

Carbonates and Evaporates

Petrology and Paleo-karst features of the Gomba hydrocarbon reservoir (Central Hungary) --Manuscript Draft--

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Petrology and Paleo-karst features of the Gomba hydrocarbon reservoir (Central Hungary)

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Abstract

The pre-Cenozoic basement of central Hungary is more or less built from different types of carbonate rocks. These carbonates are good hydrocarbon reservoirs in numerous cases, and hydrocarbon production is significant in this region in Hungary. Nonetheless, the detailed petrology of the storage rocks has not yet been investigated or published.

In this paper, investigations on the lithology of a hydrocarbon reservoir from central Hungary are presented. Based on this work, two types of pure limestone, a dolomitic limestone and a polymict breccia, can be distinguished in the research area. The limestone types are similar to the Kiscennsík Limestone Member from the Bükk Mts., but they contain significant amounts of framboidal pyrite and dead oil in the vein system. The breccia is predominantly composed of angular carbonate clasts and minor metamorphic and sedimentary rock fragments in a chaotic pattern. The breccia has some grains that may be a speleothem (e.g., a stalactite or stalagmite) by their structure and isotopic compositions. The texture of the breccia was analysed by image analysis methods and the results show that it was formed by fluid-related processes. Based on the vein petrography, there are four different fracture generations and two different hydrocarbon migration phases. The composition of the hydrocarbon-bearing fluid inclusions related to the second migration event is similar to the produced oil.

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1. Introduction

More than 60% of the world's oil and 40% of the gas reserves are held in fractured carbonate reservoirs. The pre-Cenozoic basement of Hungary has a significant volume of carbonate rocks, which are excellent reservoirs at places. There are six Total Petroleum Systems known in the Pannonian Basin Province (Dolton 2006). One of the most complex and important ones is the Hungarian Paleogene Total Petroleum System, which is located in the Hungarian Paleogene Basin in the central part of Hungary (fig. 1). The study area is the Gomba field in the W part of the basin. The field has Triassic carbonate and Eocene-Oligocene detrital reservoir rocks, complex structural and sedimentary traps and source rocks of Pliocene age. Hydrocarbon exploration and production began only at the end of the 90s (Dolton 2006), but today, it is one of the most productive areas in the country.

Although the production history is not long, the geological and geophysical research has a longer past. The structure of the region is well-known through geophysical investigation, but the petrology of the Triassic reservoir is less known because of the few cores and the very restricted amount of analysis. Nevertheless, the production history clearly shows that the available geological and fractured reservoir models do not fit well enough to explain the

production past and predict future trends. Thus, it is essential to understand the geology of the area much better than before.

Based on the available reports and unpublished information, the carbonate part of the reservoirs may have paleo karst forms (e.g., paleo cave faces, bigger sized caverns or collapses), which can significantly modify the petrophysical features of the petroleum system. The karst processes can increase or decrease the porosity, modify the migration pathways by cave passages or collapses and thus significantly modify the hydraulic behaviour of a complex reservoir. Nevertheless, it is very problematic to localize the effect of karst processes in the subsurface even though there are numerous works on understanding the hydrodynamic role of paleo-caves by several authors, including Lucia (1968, 1995, 1996), Wilson et al. (1991) Wright et al. (1991), Candelaria and Reed (1992), Lucia et al. (1992), and Loucks (1999, 2001, 2003). Based on these works, there are some typical paleo-cave formations, faces that are recognizable not only by well-log analysis but also in cores or thin sections.

Our goals are to observe, document and interpret the petrological features of the Triassic carbonate rocks and their microfracture network in the study area based on an analysis of the core material. The main aim is to recognize the evolutionary history of the Triassic beds from the early diagenetic processes to the present day, recognize the main hydrocarbon migration pathways and estimate the effects of the karst forms in the reservoir.

2. Geological settings

The investigated area is located in the northern part of middle Hungary, in the western part of the Hungarian Paleogene Basin, which is subdivided into three parts by Nagymarossy (1990). Our field belongs to the southern Buda Paleogene unit; the region is located at the boundary of the Trans-Danubian Range Unit (TRU) and the Mid Hungarian Unit (MHU) (fig. 1). The boundary between the TRU and MHU is defined by the Balaton Line, a significant

transversal fault zone, while the position of the boundary of the TRU and the Bükk Unit to the north is rather problematic. Though the boundary is unequivocally inferred by seismic studies (Szalay et al. 1976; Szalay et al. 1978), Bükk type lithologies are also sampled by deep wells on the opposite side of the hypothetical tectonic zone (Benedek 2009).

The Mesozoic sequence of the MHU is hardly known, but it greatly differs from the typical Mesozoic formations in the TRU and Bükk Unit. A close correlation with the Dinarides and the Southern Alps was suggested for the lithologies of the MHU (Haas et al. 2004; Schmid et al. 2008). The relationship is discussed in numerous works concerning both sedimentological and tectonic aspects (Árkai 1983; Kovács et al. 2000; Schmid et al. 2008).

While the Mesozoic rocks in the MHU are unknown at the surface, the formations of both the TRU and the Bükk Unit have been studied in detail from outcrops. The closest outcrops in the TRU to the investigated reservoir are located in the Buda Mts., where Ladinian dolomitized platform carbonates (Budaörs Dolomit Formation), Carnian–Norian platform dolomites and limestones (Dachstein Limestone Formation) and cherty basinal limestones (e.g., Mátyáshegy Formation) represent the Mesozoic sequence. The limestone and dolomite bodies in the Buda Mts. contain significant karst cavities and caves formed primarily by epigene (Wein 1977; Nádor and Sásdi 1991) and young, still active hypogene processes (Kriván 1959; Kraus 1982; Nádor 1991).

As far as the Bükk Unit is concerned, the limestone-dominated sequences are recrystallized and generally reached anchimetamorphic grade (Árkai 1983) with a decreasing tendency from the NE to the SW. According to the present lithostratigraphic conception, the different Middle to Upper Triassic platform carbonates in the Bükk Unit are assigned to the Bükkfensík Limestone Formation (Haas 2004). A peculiar, non-metamorphosed variety of these almost pure carbonate rocks is restricted to the NE part of the Bükk Mountains, called

the Kisfennsík Limestone Member. The unit most likely forms a small thrust sheet (Haas 2004).

The Kisfennsík Limestone consists of predominantly light-grey, whitish-yellow carbonate platform facies limestone. Tidal flat, lagoonal and reefal environments can be reconstructed in the carbonate platform sequence of the Kisfennsík block. The sequence is mainly thick-bedded or massive, containing subordinate finely bedded parts and occasionally cyclic loferites. Syngenetic brecciation is relatively frequent (Pelikán 2005). Although the type area of the formation is located in the NE part of the Bükk Mountains, there are some proven occurrences in the subsurface basement to the SW of the Bükk Mountains. It is noteworthy that although there was no significant hypogene karst formation in the Bükk Mountains, this observation is not definitively true for the Kisfennsík Limestone, whose early karstification was proven by Velledits et al. (1999).

The studied Gomba region is characterized by continuous sedimentation from the Eocene to the Miocene with numerous subsequent transgressive and regressive cycles (Benedek 2009). As a result, different marly and clayey sediments and carbonate rocks formed. Siliciclastic sequences were also deposited during the Miocene (Tari et al. 1993).

One of the most important events concerning the reservoir's evolution was the development of the Eocene Kosd Formation, which predominantly consists of debris of grey claystone, sandstone, limestone and dolomite gravels; occasionally, mollusc-bearing marls are present with travertine and coal in the upper part of the sequence. The starting member of the formation contains 2–25 cm large boulders and gravels, which is interpreted as erosional debris from the underlying Kisfennsík Limestone (Less 2005). During the Oligocene, (hemi-) pelagic fine-grained sediments formed, e.g., the Tard Clay Formation and the Kiscell Clay Formation. The latter is characterized by high TOC content, having reached the oil window

123 during the Pliocene (5 Mya); therefore, this formation is regarded as a source rock for HC
124 generation approximately 2400 m below the present surface (Benedek 2009).

125 The reservoir rocks in this area are intensively tectonized. The basin's morphology is
126 significantly determined by complex fault patterns of dominantly NE-SW strike that were
127 essentially caused by numerous subsequent Alpine compression phases (Austrian, Pyrenean)
128 and Upper Miocene transversal faults (Csontos and Nagymarossy 1998; fig. 1). The Neogene
129 structural pattern of the basin was mainly formed due to these transversal motions; one part of
130 the faults can be interpreted as rejuvenated old structures. This complicated fault pattern has a
131 significant influence on the deep basinal hydrological flow system of the reservoir.

132 Exploration of the Gomba field started at the beginning of the 2000s. Based on the
133 petrographical investigation of cores and chips, the Triassic reservoir carbonates represent the
134 Kisfennsík Limestone, so the area is interpreted as part of the Bükk Unit. Up-section, the
135 Eocene debris with high fluid storage capacity is similar to the Kosd Formation (Benedek
136 2009).

137 Based on the present hydrodynamic model, the fractured Triassic carbonates and the
138 Eocene debris behave as a common hydraulic system (Benedek 2009). The groundwater
139 beneath the hydrocarbons has a temperature of ~120 °C with a salinity of ~35‰. As a
140 consequence, it seems possible that the rock body is still under the control of hypogenic
141 karstification following the Cenozoic exhumation-related surficial karstification.
142 Understanding the ongoing karstic processes is one of the most important steps in studying
143 the hydrodynamic system of the reservoir.

145 3. Materials and Methods

146 The occasional total mud loss at certain levels of all (7) boreholes during the drilling
147 process suggests intervals with significant open pores and extremely high permeability, which

explains why a rather limited number of samples could have been collected. Hence, the sampling strategy was to concentrate on core material representing zones of the reservoir as close as possible to the highest porosity horizons. Following a careful macroscopic description, 5x5 cm sized thin sections were made from the available cores. The analysed material and the applied methods are summarized in table 1.

3.1. Fabric

The rock fabric was observed under an Olympus SZX7 binocular microscope at thin section scale and was classified after Dunham (1962) for the limestone and after Sibley and Gregg's (1987) classification schemes for dolomite. Vein texture classification was made using Bons' (2000) work. Petrographic Image Analysis (PIA) was used to characterize the breccia samples following Mort and Woodcock's (2008) scheme.

The input images were generated using thin sections by a 6000 dpi resolution slide scanner. The Corel Draw X3, Olympus Stream Essential, ImageJ, and Fractalyse software were used for image analysis and the following geometric parameters were measured.

Particle Size Distribution

There is a close relationship between the formation process and the clast size distribution of the breccias, which is why the particle size distribution (PSD) is one of the most generally measured geometric parameters (Jébrak 1997). Numerous structural geological studies showed that PSD follows the

$$N(r)=C*r^B$$

power law distribution function at each scale, where N(r) means the number of clasts bigger than r in diameter, C is a constant, and B means the gradient of the linear function in

logarithmic scale. The calculations were fulfilled using the squared area parameter in pixels according to Blenkinsop (1991).

Clast/matrix proportion

To calculate this parameter, the areas covered by clasts and matrix were considered first on the surface of the thin section. The proportion of the clasts and matrix was computed as the thin section area/total clast area.

Rotation

The grain orientation was characterized numerically by the variation coefficient of the main axes of the ellipses fitted to the clasts. The ellipse fitting method equates the second order central moments of the ellipse to those of the distribution, thereby effectively defining both the shape and size of the ellipse.

Roundness

Roundness is a parameter that can quantify the shape of the clasts. It was calculated using the ImageJ software with the following function: $\text{Round} = 4 \cdot [\text{Area} / \pi \cdot \text{Major Axis}^2]$, where Major Axis concerns the fitted ellipse, which is fitted onto the individual clasts using the same method shown before.

