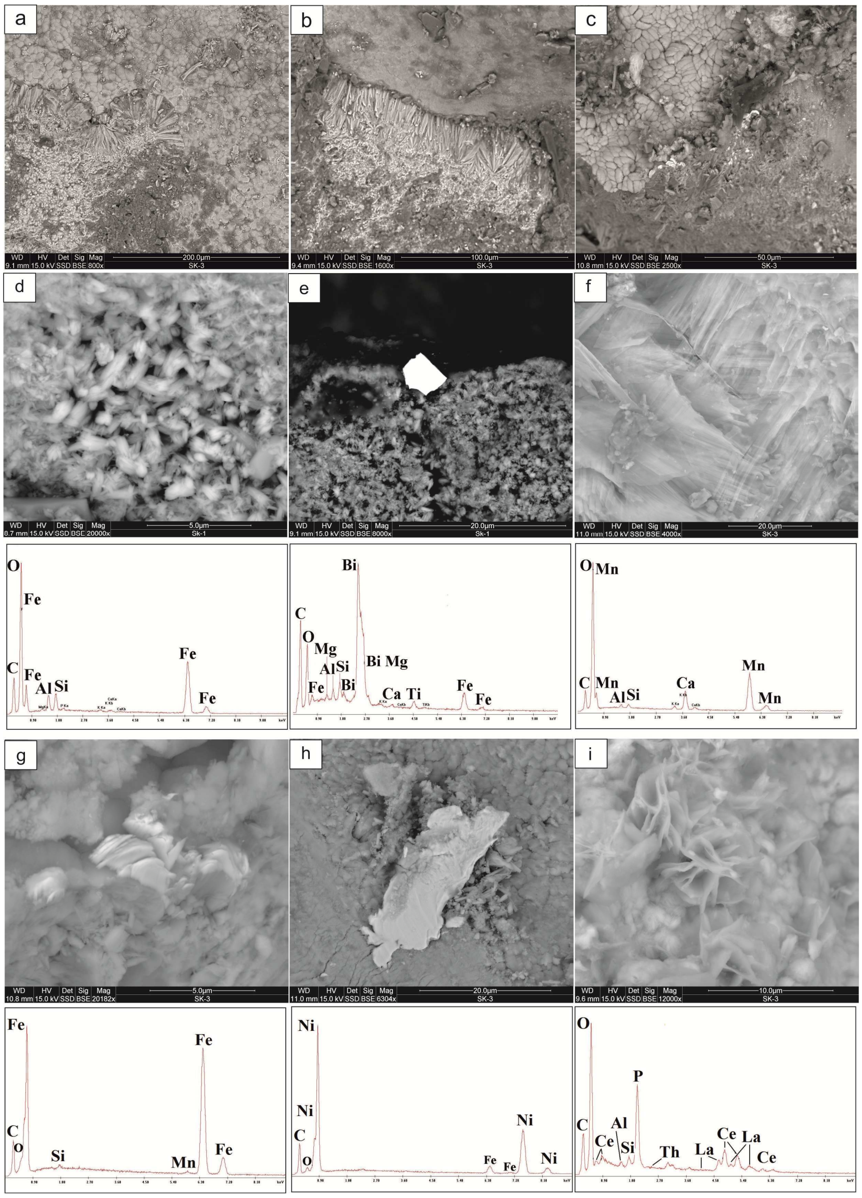


Fig. 12. a–c: Fe, Mn (±Ni) nodules within thin-sec tion with typical fine crystallised and amorphous structure: a - with a magnification of 800 x, b – with magnification of 1 600 x, c – with a magnification of 3 200 x. Backscattered electron images and chemical composition of noncrystalline phase. d- the presence of prevailing content of Fe-oxides and hydroxides, e – the presence of other additions and individual grain containing Bi, Ti elements, f – the presence of prevailing content of Mn-oxides and hydroxides, g – light-coloured phase with increasing concentration of Fe, h – light-coloured phase with increasing concentration of Ni, i – light-coloured phase with increasing concentration of Rare Earths Elements.

