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Alternative interpretation of the Bystrica Unit in Klanečnica KLK-1 borehole (Magura Nappe)

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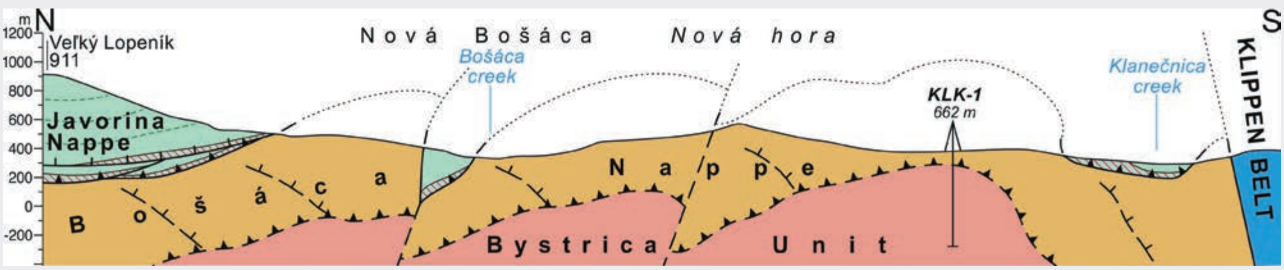
Abstract: In 1986, the KLK-1 (Klanečnica) borehole was drilled northwest of Moravské Lieskové as part of a regional oil and gas exploration programme. The well reached a total depth of 662 m and was intended to verify the occurrence and potential accumulation of hydrocarbons within the Drietoma anticline, a geophysically indicated structural high in the St. Hrozenkov–Drietoma area. The drilled succession was originally assigned to the Svodnice Fm. of the Biele Karpaty Unit down to 75 m, and to the Zlín Fm. of the Rača Unit below this depth. However, a re-examination of the preserved core material suggests that the presence of glauconitic sandstones and an inferred middle to late? Eocene age do not support the previous correlation with the Rača Unit. The lower interval of the borehole, below approximately 90 m, is here reinterpreted as belonging to the Bystrica Mb. of the Bystrica Unit. The borehole cores reinterpretation is supported by the abundant occurrence of larger foraminifera, lithologically variable quartz-glauconitic sandstones, and thick beds of dark grey silty claystones to marlstones, all characteristics also of the Bystrica Mb. Furthermore, the western extent of the Bystrica Unit does not appear to terminate at the Nezdenice Faults, as previously supposed, but continues westwards beneath the Biele Karpaty Unit, albeit to a limited subsurface extent.

Key words: Bystrica Mb., Vsetín Mb., Magura Nappe, Flysch Belt, structural high, hydrocarbon exploration

Graphical abstract



Highlights

- KLK-1 borehole – depth 662 m – drilled in 1986 as part of hydrocarbon exploration – may represent one of the few known occurrences of the Bystrica Unit west of the Nezdenice Faults
- 0–90 m: Svodnice Fm. (Biele Karpaty Unit – Paleocene to early Eocene quartz-carbonate sandstones)
- 90–662 m: previously assigned to the Zlín Fm. (Vsetín Mb. of Rača Unit), is here reinterpreted as the Bystrica Mb. (Bystrica Unit), all in Magura Nappe (quartzy glauconitic sandstones with abundant redeposited larger foraminifera, and thick beds of dark grey silty claystones to marls; nannoplankton: middle Eocene – NP17, Bartonian)

Introduction

Drilling in the western part of the Flysch Belt commenced before and continued during the First World War, targeting structures considered prospective for oil accumulation. Deep wells were drilled in the Kysuce region, including Korňa T1 and Svrčinovec SVR-1. During the interwar period, additional wells were completed – T2 (Predmier) and S-1 (Staškov) (Plička et al., 1958).

At the turn of the 1950s and 1960s, the B-2 well (665 m; Oravská Polhora; Porubský et al., 1963) continued the verification of potential hydrocarbon accumulations. In the 1980s, drilling depths increased to 1200 m: in addition to shallow mapping wells such as KLK-1 (Klanečnica, 662 m), several deep structural boreholes were realised mainly in eastern Slovakia, including Zboj-1 (5002 m; Ďurkovič et al., 1982), Smilno-1 (5700 m; Leško et al., 1987), FPJ-1 Oravská Polhora (2417 m; Potfaj et al., 1989), and Zborov-1 (5500 m; Wunder et al., 1990).