Grain roughness

The fractal dilation method was used to analyse the roughness of the grains. In this approach, each occupied point is surrounded by a square of size ϵ , the surface of which is considered to be completely occupied. The size of these squares is then gradually enlarged, and we measure the total surface $A(\epsilon)$ covered at each stage. As the squares are enlarged, any

197 details smaller than ε are overlooked and we gradually obtain an approximation of the original
198 form. Because more and more squares overlap, the total occupied surface for a particular
199 value ε is less than what it would be if the same number of occupied points that make up the
200 original form were surrounded individually. By dividing this total surface by the surface of a
201 test square (ε^2), we obtain an approximation of the number of elements $N(\varepsilon)$ necessary to
202 cover the whole.

203 The statistical database built from the above mentioned parameters was analysed by
204 the SPSS 20 software. For extreme data handling, boxplots were used, and the Kolgomorov-
205 Smirnov method was applied for the normality test of the parameters.

207 **3.2. Phase analysis**

208 The microtexture of the samples was analysed by an Olympus BX41 polarization
209 microscope. A cathode luminescence microscope was used to characterize the overgrowth of
210 the different constituents and cement minerals. Cathode luminescence microphotographs were
211 taken at the Institute for Geological and Geochemical Research's Centre for Astronomy and
212 Earth Sciences, Hungarian Academy of Sciences, using a Reliotron (cold cathode) instrument
213 mounted on a Nikon Eclipse E600 microscope using a Nikon 4500 digital camera. The
214 cathodoluminescent apparatus operated at a 7–8 keV accelerating voltage and 0.25–0.63 mA
215 beam current.

216 A Rigaku Ultima IV X-ray diffractometer was used to determine the mineralogical
217 composition of the insoluble residue. Insoluble residue was prepared by dissolution with 10
218 m/m% acetic acid in 20 °C. To characterize the clay minerals, oriented specimens were
219 measured on a fraction of <2 μm diameter. Air-dried and ethylene-glycol solvated (16 h, 60
220 °C) samples were X-rayed to identify the swelling clays.

A U-RFL-T type UV fluorescence module and a UMNU2 type filter (exciting filter 420-480 nm, emission filter 520 IF, dichromatic mirror 500 nm) was applied to detect the carbonaceous material in the thin section. This set was installed on an Olympus BX41 polarization microscope. Carbonaceous material analyses were performed on a Thermo Scientific DXR Raman microscope equipped with a diode-pumped frequency-doubled Nd-YAG laser at 10 mW maximum laser power. The samples were irradiated by laser light at a wavelength of 532.2 nm, with the laser beam focused using a 100× objective lens, resulting in a spot size of ~0.7 μm. The backscattered light collected by the microscope objective was filtered via an edge filter, dispersed by a single grating (1800 grooves mm⁻¹) and gathered in a CCD detector cooled to -20 °C by the Peltier effect. The instrument has a spectral resolution better than 2 cm⁻¹ and a spatial resolution of a few cubic micrometres; a 25 μm pinhole aperture was used for each measurement. In every case, 1 mW laser power was used to record the spectra. Sample exposures were obtained by operating the DXR Raman microscope in auto-exposure operating mode, in which the instrument attempts to reach a specified signal-to-noise ratio (S/N) during the measurement (in this case, S/N = 60).

We used UV methods to characterize the petroleum inclusions (from the vein system). During the detection, we used the above mentioned Olympus microscope with an Olympus U-MNU-2 filter cube and an Olympus 100 W mercury light source. We collected 18 spectra during the measurement. To optimize the signal-to-noise ratios, we chose the spectrum of the highest intensity among the collected spectra of the single petroleum inclusions. To facilitate a comparison between different petroleum types, each spectrum was transformed into XYZ chromaticity coordinates and was plotted in the CIE-1931 chromaticity diagram (Smith and Guild 1931). This method was also applied to characterize the crude oil from the Gomba-1 well.

3.3. Mineral chemistry

The geochemical properties of the different rock-forming phases (including framework grains and cement) were analysed by XRF and SEM EDS instruments. A Horiba Jobin Yvon XGT 500 micro-fluorescence spectrophotometer was used for the XRF measurements with a 15 keV accelerating voltage and 10 µm aperture size. Mg-content measurements of the calcites were recorded by a Hitachi S-4700 FE scanning electron microscope with an Energy Dispersive detector. All the measurements were made at a 20 keV acceleration voltage.

The carbon and oxygen isotopic compositions of selected textural elements were determined in the Hungarian Institute for Geological and Geochemical Research using the following methods. Sampling was conducted by hand-drill, and the recovered powder was put into a 10 ml threaded borosilicate bottle closed down by septum after the volume above carbonate was rinsed by He-gas. Carbonate was exposed with water free phosphoric acid (H₃PO₄) at a stable temperature (72 °C). After the 100% carbonate – acid reaction and after isotopic equilibrium was reached (2 hours), the δ¹⁸O and δ¹³C values of the gas exposed from the carbonate were measured by a Finnigan delta plus XP vehicle carrier gas mass spectrometer (Spötl and Wennemann 2003). The institute applied the international standards NBS-18 and NBS-19 and Carrara lab standards. The results were related to the V-PDB (Vienna-PeeDee Belemnite) standard (Coplen 1996) and given in traditional δ¹⁸O and δ¹³C values (expressed in ‰) under the following formula: $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$, where R_{sample} and R_{standard} are the ¹⁸O/¹⁶O and ¹³C/¹²C isotope ratios defined in the sample and the standard (McKinney et al. 1950). The uncertainty of the measurement was better than 0.2‰.

3.4. Thermometry

Due to the maturation of the carbonaceous material (CM), significant irreversible modification can take place, which can be detected in Raman spectra. Numerous thermometry

methods were calibrated for this phenomenon during recent decades (Yui et al. 1996; Beyssac et al. 2002a; Rahl et al. 2005; Lahfid et al. 2010; Zhou et al. 2014). All the calibrated methods calculate the maximum temperature of the CM, considering the position of the graphitic peak and the amplitude, full width at half maximum (FWHM), and area of 3 or 4 defect peaks. From the above mentioned thermometers, Beyssac et al. (2002a), Rahl et al. (2005), and Lahfid et al.'s (2010) methods were used on 18 samples.

The Seasolve PeakFit 4.12 software program was employed to evaluate the Raman spectra. A Gaussian deconvolution approach based on the Voigt-type curve fitting procedure was used to determine the peak position (centre), amplitude, full-width-at-half-maximum (FWHM), full width at base, and integrated area of the bands of interest.

In our case, there is a possibility to determine the formation temperature of the vein filling phases by fluid inclusion thermometry. Fluid inclusion petrography and micro-thermometry were performed on thin sections made from limestone samples. Prior to the analytical procedures, double-polished thick sections (75-150 μm) were prepared from the cores. The preparation of thick sections followed the instructions of Shepherd et al. (1985). The sections were then examined to classify fluid inclusion assemblages following the criteria of Goldstein and Reynolds (1994). Micro-thermometry was carried out using a Linkam THMSG-600 heating-freezing stage mounted on an Olympus BX-41 microscope. The stage was calibrated using synthetic fluid inclusions trapped in quartz. The homogenization temperatures (T_h) have standard errors of ± 1 $^{\circ}\text{C}$. The homogenization temperature was usually determined by the cycling method (Goldstein and Reynolds 1994). The salinities of the aqueous inclusions were calculated from the final ice melting temperatures ($T_m(\text{Ice})$) and reported in m/m% of NaCl equivalent (Bodnar 1993).

4. Results

The results show two different types of carbonates (limestone and dolomitic limestone); there is a thin polymictic breccia horizon in the upper part of each borehole, and there are breccia zones that are involved in the massive carbonate rock body. The detailed results are given for each rock type separated in the following section (fig. 2).

4.1. Carbonates

The top of the Mesozoic basement is marked by a sharp reflection in the seismic images, but due to the above mentioned total mud loss, the Triassic/Eocene unconformity could not be detected precisely in the sampled core material. The boundary was defined by well log parameters (permeability, porosity, and total gamma). All the analysed carbonate rocks are strongly fractured and dissolved.

4.1.1. Limestones

Two macroscopic limestone types can be defined: Type A is a light grey, massive oncoidal limestone, and Type B seems to be a leached variety of Type A with a light brown, whitish colour and hygroscopic behaviour. The Type B limestone is very friable and can be characterized by rather weak consistency. It is known from only 40 cm thickness in a single well.

4.1.1.1. Limestone type A

4.1.1.1.1. *Texture and grain types*

The Type A limestone is a peloidic, oncoidic grainstone (fig. 3/a, b). It consists of peloids and oncoids with foraminifera, alga, echinoderms and ostracod bioclasts in the centre of the coated grains. The peloids and oncoids are well sorted. The oncoids are 1–3 mm, and the peloids are ~50 µm with isometric shape. Coating related laminae with microsparitic interlaminar infilling are well preserved. The rock texture is grain supported, and there are

different types of calcite spar in the intergranular porosity. The samples contain authigenic euhedral quartz crystals, which do not show fabric selective appearance; rather, they are dispersed in the sediment texture (fig. 3/d). They always contain calcite inclusions.

4.1.1.1.2. Cement phases

The inner-skeletal porosity is filled by microsparite, while the intergranular porosity is filled by isopach fibrous calcite cement and equigranular blocky calcite cement (BC) (fig. 3/c). The synsedimentary fenestral porosity is commonly filled by radiaxial fibrous calcite cement (RFC), but micrite occurs as well. RFC and BC do not show luminescence, but the microsparite has a bright orange luminescent colour.

4.1.1.1.3. Microstructure

Based on the fracture intersection and vein morphology, four fracture generations (F1; F2; F3; F4) can be defined. The F1 generation can be characterized by syntaxial, symmetric blocky calcite veins (fig. 4/a). Features indicative of growth competition are observable along both sides of the vein walls. The F1 vein generation seems to have been reactivated and encloses the F3 fracture generation. The F2 veins exhibit symmetric syntaxial vein morphology with elongated (150 μm long) calcite crystals (fig. 4/b). The distance of the opposite vein walls is equivalently $\sim 200 \mu\text{m}$. Textural features of growth competition are not observed; nevertheless, a porosity increase related to dissolution is recognized. Both the primary intergranular and secondary pores are filled by bitumen. Raman spectroscopy measurements confirm presence of organic material through its G (graphitic – 1591 cm^{-1}) and D1 (defect – 1344 cm^{-1}) bands. The F2 filling calcite crystals contain secondary oil fluid inclusions, which have a bright green colour in UV lights. Based on the CL images, the calcite cement growth was a multiphase process. The F3 generation is a narrow ($<20 \mu\text{m}$), dark

coloured anastomosing vein type (fig. 4/c) with significant bitumen content. Microfabrics in this vein type are not detectable by petrographic tools because of the presence of the above mentioned bitumen. Locally, the F3 fractures have much larger apertures and enclose ~40 µm sized authigenic, bladed calcite crystals. The F4 vein generation has a symmetric syntaxial vein morphology with an average diameter of >2 mm and consists of blocky calcite. Well-developed growth competition features are visible on the vein walls (fig. 4/d). The first calcite generation near the wall is bladed, but there are blocky calcite crystals along the inner side. All the calcite crystals are twinned. There is no intergranular porosity inside the veins, which are lined by micritic carbonate with abundant framboidal pyrite crystals.

The vein filling calcite contains many primary and secondary water and oil inclusions. Water-containing fluid inclusions were suitable for micro-thermometry measurement. Based on 16 primary fluid inclusions, the homogenization temperature varies around ~125 °C, which is the entrapment temperature of the paleofluids (fig. 5/a). Based on the melting point of these inclusions, the salinity of the paleo pore fluids is -4.0% NaCl equivalent.