Besides Fe and Mn oxides, the ferruginous accumulations contain small amounts of barite, ferrous sulphides (most probably pyrite, Fig. 12 g, h) and apatite. Th-monazite grains (Fig.12 i) and a few metallic Ni–Fe particles were encountered as well, but the origin of the latter is unclear.

Fe-Mn nodules are most common in the deep-water environment where their qualitative composition reflects the high content of Fe and Mn. That is the reason why they are often referred to as iron manganese concretions (Depowski et al., 1998), but the content of Ni also showed increased content of Al what indicates continental environment. Therefore, it is more likely that studied nodules were precipitated under anoxic conditions.

Discussion

The Late Cretaceous evolution of the southern part of the Western Carpathians edge is connected with tectonic, sedimentary and environmental changes. The Silica nappe is a specific example of nappe, which root position and definitive structure emplacement are not explained sufficiently. Sedimentary record of Gombasek beds from Silica nappe analysed in this study represents an important record of depositional conditions in the Central Western Carpathians, based on which it is possible to compare relations between erosion, mineralisation, sedimentation and tectonic evolution.

Rear position and structural core elasticity of the Silica nappe during the Alpine orogeny shortening allowed to form bulge at this part of the nappe in the Early Cretaceous related with weathering of the Cretaceous and the Jurassic age deposits. Adjacent Gemeric Superunit generated transpressional shear zones and also supported compression state of the south edge. The Upper Cretaceous thrusting of the Silica nappe to the north related with the general sedimentary hiatus in the Central Western Carpathians at that time period. As a result, the Middle Triassic wetterstein limestones were exposed to the weathering and their karstification started. Some of the cave systems (Marschalko and Mello, 1973), silkholes (Cílek and Svobodová, 1999) and caverns were created and therefore sediment deposition was allowed.

Before the sedimentation of the Gombasek beds, infiltration of the solutions saturated with the higher content of Fe, Mn, Ni and organic matter was allowed to penetrate to deep karst caverns. At this evolution stage of the area, the Late Cretaceous clastic sedimentation at the top part of the Silica nappe was restricted into this depositional environment. Only micron-size particles would be deposited on the bottom (grain with higher content of Bi, Fig. 12), where degradation of the organic matter under anoxic conditions predominated. Described depositional conditions were appropriate for the precipitation of the pyrite crusts and crystals as well as nodules of Fe, Mn ± Ni composition. Similar crusts were in Slovak Karst area interpreted as a result of the limestone weathering by Kováčik, 1955 and Gaál, 2008. However, analysis of the crusts and nodules presented in this study only showed the low content of the Al (also established by Gaál (2008)) and atypical higher content of the Ni. Therefore, their interpretation as a product of limestone weathering is not very likely. Higher content of the Ni, Co and Cr was also interpreted from dark mudstones (Marschalko and Mello, 1993).

In consequence of the ongoing limestone karstification (eventually tectonic processes) caverns, in which chemical precipitation occur, were gradually opened and conditions for the clastic sedimentation have been formed. During this stage, sediments known as Gombasek beds were episodically deposited and depositional conditions were transformed into the oxidic ones. The rising of the pressure from overlying sediments in combination with oxidation of the pyrite crusts and nodules results into solutions formation which syn-depositionally penetrated overlying sediments and have been (post-depositionally) concentrated on the both bedding planes and tectonic joints in sediments where their precipitation starts.

Creation of the nodules and pyrite concretions is restricted only to the first described depositional phase what is indicated by their presence only on the base and not within the clastic sediments. Therefore, it is clear that the depositional conditions have to be changed at the beginning of the Gombasek beds deposition.

As the last depositional phase of the studied deposits, breaking of the caverns tops and/or raising of the tectonic activity during the Late Cretaceous deposition of the Gombasek beds could be designated. In the studied deposits, this phase has been recorded by the presence of beds with angular limestone clasts, which concentration is higher in the upper part of the sedimentary record.