This period coincided with deep structural drilling in the Czech Flysch Belt, e.g. Jablůnka-1 (6506 m; Pesl et al., 1982) and Gottwaldov-2 (4790 m). Although Lubina-1 (3236 m; Leško et al., 1982) was located south of the Flysch Belt, it penetrated Magura Nappe flysch successions at interval 2706–3236 m. Some boreholes also served multidisciplinary purposes: FPJ-1 (Oravská

Polhora) was also aimed at the exploration of a I-Br water reservoir (Franko & Potfaj, 1983), and SVR-1 evaluated the potential for Carboniferous coal seams beneath the Flysch Belt (Plička et al., 1958).

Leško (1980) proposed drilling a 6500 m borehole to investigate the basement of the Flysch Belt and potential hydrocarbon accumulations in the St. Hrozenkov–Drietoma area. Significant seismic reflectors beneath the flysch sequences, between 4000–6500 m depth, were targeted. Gravimetric and seismic data (Tomek, 1976) suggested low-density bodies beneath the Bystrica Unit in the Záriečie–Kolárovice area represented Oligocene–Miocene molasse deposits folded beneath the flysch and Inner Carpathian units.

The Drietoma area was selected for its presumed basement uplift, the "Drietoma Structure", interpreted from seismic and gravimetric data (Leško, 1980). Reflectors at ~3500 m were attributed to the base of the Biele Karpaty Unit, at ~6000 m to the base of the Magura Nappe, and at ~7000 m to the crystalline basement, possibly overlain by a Paleozoic–Mesozoic to Miocene(?) sedimentary cover.

Similar conclusions were reached by Němec (1978, 1980), who termed the structure in front of the Pieniny Klippen Belt the "Hrozenkov Elevation" based on seismic profiles 109R/76, 124R/76, and 124A–C/77. Potfaj (1986a, b) later summarised geophysical data from Drietoma–Klanečnica, highlighting the ambiguity in interpreting such elevation. Although the projected deep borehole (Leško, 1980) was planned for 1981, it had been never drilled.

Another borehole within the Drietoma elevation was initially proposed by Kysela (1984 in Potfaj & Bodiš, 1987) in the Drietoma Valley, but the location was later changed to the right-bank valley of a Klanečnica tributary opposite the settlement of Plevovec, but was ultimately relocated and drilled in the valley of its left-bank tributary northwest of Moravské Lieskové village, approximately 40 m from the stream, on the right bank at an elevation of 345 m (approx. 48.86236° N; 17.76045° E; Potfaj et al., 1986; Dvořáková et al., 1989).

Drilling of the KLK-1 borehole took place from August to November 1986, reaching 662 m instead of the