Simultaneously to the complex vein system, a well-developed microstylolite system formed with an anastomosing geometry. The maximum amplitude is ~1 mm, and pressure solution films are easily detected on the CL images through their bright orange luminescent colour.

4.1.1.1.4. Phase analysis (XRD, Scanning, Raman)

The analysed rock types consist of calcite crystals; other carbonate minerals (dolomite, aragonite) were not detected by the applied techniques.

The most common non-carbonate mineral is pyrite. It has a framboidal form and a bimodal size distribution and fabric position. The smaller sized crystals are related to biogenic

constituents, while the bigger ones appear in fractures. The mineral composition of the insoluble residue is summarized in table 2.

The results of the thermometry calculations from the carbonaceous material uniformly suggest $T_{\max} \sim 220$ °C. The data are summarized in table 3.

4.1.1.1.5. Mineral chemistry

The chemical composition measurements on the different cement phases by SEM-EDAX do not indicate high Mg-calcite (>4 mol. %). Additionally, based on this measurement, there is no detectable difference in the composition of the two different sized pyrite populations; both have a negligible amount of trace metals and can be regarded as pure FeS₂.

Based on the stable isotopic measurements, the carbon and oxygenic isotope composition of the host rock is $\delta^{18}\text{O}$: -4.0 and $\delta^{13}\text{C}$: +4 (±0.2‰).

4.1.2. Limestone type B

There is no significant difference between the Type A and Type B limestones regarding their framework composition; the Type B limestone is also a peloidal, oncoidal grainstone with some degree of late diagenetic micritization. There are also no differences in their cement phases.

Based on the results of phase analysis, Type B is similar to Type A. The former is composed of pure calcite crystals; there is no trace of dolomite or aragonite. The amount of the dissolution residue is less than 1 m/m%. A significant difference from Type A appears concerning the mineral composition of the insoluble residue (summarized in table 2); the dickite content of the residual is ~90%, which is much higher than the ~40% in Type A (table 2).

4.1.3. Dolomitic limestone

4.1.3.1. Texture

The rock-forming biogenic and other grains are similar to the non-dolomitic limestones, suggesting a similar grainstone precursor texture. As a result of the fabric selective dolomitization, a planar-E dolomite (Sibley and Gregg 1987) developed (fig. 6/b).

4.1.3.2. Cement phases

The primary cement phases among the rock-forming grains are not recognizable due to the effect of dolomitization, but the abundance of the above mentioned radiaxial calcite cement is much higher than in the case of the non-dolomitic limestone members. In several parts of the samples, large (>300 µm) calcite pseudomorphs can be found in the fabric. According to their textural characteristics (shape of the grains), these calcite pseudomorphs most likely formed after anhydrite crystals (fig. 6/c).

4.2. Breccia

4.2.1. Texture

Breccia zones are defined mainly in the upper few metres of the Triassic carbonates close to the proposed Triassic/Eocene boundary. Subordinately, breccia horizons are detected inside the carbonate bodies in deeper zones. Based on the observations, the breccias at different horizons are rather similar, so their descriptions are summarized together (fig. 7).

The studied breccias have a polymictic nature. Lithologically, the most common clast type is the above characterized limestone. Subordinately, laminated calcrete clasts and those common in the overlying Eocene sequence (i.e., metamorphic rocks, siltstone) occur.

The average grain size of the different clast types is different. The limestone clasts are larger (cm scale), while the others are smaller than a few millimetres in diameter. The roundness for both the carbonate and non-carbonate clasts follows a normal distribution based on the Kolmogorov-Smirnov test, but the frequency of the carbonate grains is smaller than that of the non-carbonate grains (table 4; fig. 8).

The variation coefficient of the main axis of the clasts (0.69) shows a chaotic texture. The dilation between the clasts is very variegated; the grains are connected with each other in many cases, but in some cases, there is more than a centimetre of space between the grains. The matrix content of the breccias is significant (> 60%). Based on all these descriptive and numerical textural parameters, the breccia in question can be characterized as chaotic breccia (Mort and Woodcock 2008). The results of the image analysis are summarized in fig. 8.

3.2.2. Matrix and cement phases

The matrix mostly consists of carbonate rock clasts and quartz, but calcite, anatase, feldspar and muscovite mineral fragments are present as well.

Two different types of cement phases are defined by CL microscopy. There is a fine crystalline phase in the matrix with a bright purple luminescent colour. Around the purple phase, there are numerous individual calcite crystals with dull orange luminescent colour and a very bright orange overgrowth (fig. 9). Based on the CL images, the purple phase seems to be a type of kandite mineral, which seems to be authigenic based on the SEM observations.

Microstructure

Only the F1 and F4 fracture generations are detectable in the breccia zones, whereas F2 and F3, which contain a large amount of bitumen, do not seem to be evolved in this lithology. The F1 generation is only detectable inside the carbonate clasts, while the F4

generation cuts the entire matrix. The F4 fractures exhibit chaotic spatial distribution; they follow the surfaces of the larger clasts. Both microfracture generations (F1, F4) have a notable secondary porosity by dissolution.

Microstylolite systems are not evolved in the breccia zones, but the pressure solution is significant along the clast boundaries resulting in a stylobreccia texture.

3.2.3. Phase analytics

Based on the XRD measurements, the most common minerals in the matrix of the breccias are dickite (40–50%), illite±muscovite (25–35%) and quartz (20%). Subordinately, pyrite, anatase and goethite are detected as accessories.

3.2.4. Mineral Chemistry

Three XRF maps were recorded from different regions of the matrix for the following elements: Si, Al, Fe, Mn, P, S, Ni, Co, Ba, Sr, Ce, and Pb. Based on the element maps, none of these elements shows fabric selective distribution. The isotopic composition of a calcrete pebble is $\delta^{18}\text{O}$: ~ -6.5 and $\delta^{13}\text{C}$: ~ -6.0 , while that for the limestone is $\delta^{18}\text{O}$: ~ -3.5 and $\delta^{13}\text{C}$: ~ 2.0 ($\pm 0.2\text{‰}$) (fig. 10).

5. Discussion – Petrological characteristics of the main rock types

5.1. Limestone

Based on the core analysis, there are three different carbonate rock types in the reservoir. Among them, the most widespread is Type A limestone, which is an oncoidal, peloidal grainstone. Due to the low amount of core samples, the exact classification of the rock types into lithostratigraphic units is very ambiguous. Based on the petrotectonic position of the investigated formations, the study area should belong to the Mid-Hungarian Mega Unit,

but previous reports (Benedek 2009) and data from the neighbouring fields suggest that it is more likely a part of the Triassic Kíssfennsík Limestone Formation in the Bükk Unit. As our results do not give any clear evidence to the contrary, the carbonate rocks in the studied reservoir are hereafter supposed to be of Bükk type.

Tidal flat, lagoonal and reefal environments can be reconstructed for the Kíssfennsík Limestone in the Bükk Mts. (Velledits et al. 1999). The beds in the Gomba Field represent a high kinetic energy part of the tidal flat, which is supported by the presence of oncoids, fossils representing the photic zone (e.g., algae), and the fenestral porosity of the samples. The stable isotopic data show a typical Triassic platform composition (Schimpf 2011; Verheyden et al. 2014). The measured stable isotopic values fit with the green algae zone (Milliam 1974), possibly due to the high algae content of the rock (fig. 11).

The mineralogical composition of the limestone samples is rather homogeneous; the studied core sections are composed of pure calcite. The proportion of non-carbonate phases is usually below 1%. Quartz, pyrite, mixed layer phases (illite±muscovite), dickite, anatase and goethite appear as accessory minerals.

The disperse distribution of euhedral quartz crystals in limestone is usually not an uncommon phenomenon; quartz often appears in such a textural position in hypersaline environments. Quartz with the observed morphological and mineralogical characteristics can crystallize during pedogenesis or very shallow diagenesis (Nash et al. 2003; Varga and Raucsik 2014). Based on the geological evolution of the study area (assuming an identical history to the Kíssfennsík Limestone), pedogenesis could have happened during the Palaeocene. Quartz with calcite inclusions are considered to be the result of pedogenetic silica migration.

The bimodal size distribution of the framboidal pyrites suggests two generations, but this observation is not definitively confirmed by their similar chemical compositions. The

smaller pyrites (<15 µm) usually occur near the bioclasts or the early cement phases; therefore, its formation is considered to be early diagenetic. A possible process that produced the pyrite may be sulphate reduction. In this case, the sulphur content of the organic matter is reduced by bacteria, which leads to framboidal pyrite formation near the organic matter. The larger pyrites (>50 µm) are detectable solely near the fracture system in both the Triassic carbonates and Eocene breccia. Based on experimental results (Hallbach et al. 1993) and field observations (Sweeny and Kaplan 1973), framboidal pyrites can evolve up to ~200 °C, while the minimal temperature under laboratory conditions without involving sulphate reducing bacteria (SRB) is in the range of 65–80 °C. This temperature may even be 40–60 °C less than that needed under natural circumstances (Maclean et al. 2008). In our case, there is no direct evidence for SRB contribution toward the generation of the larger pyrite. However, based on the CM Raman measurements, our samples reached a higher temperature than the maximum possible formation temperature for framboidal pyrites, which is not a contradiction because the pyrites are at a younger texture position than the carbonaceous material in the fracture network. In this case, the reduced material should not be the synsedimentary organic matter of the limestones; rather, it is the bitumen seal of the veins. Because organic matter in this position is likely a result of hydrocarbon migration, it is suggested that the carbonaceous material records the reached maximum temperature during the burial, and the large pyrite crystals grew during uplift following oil migration to the reservoir.

There are several subsequent cement phases in the analysed samples. The fibrous, radial, and clear calcite cement, which covers the ooids and oncoids, is considered to be the first phase (fig. 3/b). It has low Mg-content (< 4 mol%), which may suggest a meteoric origin (Hayes and Boles 1993). Based on its textural position, this phreatic cement possibly formed during early diagenesis close to the surface.

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517 Radiaxial fibrous cement (RFC), which can form in different environments, is clearly
518 in a younger textural position. New research (Richter et al. 2011) says that it could develop
519 not only in marine phreatic zones but also in a continental vadose zone, and the resulting
520 cement may form by both diverse biogenic and abiogenic processes. Although the most
521 common environment of this cement type is the intratidal and upper bathial zone up to 600 m
522 depth (Richter et al. 2011), this cement also has been documented to form in numerous caves
523 (Neuser and Richter 2007; Richter et al. 2011). The position of the RFCs in the samples is not
524 fabric selective. Based on its low Mg/Ca ratio, this calcite also precipitated from meteoric
525 fluids, which is in good agreement with the results of Wilson and Dickson (1996), who said
526 that RFC forms from meteoric porous fluids instead of seawater in subtropical or tropical
527 platforms. Based on its texture, mineral chemistry and worldwide analogies, the RFC in our
528 samples is believed to have an early diagenetic origin.

529 The blocky calcite cement is a typical deep burial cement type in our samples. The
530 Mg/Ca ratio is low, but calcite crystals enclose numerous tiny dolomite inclusions, which are
531 typically only a few micrometres across. The presence of dickite in the limestone shows a
532 burial formation temperature as high as >200 °C (Zotov et al. 1998). This value is consistent
533 with the calculated maximum temperature based on the typical Raman spectra of the
534 carbonaceous material ($\sim 220 \pm 50$ °C).