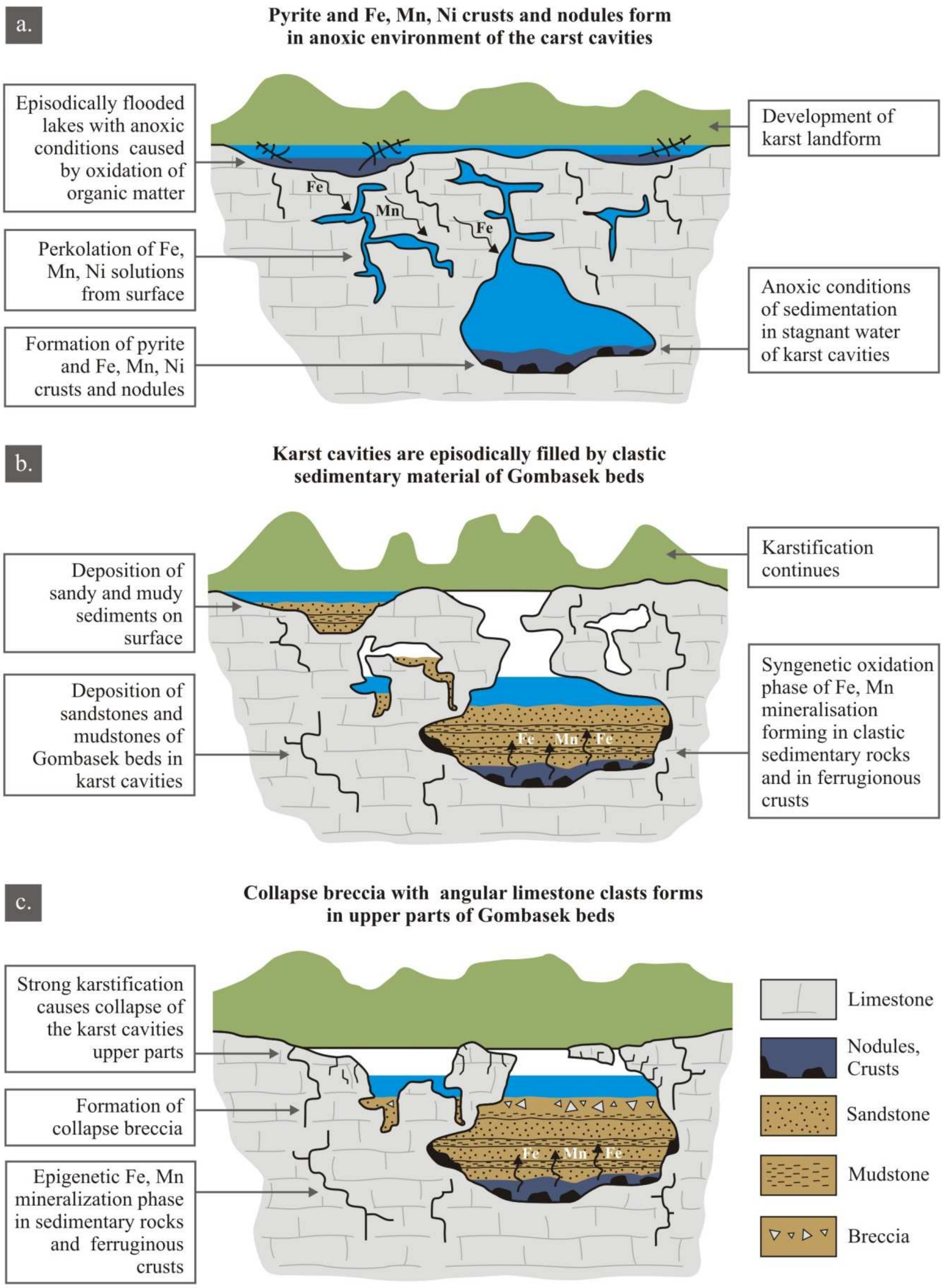


Fig. 13. The schematic model of polystage evolution of Gombasek beds/layers within studied cavern: a – "1st stage" – Formation of pyrite , as well as Fe, Mn, Ni crust and nodules, b – "2nd stage"- Karst cavities were episodically filled by clastic sedimentary material of Gombasek beds, c –"3rd stage" – Formation of collapse breccia with angular limestone clasts forms in upper parts of Gombasek beds.