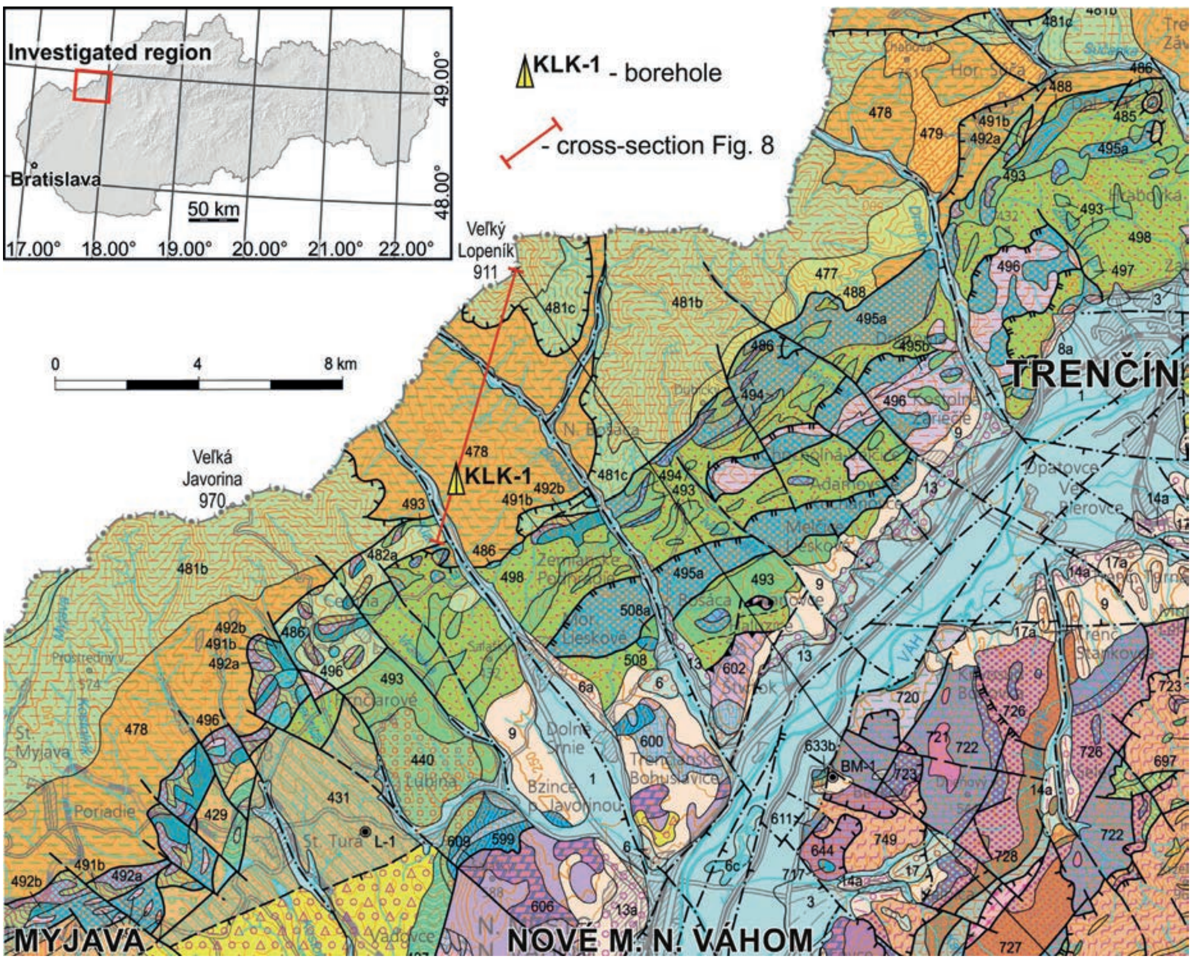


Fig. 1. Geological map displaying the location of the Klanečnica KLK-1 borehole (geological map of Elečko et al., 2008).
(Biele Karpaty Unit: 477 – Drietomica Beds, 478 – Svodnice Fm., 481b – Javorina Beds, 481c – Ondrášovec Beds, 482-513 – Pieniny Klippen Belt)

planned 650 m. Project documentation and detailed well evaluation are not preserved in the Geofond archive; only brief characterisations exist (Potfaj et al., 1986; Potfaj & Bodiš, 1987).

The borehole was part of hydrocarbon exploration in the Flysch Belt, targeting the verification of an anticlinal structure in the Nová hora area. Objectives included assessing basal sequences of the Biele Karpaty Unit and, where possible, the tectonic footwall, alongside petrogeochemical analyses (organic content, maturation) and reservoir properties (Potfaj et al., 1986).

Lithostratigraphic interpretation by Potfaj et al. (1986) assigned the uppermost 75 m of the borehole to the Svodnice Fm. of the Biele Karpaty Unit (Paleocene to early Eocene) and below a breccia interval interpreted as a thrust zone of the Biele Karpaty Unit; from approximately 75 m depth the underlying succession was assigned to the Zlín Fm. of the Rača Unit. Methane emissions were observed within the tectonic breccia at 75 m. At depths of 118, 134, 216, 318, and 505 m, methane-rich Na–Cl–HCO_3–I–Br waters were encountered, with maximum flow rates of 0.1 to 3.5 l·s^{-1} and temperatures up to 16 °C.