535 The tectonic evolution of the region had to be rather complex as suggested by the
536 subsequent brittle deformation events recorded by fractures and intensive brecciation. The
537 real age of the vein filling by calcite is unknown, but the microstructural results show that the
538 F1, F2 and F3 fracture generations are older than the main brecciation event, while the last
539 generation (F4) must be younger. Furthermore, we know that the vein filling in F3 has
540 bitumen with high $T_{\max}$, while the F4 generation calcite contains fluid phase hydrocarbon
541 inclusions. All the data indicate that the above mentioned uplifting event happened after the

cementation of the F3 fractures but prior to or during the F4 filling by calcite, when the formation temperature was lower than in the case of F3 (fig. 12). This model is supported by the micro-thermometry of the F4 generation fluid inclusions (based on 16 samples) (fig. 5/a). The primary fluid inclusions show a ~125 °C homogenization temperature, which is similar to the temperature of the recent fluid. The data suggest that the F4 fracture generation formed due to relaxation during the uplift phase. This fracture generation has to be part of the presently active reservoir as supported by the similarity of the spectra of the oil inclusions and the produced crude oil (fig. 5/b).

5.2. Dolomitic limestone

Hereafter, limestones with dolomite content of >40% are defined as dolomitic limestone. The original packstone texture of the rock type is recognizable in all the studied samples despite the destructive dolomitization. This texture clearly suggests deposition in a low energy sedimentation environment, most likely along the inner side of a carbonate platform. This scenario is also proven by the presence of calcite pseudomorphs, implying an intensive evaporation process. There is no known analogy for this carbonate type from the Bükk Unit, so neither the horizontal nor the vertical extension of the body could be estimated. Dolomitic limestone samples represent the deepest section of the Gomba-1 well, and there is no information about the continuation of the body downwards, which nevertheless may be a more significant part of the reservoir than was previously believed.

5.3. Breccia

Breccias occur in two different stratigraphic positions in the reservoir. The thicker horizon is located at the Triassic-Eocene boundary, while the thinner zones appear deeper, inside the carbonate body surrounded by homogeneous, hardly deformed limestone.

Breccias can be formed by both tectonic and non-tectonic processes. Tectonic breccias are subdivided into three genetic categories: attrition breccia, disturbed crush breccia and implosion breccia, as described by Sibson (1986). The first two types require a compression stress field and results in a fault breccia or cataclasite texture. In our samples, there is no evidence for shearing and there are no microstructures (e.g., fluid inclusion planes, microveins) that should suggest a compression stress field. Contrary to the previous ones, the implosion or hydraulic breccia does not require a compression stress field; rather, it only needs an intensive burial and high fluid content.

One of the most common breccia types of non-tectonic origin forms due to the collapse of a rock body due to processes that increase the pore volume, e.g., karstification. Usually, rockfalls, cave sediments and collapse breccias could form during the karstification and burial of a karst region (White and White 1969). A geometric characterization of the texture of this breccia-like sediment was done by Loucks (1999). Currently, this criterion system is applied for the description of fault breccias (Mort and Woodcock 2008). Thus, the basis for discrimination between breccia types is a set of different geometrical parameters, but the lithological composition could be a very important parameter as well.

The investigated breccia types are rather heterogeneous and both concern the composition and structure. The most common and largest clasts consist of the above described carbonates, but there are also metamorphic and siltstone fragments. Based on the results of isotopic measurements on the calcrete-like fragments, the mother fluid of this form was of meteoric origin. Consequently, we can conclude that these fragments are not stromatolite fragments, but these clasts may represent pieces of calcite veins or any fresh water form, e.g., a speleothem (fig. 10). There is no datum in the literature about a vein type similar to these fragments from the wider region. Hence, the laminated carbonate clasts are considered to be speleothems (e.g., dripstone fragments). Although the overlying Kosd Formation contains

calcrete pebbles, these could not survive even short transportation and so must have been destroyed.

The subordinate mineral grains in the matrix (quartz, anatase, feldspar and dickite) of the breccia are not typical in the above described limestones. The mass proportion of the dissolution residue of the breccia is ~10 m/m%, ten times what is typical for the carbonate samples. The most probable reason for the relative increase in insoluble contents is the decreasing carbonate content from dissolution. Nevertheless, in the case of dissolution, the clasts should show a very complicated shape (Jébrak 1997), which has not been observed in the present case. That is why the occurrence of these mineral grains should be the result of postgenetic brecciation rather than syngenetic, intrabasinal transportation.

The starting member of the Kosd Formation in the Bükk Unit consists of 2–25 cm sized gravels, which mainly represent the Kisfennsík Limestone. Moreover, this member contains laminated fresh water limestone fragments in a subordinate amount. Thus, the breccia studied in the Gomba wells is identical to the Kosd Formation, even if the roundness of the clasts from the Kosd Formation usually increases to the SW (towards the Gomba field) (Less 2005), which is not typical here at all. The roundness of the carbonate clasts is smaller on average (0.63) than that for non-carbonate clasts (0.73) (fig. 8/b), which suggests that the more resistant non-carbonate clasts represent a long distance area, while the carbonate clasts were derived from a much closer source and most likely did not move at all. This latter model is coherent with the presence of well-preserved speleothems in the breccia because speleothems cannot withstand transportation. In addition, the unimodal, normal distribution of the roundness data of the carbonate clasts suggests that there was only a single process responsible for their shape.

Breccias with a similar fabric can form by different tectonic and non-tectonic processes. Using the classification scheme of Jébrak (1997), the breccias in the Gomba field

could be interpreted as hydraulic breccias based on their measured geometric parameters (fig. 8/c). Similar rocks are known from the wider surroundings at the Triassic-Eocene boundary (Magyari 1994), confirming that the genetics of the breccia in this study are similar to those spread around the karstic area in the Buda Mts. This locality is as close as 50 km to the west of the Gomba field. Here, based on the model of Magyari (1994), marls with high fluid content were deposited and infiltrated into the surface of the fractured and karstified Triassic limestone in the early Eocene. During the ongoing burial, the elevated fluid pressure allowed the brecciation of the underlying carbonate body. These breccia layers have very similar textural features to those described in the Gomba wells; both are matrix supported, there are no shear indicators in the matrix or along the rock fragments and the roundness of the grains varies. An analogous model can be applied for the study area. Here, fluvial sediments (Kosd Formation) with high fluid content were deposited onto the karstified surface and subsided into higher depths afterwards. Because of the impermeable cover (marly and clayey sequences) the fluids infiltrated into the karstic holes and were unable to escape through microfractures, so the fluids had to cause overpressure and brecciation through hydrofracturing during the Eocene (fig. 12).

In addition to the clast geometric parameters (fig. 8), the textural position of the pyrite coating on the rock fragments is in line with this theory. The youngest fingerprints of the evolution preserved in the samples are the above mentioned larger pyrites along the F4 vein generation. The maximum formation temperature of the framboidal pyrites is approximately 200 °C. As the temperature of the maximal burial in the study area was $\sim 220 \pm 50$ °C (based on the Raman measurements), this pyrite generation had to crystallize during uplift. Geochemical methods had previously confirmed that hydrocarbons are still migrating from the Triassic layers to the Eocene conglomerates, which also have high pyrite content (Benedek 2009). The pyrite in the conglomerate (Kosd Formation) has an identical textural position to that of the

Triassic carbonate breccia that coats the clasts. The SEM-EDAX measurements confirm that there are no trace elements in the pyrites either in the breccia or in the conglomerate, so precipitation from a high temperature hydrothermal fluid is not probable. The similarities between these pyrites suggest that the pyrite formed due to the same process. In our hypotheses, the framboidal pyrite zone formed at the front of the migrating hydrocarbons. In the deep zones, where the temperature was above 100–160 °C, hydrocarbons could produce sulphur-rich fluids by thermal sulphur reduction. When these fluids reached the recent temperature zone, framboidal pyrites formed near the migration pathways. Hydrogen sulphide that developed by sulphate reduction could have increased the pore volume as it is observable in the cores (fig. 3/a).

Hydrofracturing is a theory can give an adequate interpretation for the genetics and evolution of the breccias at the Triassic-Eocene boundary but cannot explain the polymict breccia in the deeper parts of the carbonate body. Following the nomenclature of Loucks (1999), these rocks can be classified as “matrix supported chaotic breccias”. Based on recent analogies, the formation of this breccia type is possible either by cave wall collapse or fluvial transportation (White and White 1969). The latter method inevitably requires a matured karst. Based on the analogies from the Trans-Danubian Mega Unit and the Bükk Unit, there was intensive epigenic karstification during the Palaeocene and early Eocene, which resulted in a dissected surface. Based on these analogies, it is presumable that the buried Gomba reservoir was karstified, at least during the Palaeocene and early Eocene, because it was in an uplifted position (inferred by the presence of the quartz in the textural position mentioned above) and there was significant precipitation during these ages. Because of the small amount of breccia samples from the deeper section, it is impossible to recognize their genetics, but this rock must have been formed by karst processes. Based on its stratigraphic position and

petrographic and microstructural features, the breccias in the deeper section possibly represent collapse breccia and, in part, cave sediments.

6. Conclusions

The analysed cores suggest a complex evolution of the storage rock body. The effect of karstification was very important from several different aspects. It contributed to the formation of the several metre thick, high permeability zone at the Triassic-Eocene Boundary, which is a hydrobreccia surface. This breccia horizon likely could have formed during the burial. The thin polymictic breccia horizons in the deeper zones can be interpreted as paleo-cave faces, e.g., collapse and/or cave sediments. Nevertheless, the number of karstification phases and their ages are unknown. From the reservoir's perspective, another essential process occurred during the late uplift phase. During uplift, the rock body relaxed and the F4 fracture generation formed, which is, besides the breccia horizons, the main pathway of the fluid migration at present.

Currently, the reservoir is in a relative uplifted position, but ~120 °C water migrated with significant flux from the deeper zone to the Eocene layers along the karstable carbonates and the F4 fracture system. Thus, it is probable that the reservoir is an active hypogene karst system even at present.

Disclosure of potential conflicts of interest

The authors declare that they have no conflict of interest.