Conclusions

Gombasek beds as sediments deposited in the karst environment represent a valuable record of the Late Cretaceous nappe events, which allow a better recognition of the rear position of the Silica nappe within the Central Western Carpathians.

Analysed sedimentary record from the Gombasek quarry indicates the polystage evolution of the Gombasek beds. Three main genetic stages, which relate to the tectonic settings of the Silica nappe could be designated:

1. Overthrusting of the Silica nappe on the Gemeric Superunit during the Early – Late Cretaceous – Regarding the climatic conditions, only small temperature variations and therefore good conditions for the karst formation occurred during this stage. As a result, long-term weathering and karstification of limestone was initiated.
2. Precipitation of the Fe, Mn ±Ni crusts and nodules from the concentrated aqueous solutions under the anoxic conditions – During this stage, clastic sediments in the karst structures (caverns) were not deposited what indicates only the lower stage of the karstification.
3. Deposition of the Gombasek beds – Higher stage of karstification, most likely supported also by ongoing uplift of the Silica nappe allowed connection of the underground karst structures with the surface. Karst structures were opened and behave like sedimentary traps for the Gombasek beds. These were deposited in relatively quiet water condition with recurrent sediment inflows.
4. Breaking down of the karst structures indicating the presence of the limestone clasts in the upper parts of Gombasek beds – This last stage could relate to the increased tectonic activity of the Silica nappe during the Late Cretaceose period.

References

Andrusov, D.: Stratigrafie a tektonika severniho okraje Silické planiny a Drnavy na Slovensku - *Čas Bratislava. Roč. X, 243-246*, 1936.

Biely, A. (ed.), Bezák, V., Elečko, M., Kaličiak, M., Konečný, V., Lexa, J., Mello, J., Nemčok, J., Potfaj, M., Rakús, M., Vass, D., Vozár, J., Vozárová, A.: Geologická mapa Slovenskej republiky 1 : 500 000. 1. vyd., *MŽP SR, ŠGÚDŠ, Bratislava*, 1996.

Bystrický, J.: Slovenský kras. Stratigrafia a Dasycladaceae mezozoika Slovenského krasu. (Stratigraphie und Dacycladazeen des Gebirges Slovenský Kras*). Ústr. Ústa. geol., Bratislava, 1-204*, 1964.

Cílek, V. & Svobodová, M.: Svrchnokřídové výplně závrtu v lomu Hosťovce a Gombasek ve Slovenském krasu. *In: Výskum a ochr. prír. Slov. krasu, J. Šmidt (ed.), 41-48, 1999.*

Činčura, J.: Paleoalpine paleokarst of the Western Carpathians. Proceedings of XVII. Congress of Carpathian-Balkan Geological Association. *Geol. Carpathica 53, Special issue, 5*p, 2002.

Dašková, J., Konzalová, M., Cílek, V.: Tracing of palynomorphs in the eastern Slovakian Karst. *Acta Musei Nationalis Pragae, Series B - Historia Naturalis 67 (1-2), 51-62,* 2011

Depowski, S., Kotlinski, R., Ruhle, E., Szamalek, K.: Surowce mineralne mórz a oceanów. *Wydawnictvo naukowe Scholar, Warszawa, 384p.,* 1998.

Gaál, Ľ.: Geodynamika a vývoj jaskýň Slovenského krasu. *Speleologica Slovaca 1, 168s,* 2008.

Gaál, Ľ., Bella, P.: Vplyv tektonických pohybov na geomorfologický vývoj západnej časti Slovenského krasu. *Slov. kras 43, Liptovský Mikuláš, 17-36*, 2005.

Gasparatos, D.: Fe-Mn concretions and nodules to sequester heavy metals in soils (2012) Environmental Chemistry for a Sustainable World. Vol 2: Remediation of Air and Water Pollution*, pp. 443-474. doi: 10.1007/978-94-007-2439-6_11, E. Lichtfouse, J. Schwarzbauer, and D. Robert (Eds.), Berlin: Springer, 2012.*

Gasparatos, D., Tarenidis, D., Haidouti, C., Oikonomou, G.: Microscopic structure of soil Fe-Mn nodules: Environmental implication*. Environmental Chemistry Letters, 2, 4, pp. 175-178. doi: 10.1007/s10311-004-0092-5,* 2005.

Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, ST., Lupták, B., Méres, Š.: Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia) P-T conditions and in situ 40Ar/39Ar UV laser probe dating of metapelites. *J Metamorph Geol 19: 197–216,* 2001.

Kochanová, M., Mello, J. a Siblík, M.,: Fosílie wettersteinských vápencov Slovenského krasu (lokalita Silička). *Geol. Práce, spr. (Bratislava), 63,55-66,* 1975.

Kováč, M., Nagymarosy, A., Oszczypko, N., Ślączka, A., Csontos, L., Marunteanu, M., Matenco, L. and Marton, E.: Palinspastic reconstruction of the Carpathian-Pannonian region during the Miocene. In: Geodynamic Development of the Western Carpathians (ed. M. Rakuš). *GÚDŠ Bratislava: 189-217*,1998.

Kováčik, J.: Reziduálne železné rudy z Plešiveckej planiny. *Geol. sborn. 6, 3-4, Bratislava, 232-251*, 1955.

Kráľ, J.: Fission track ages of apatites from some granitoid rocks in West Carpathians. *Geol Zbor Geol. Carpath 28, 269–276,* 1977.

Marschalko, R., Mello, J.: Turbidities as filling of cabities in Triassic limestones of the Silica nappe (Western carpathians, plesivec Karst Plateau). *Geologica Carpathica 44, 1, Bratislava, 35-42,* 1993.

Mello J., Elečko M., Pristaš J., Reichwalder P., Snopko L., Vass D., Vozárová A., Gaál Ľ., Hanzel V., Hók J., Kováč P., Slavkay M. & Steiner A.: Explanations to geological map of the Slovak Karst 1 : 50 000. *Dionýz Štúr Publishers. 1-255,* 1997.

Mello, J.: Facial development and facial relations of the Slovak Karst Middle and Upper Triassic (West Carpathians, Southern part of Gemerids). *Schrift. Erdwiss. Komm. Osterr. Akad. Wisss. 2, Wien, 147-155,* 1974.

Mello, J., Snopková, P.: Upper Cretaceous filling in the cavities of Triassic lmestones in the Gombasek querry. *Geol. Práce, Správy, 239-253,* 1973.

Pettijohn, F.J., Potter, P.E., Siever, R: Sand and Sandstone. *Springer-Verlag New York,* 1987.

Plašienka, D., Janák, M., Lupták, B., Milovský, R., Frey, M.: Kinematics and metamorphism of a Cretaceous core complex: the Veporic unit of the Western Carpathians. *Phys Chem Earth (A) 24: 651–658,* 1999.

Plašienka, D., Broska, I., Kissová, D., Dunkl, I.: Zircon fission-track dating of granites from vepor-Gemer belt (Western Carpathians): constraints for the Early Alpine exhumation history. *Journal of Geosciences. 52, 112-123,* 2007.

Poller, U., Uher, P., Broska, I., Plašienka, D., Janák, M.: First Permian–Early Triassic zircon ages for tin-bearing granites from the Gemeric Unit (Western Carpathians,Slovakia): connection to the post-collisional extension of the Variscan orogen and S-type granite magmatism. *Terra Nova 14, 41–48,* 2002.

Sasvari, T., Jacko, S., Kondela, J.: Structural. tectonic architecture of limestone quarry. Gombasek on Plešivec Plateau of Silica Nappe. *Acta Montanistica Slovaca, 11 (1), pp. 70-85,* 2006.

Uher, P., Broska, I.: Post-orogenic Permian granitic rocks in the Western Carpathian–Pannonian area: geochemistry, mineralogy and evolution. *Geol Carpath 47, 311–321,* 1996.

Zhang, M., Karathanasis, A.D.: Characterization of iron-manganese concretions in Kentucky alfisols with perched water tables. *Clays and Clay Minerals, 45,3, pp. 428-439,* 1997.