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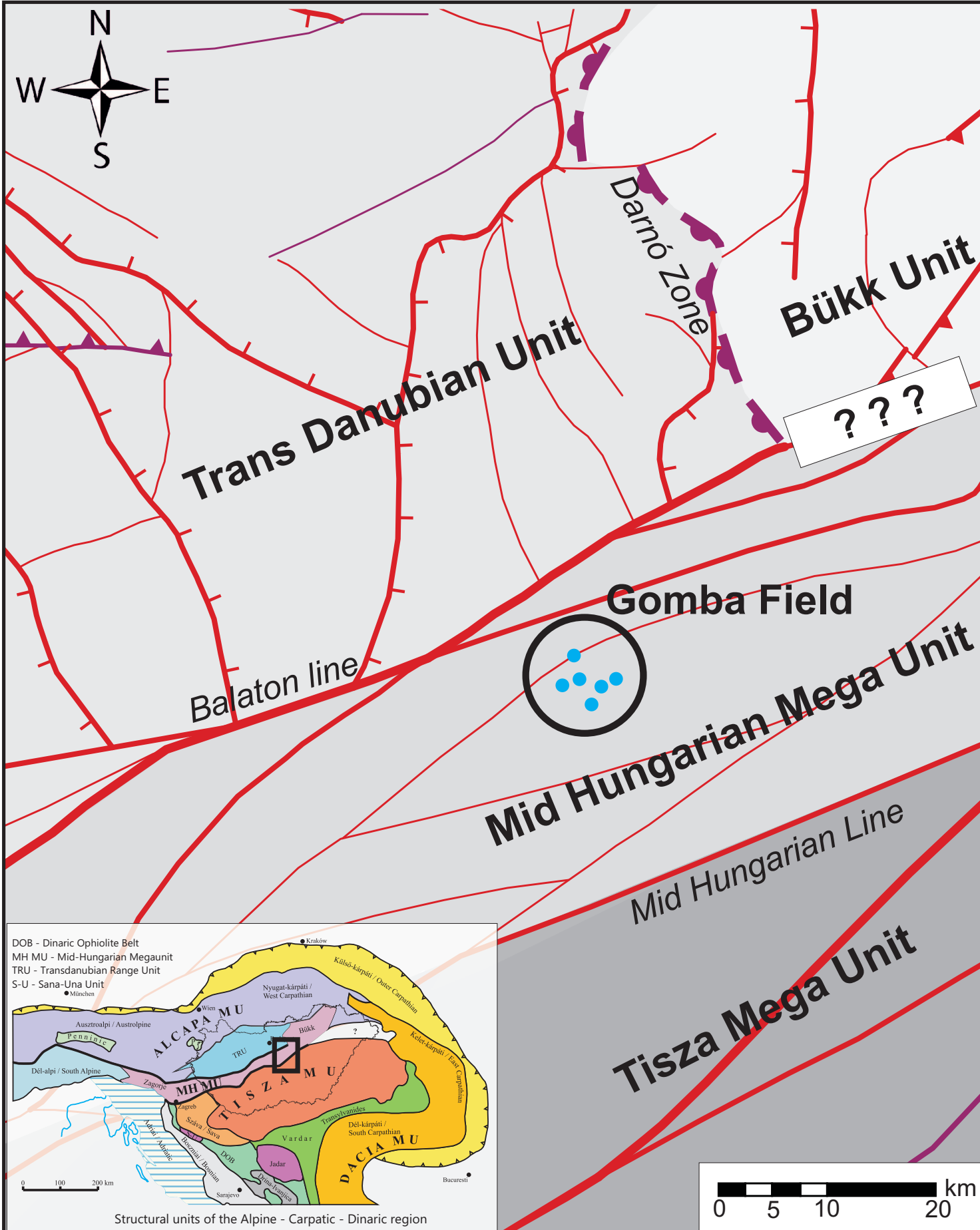
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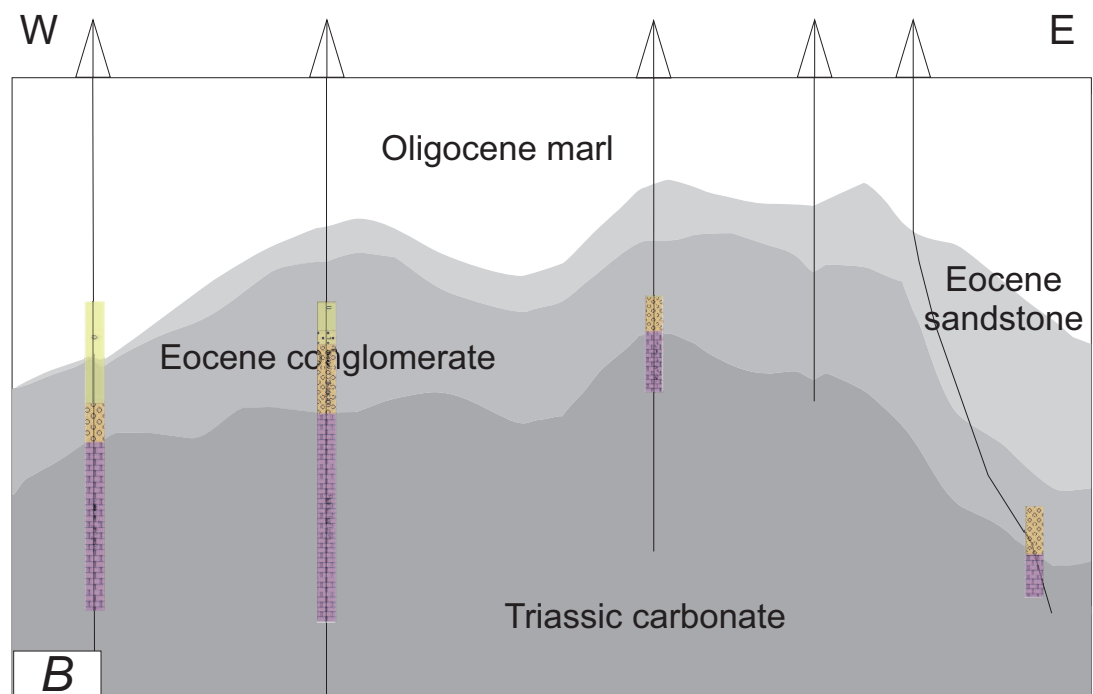
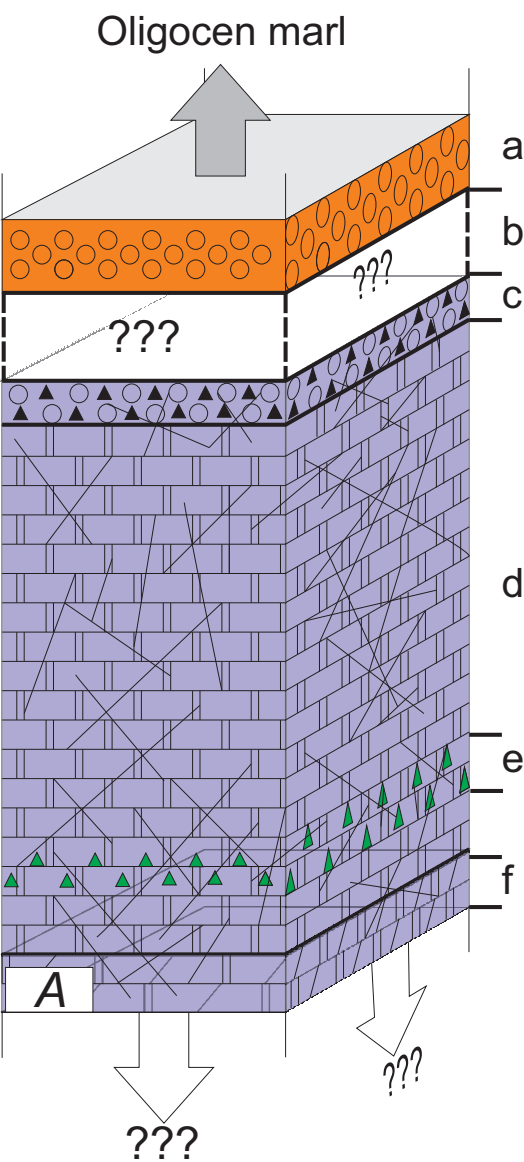
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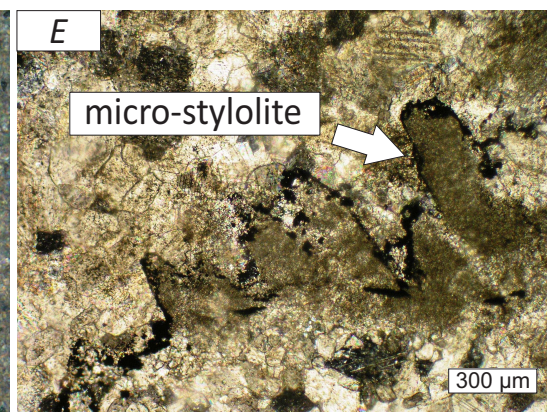
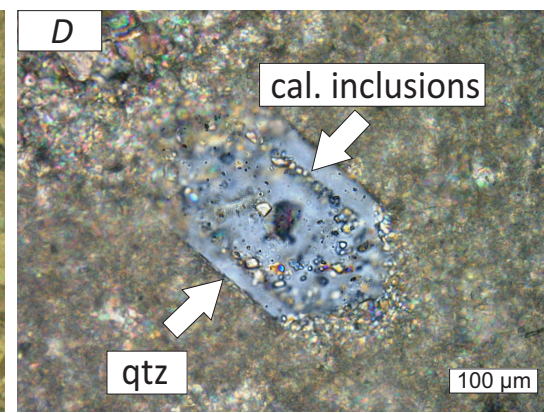
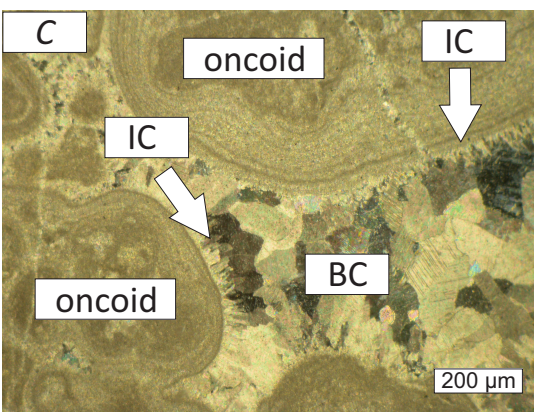
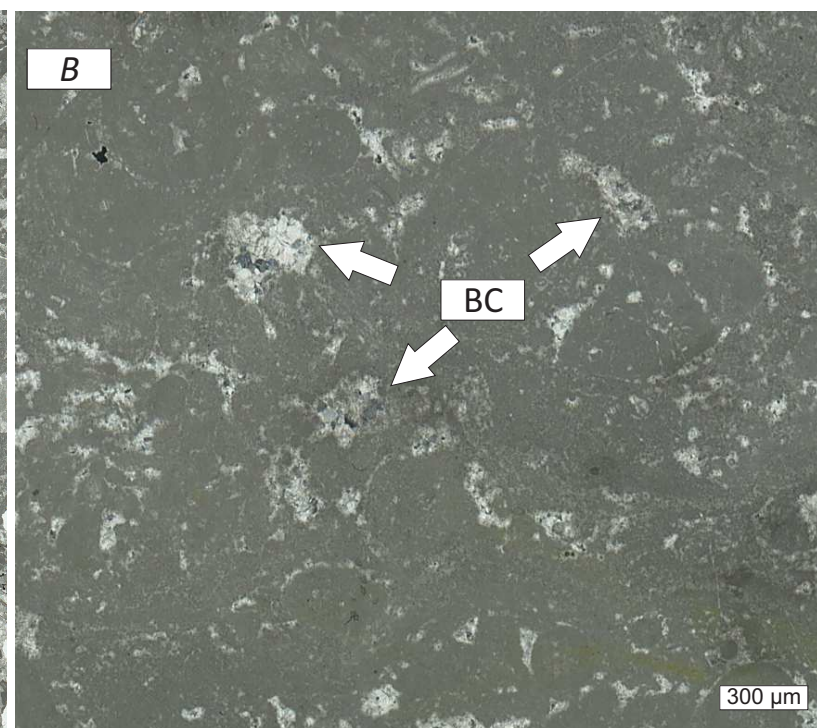
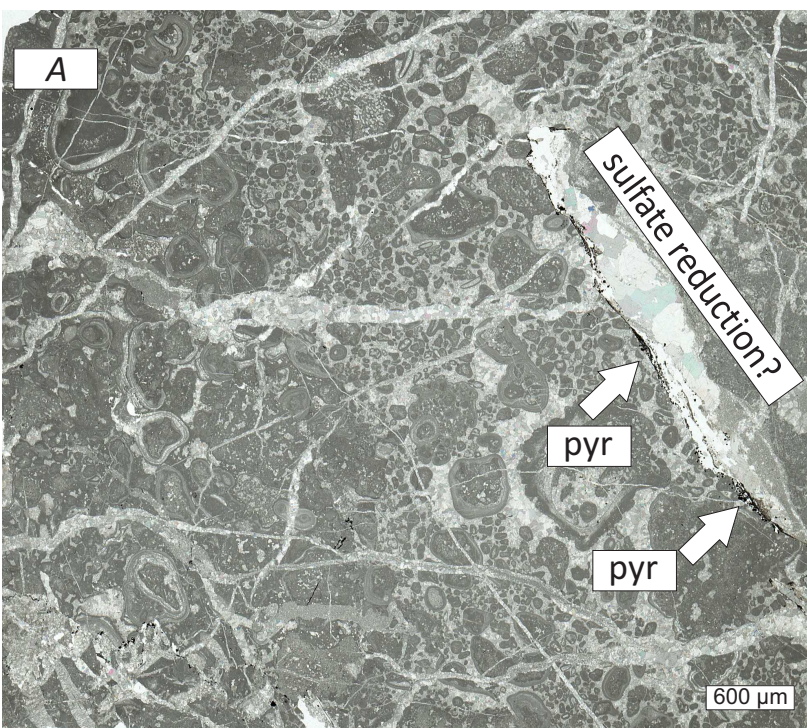


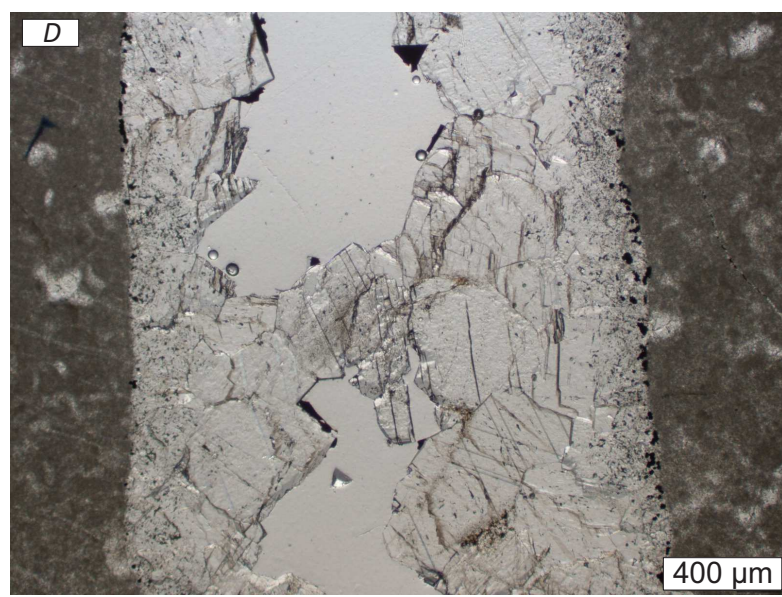
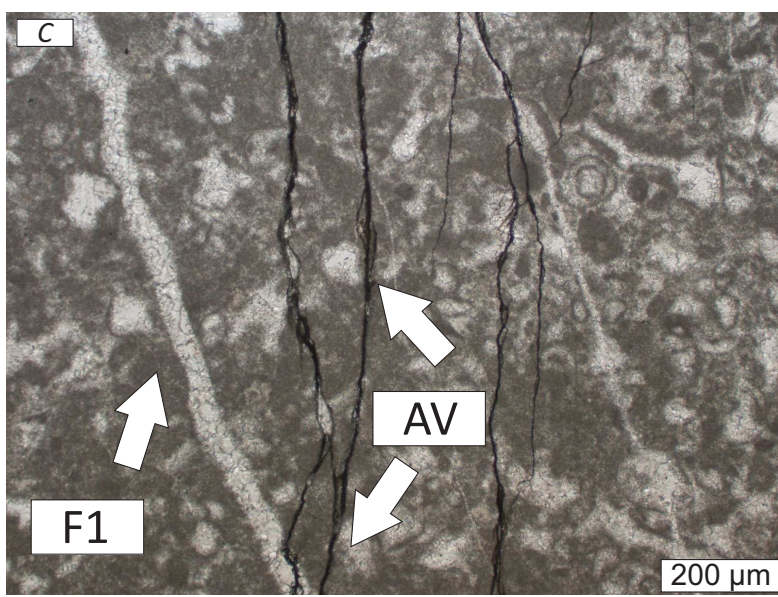
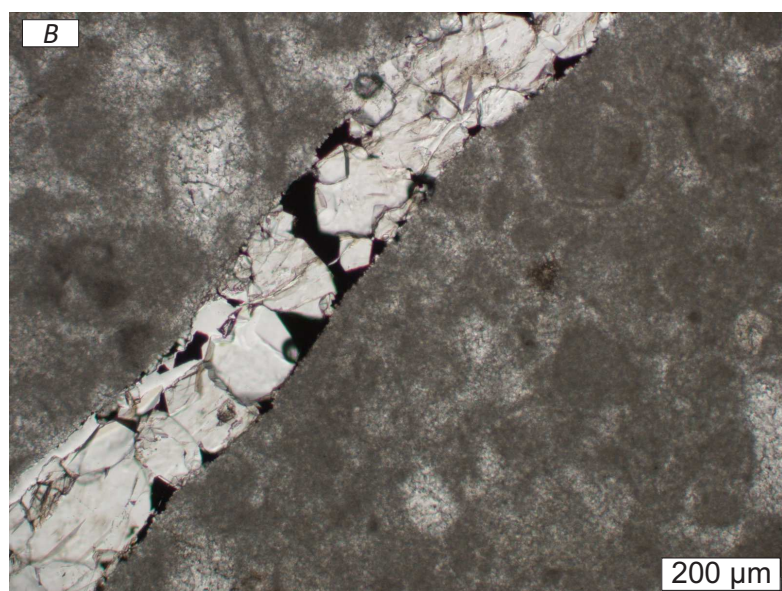
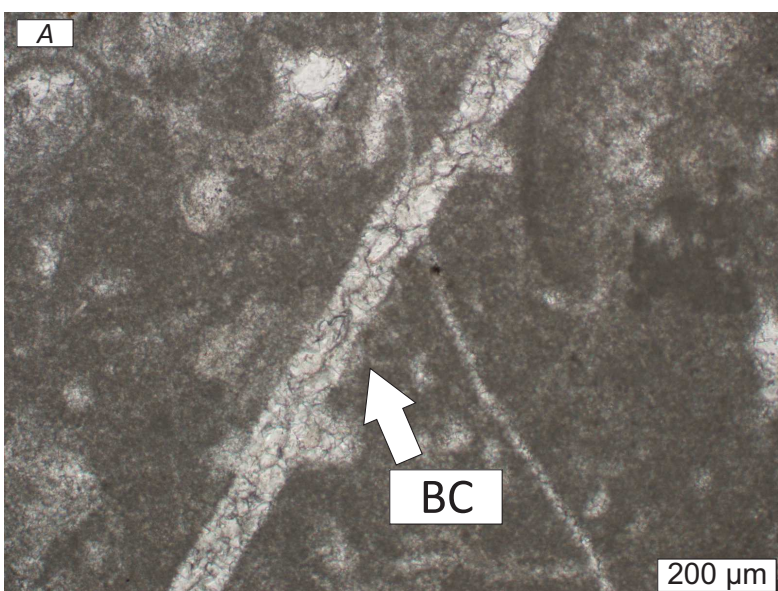
TECTONICS

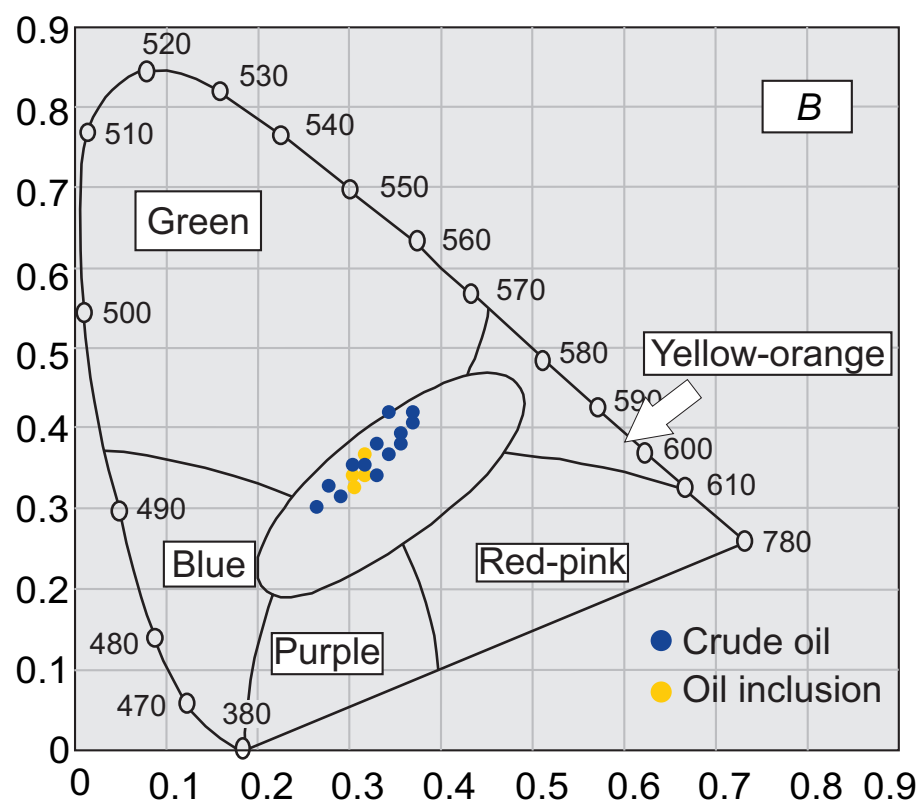
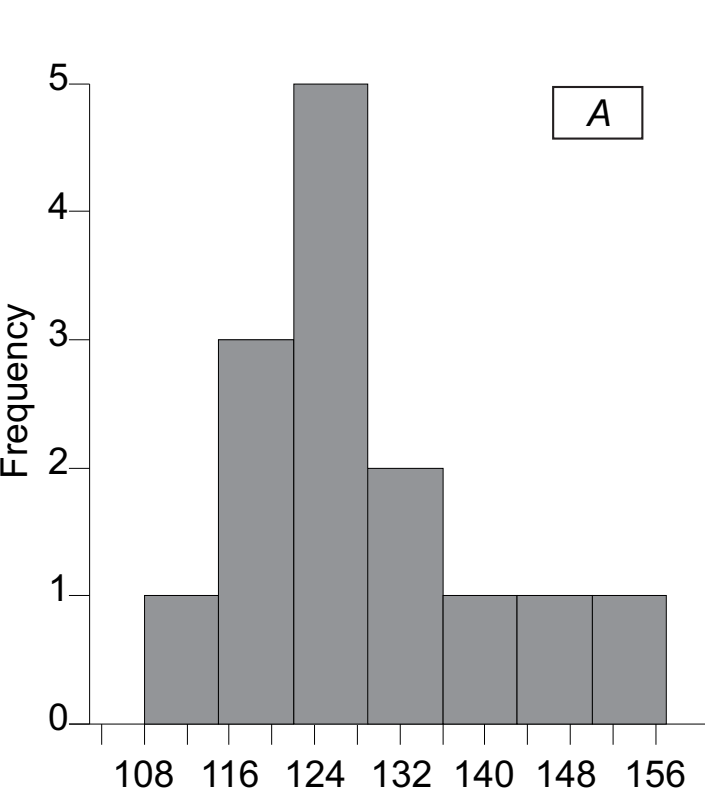
- First-order Cenozoic tectonic line
- Second-order Cenozoic tectonic line
- Second-order Cenozoic fault
- Second-order Cenozoic overthrust
- Third-order Cenozoic tectonic line
- First-order Mesozoic nappe
- Second-order Mesozoic tectonic line
- Second-order Mesozoic overthrust
- Third-order Mesozoic tectonic line

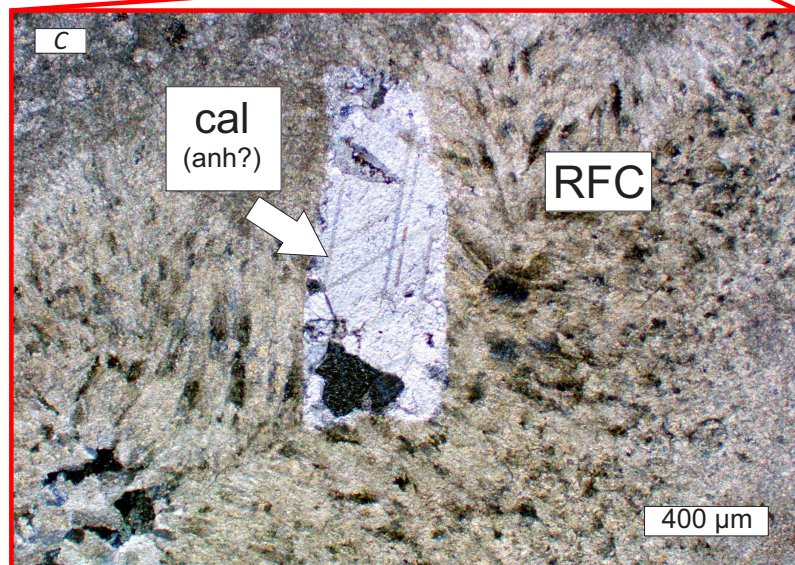
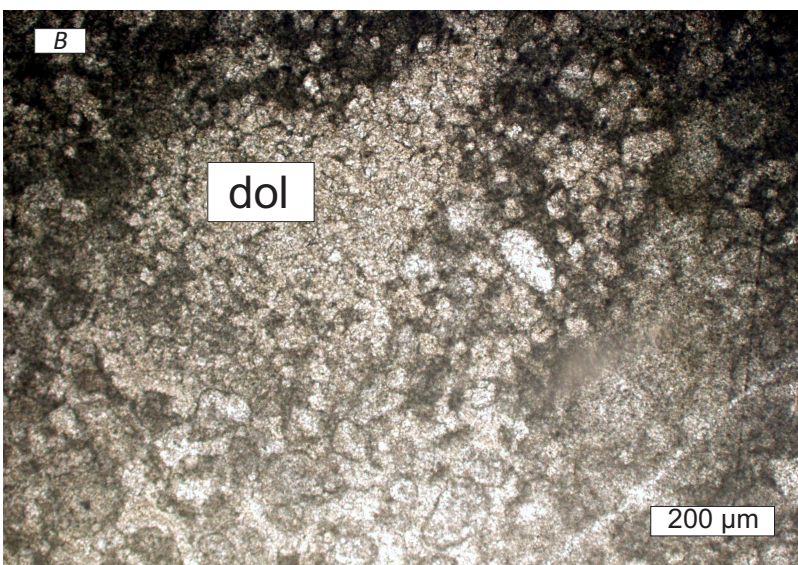


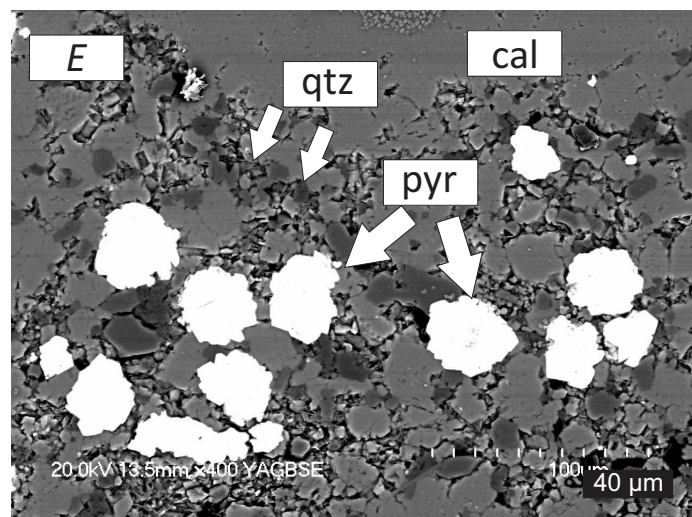
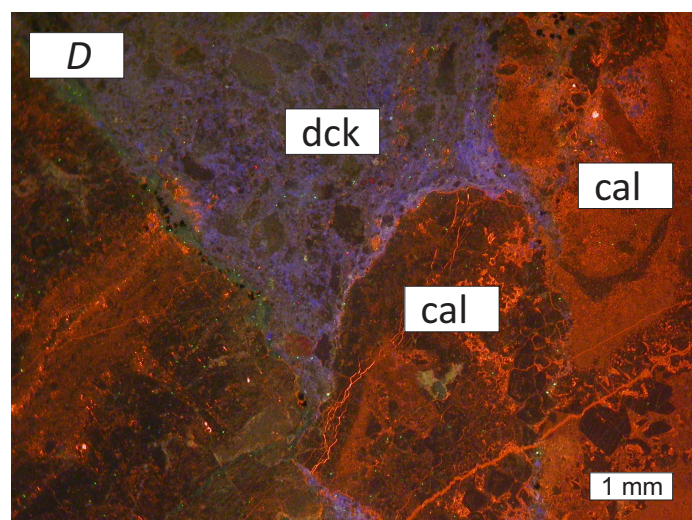
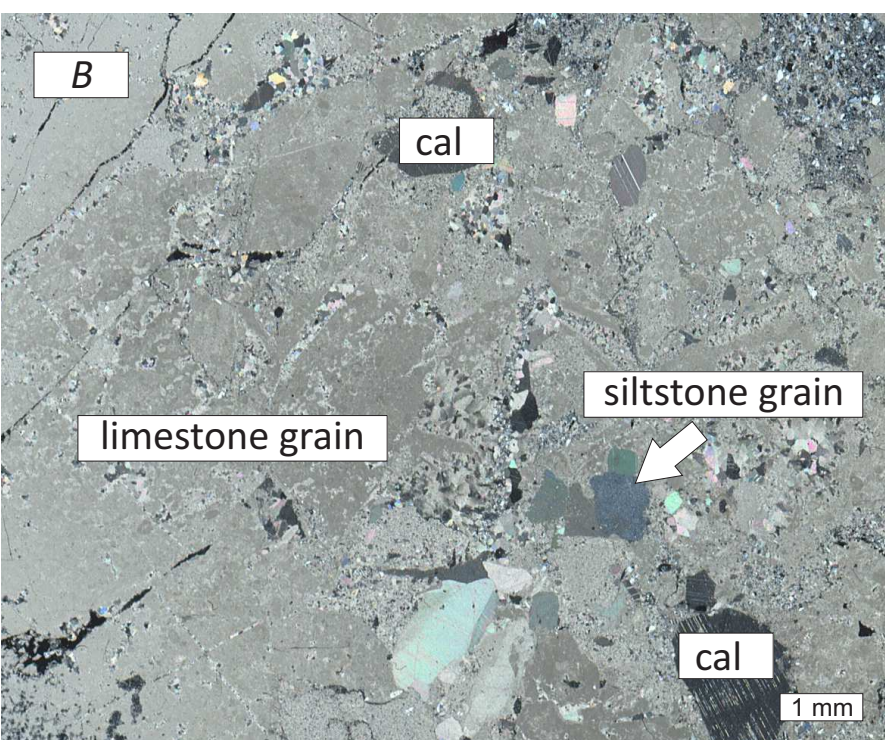
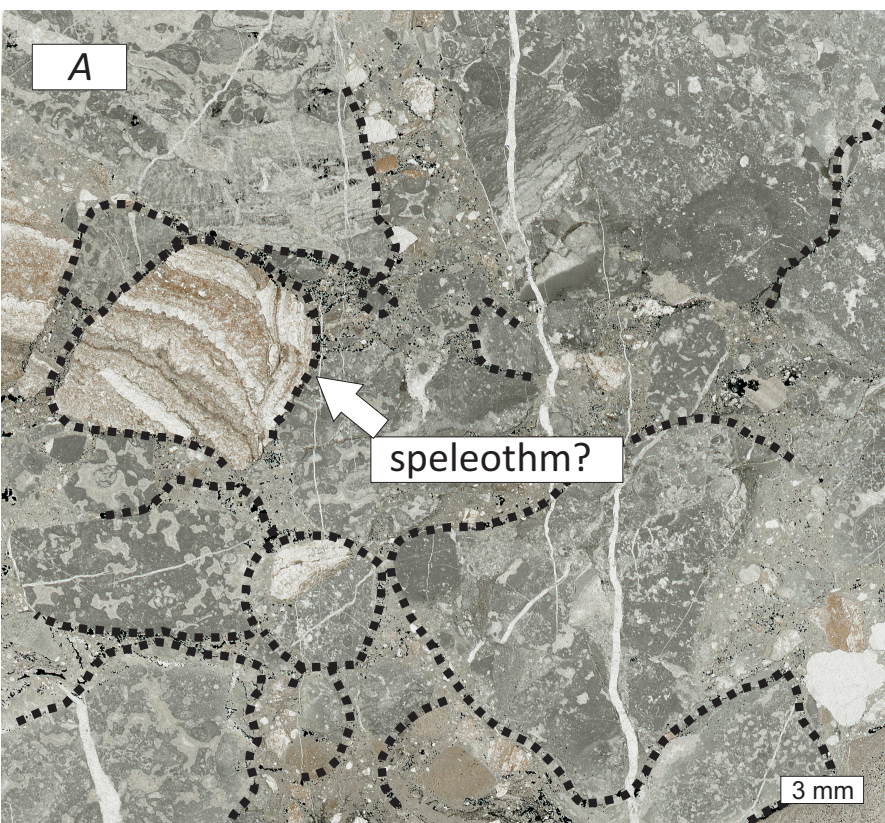
- a: Eocene conglomerate (Kosd Formation)
- b: Unknown high permeability zone
- c: Triassic polymict breccia
- d: Triassic platform limestone (Kissfennsík Limestone)
- e: Polymict breccia (not individual strata)
- f: Triassic platform dolimitic limestone

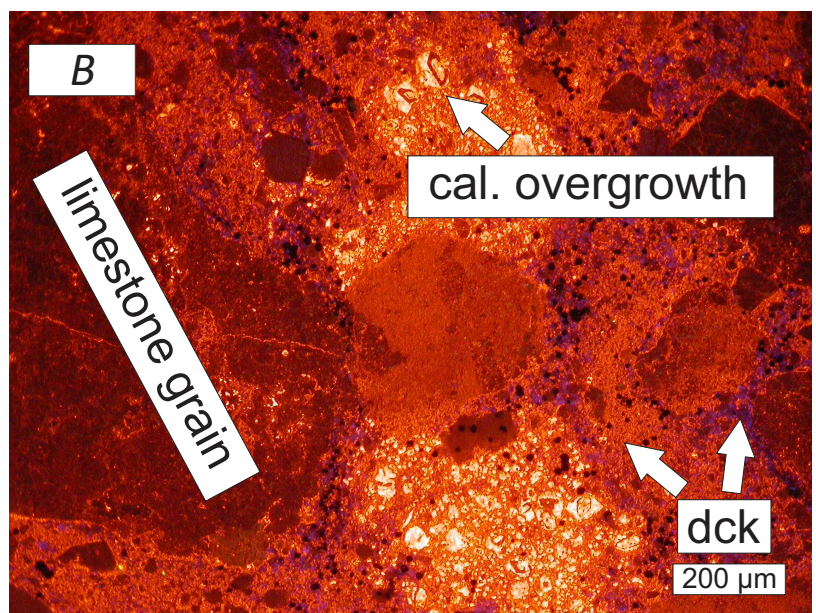
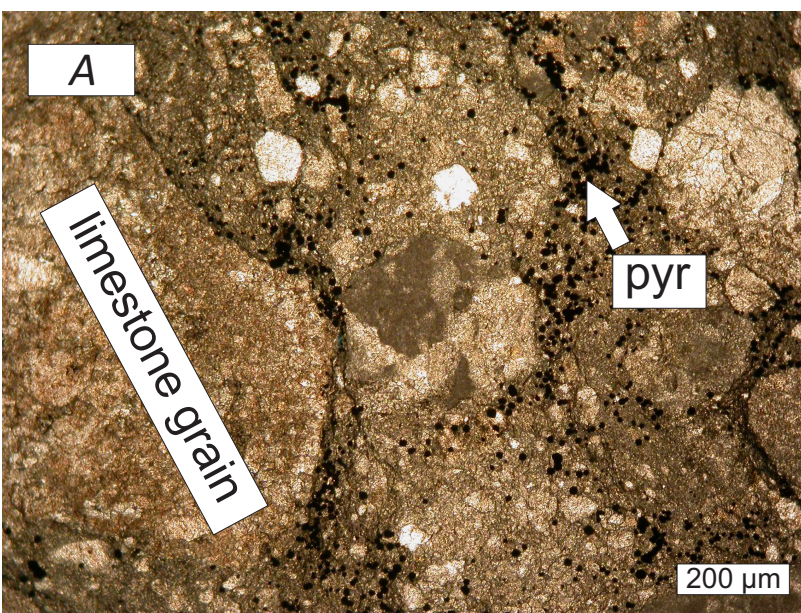


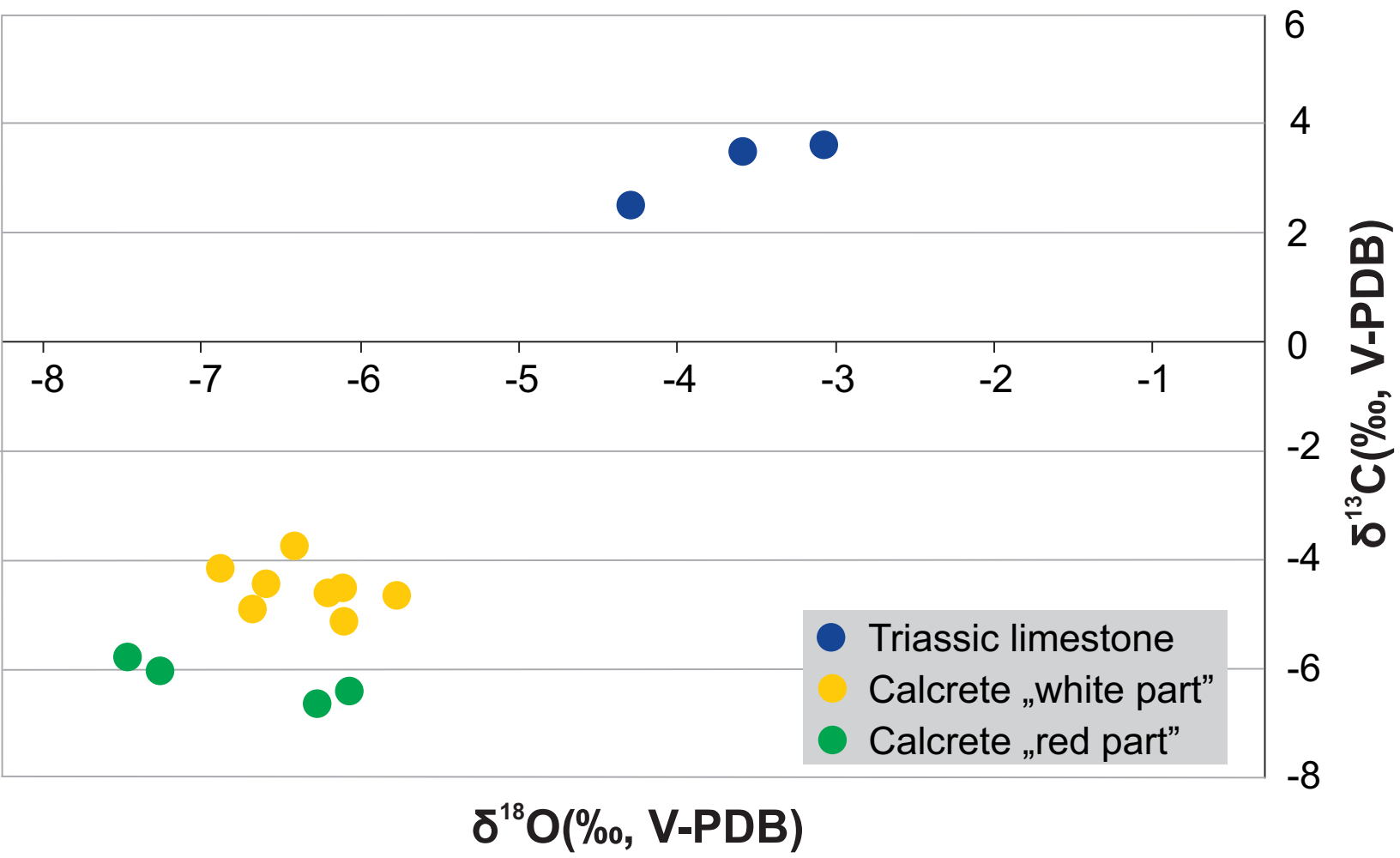


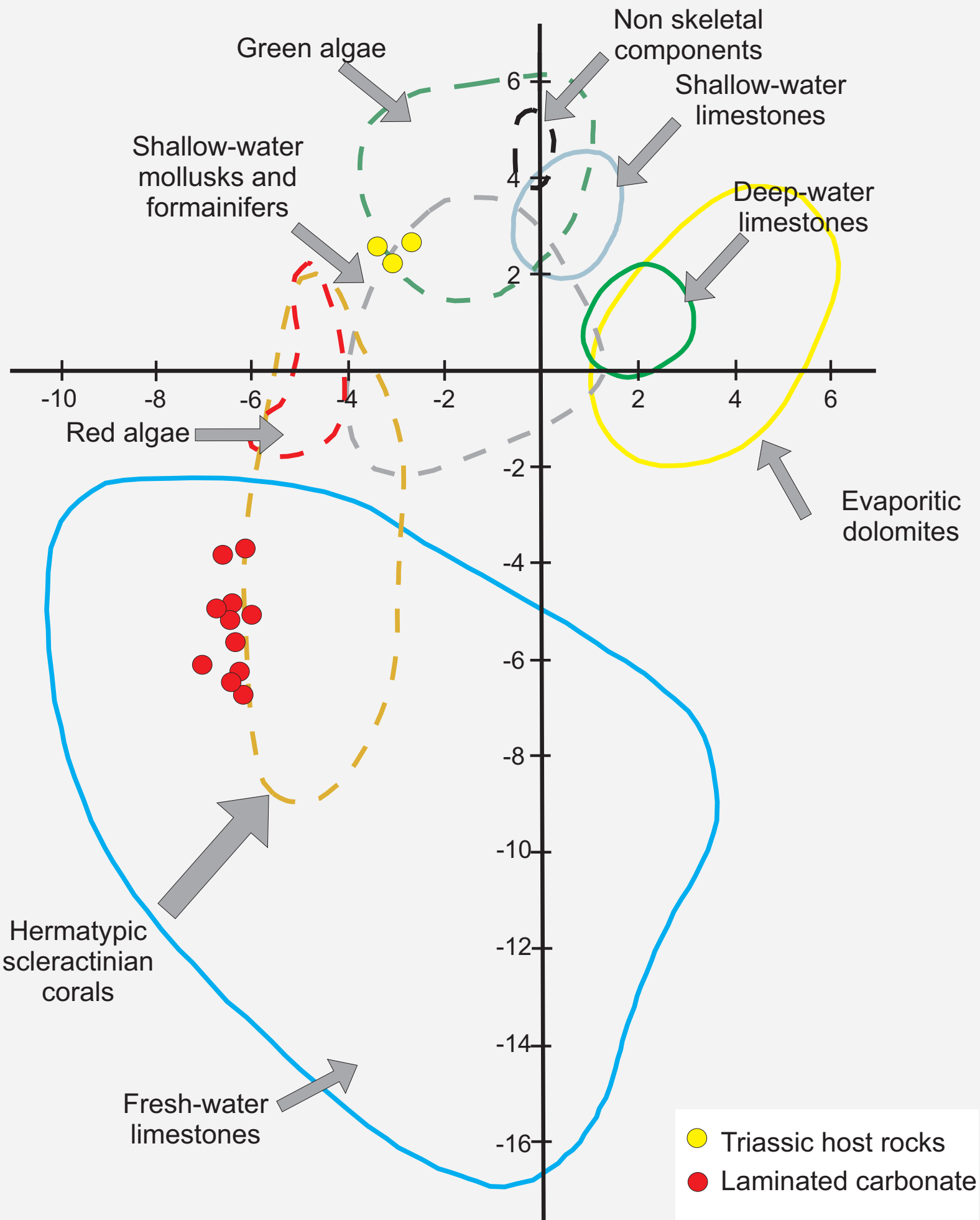












Depth

Triassic-Paleocene

Paleocene

Eocene

Oligocene-Miocene-Pliocene-Pleistocene-Holocene

Present

Epigenetic karst denudation

Deposition of Kosd Formation

Hydrocarbon generation and migration

Forming of F1, F2 and F3 vein generation ?

Hydrofracturing and brecciation

Forming F4 vein generation ~130°C

Diagenesis of the Kiszfennsík limestone

early oil migration?

Max. depth of burial
Tmax~220 °C

Bitumenization

Hypogene karst?
Sulfate reduction?

TIME

	Gomba_1 well	Gomba_3 well	Gomba_6 well	Analysis
Macroscopy core analysing	12	26	4	Number of analysed cores
Thin section analysing	9	17	4	Number of analysed thin sections
Image digitizing	3	17	4	Number of digitized thn sections
Cathode luminescence microscopy	-	3	-	Number of analysed thin sections
UV microscopy	-	18	-	Number of analysed thin sections
Scanning electron microscopy	-	2	-	Number of analysed thin sections
Raman spectroscopy		18	-	Number of measured carbonaceous materials
Micro thermometry	-	18	-	Number of measured fluid inclusions
X-ray powder diffraction	-	5	8	Number of measured samples
X-ray fluorescence		3	-	Number of mapped samples
Stabile Isotope measurements	-	14	-	number of sampling points

	A type limestone ¹	B type limestone ¹	Dolomitic limestone ²	Breccia ¹
Dolomite	-	-	37%	-
Quartz	-	-	-	???
Illite+Muscovite	~20%	~60-70%	-	~50-60%
Pyrite	~30%	-	-	???
Dickite	~30%	~30%	-	~5-10%
Anatase	~10%	-	-	~5-10%
Gypsum	-	-	-	~5-10%
1: Valid for the insoluble residue				
2: Valid for the Bulk				

	Rahl et al., 2005	Lahfid et al., 2010	Beyssac et al., 2002a	Qin et al., 2014
F2_1	221°C	234°C	337°C	599°C
F2_2	227°C	238°C	365°C	589°C
F2_3	231°C	224°C	382°C	526°C
F2_4	215°C	261°C	337°C	540°C
F2_5	229°C	224°C	335°C	554°C
F2_6	232°C	236°C	341°C	540°C
F2_7	192°C	232°C	342°C	576°C
F2_8	247°C	233°C	340°C	522°C
F2_9	234°C	230°C	361°C	583°C
F2_10	194°C	233°C	342°C	554°C
F2_11	241°C	210°C	360°C	538°C
F2_12	223°C	248°C	348°C	548°C
F2_13	202°C	246°C	333°C	548°C
F2_14	241°C	225°C	348°C	579°C
F2_15	265°C	238°C	365°C	535°C
F2_16	201°C	231°C	333°C	564°C
F2_17	247°C	231°C	360°C	538°C
F2_18	243°C	224°C	349°C	580°C
mean	226°C	233°C	348°C	556°C
std	20.00	11.09	13.78	23.04

	Min	Max	Average	STD
Area (mm ²)	0.04	92	5.96	14.16
Rotation	1.5	175	92	43
Roundness	0.21	0.97	0.63	0.17
Roughness	1.04	1.14	1,08	0.02
PSD= - 1.0072 <i>x</i> + 9.3316 (<i>R</i> ² = 0.9437)				