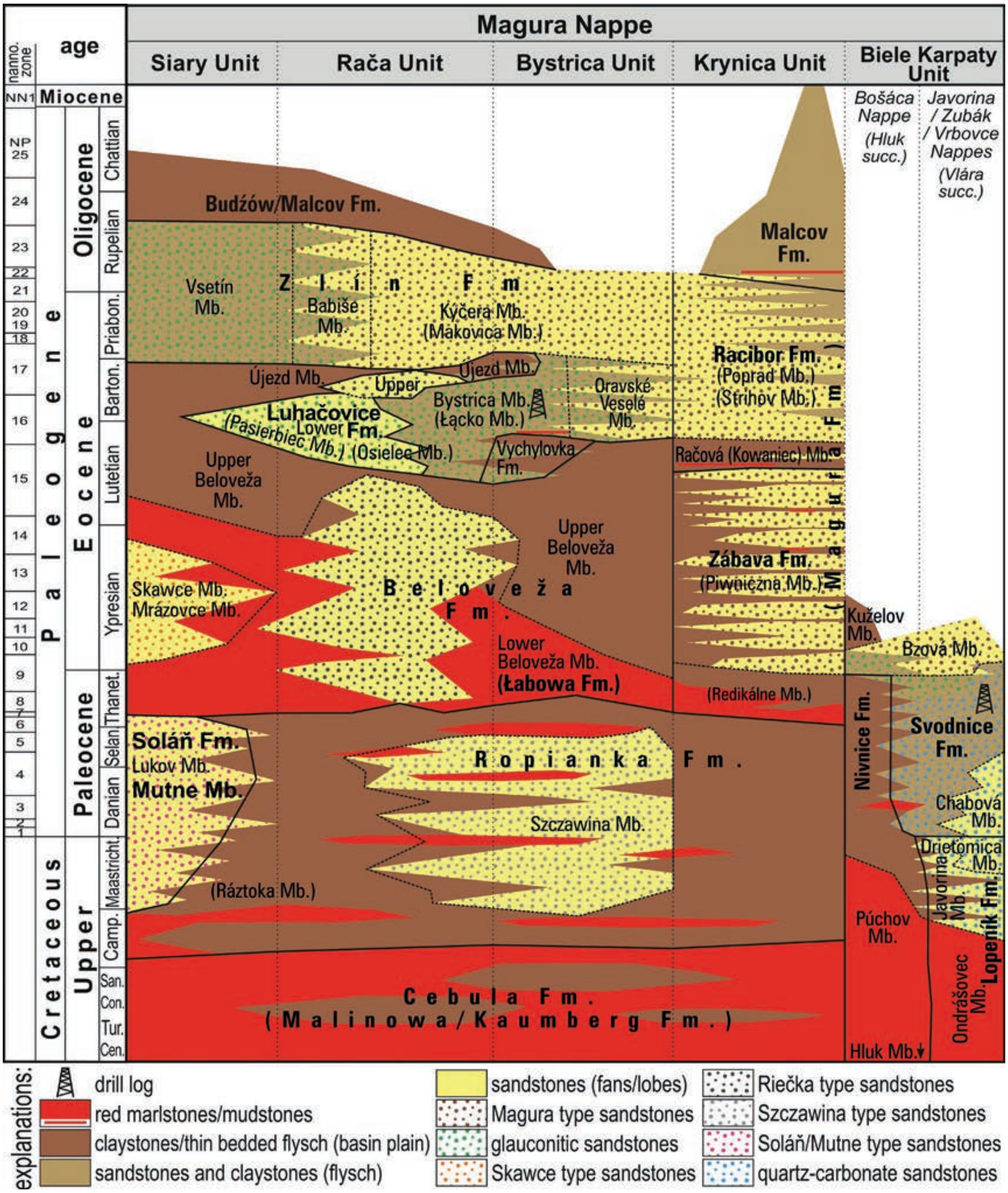


Fig. 2. Lithostratigraphic scheme of the Slovak western part of the Magura Nappe (Hók et al., 2019).

Iodine concentrations reached approximately 27 mg·l⁻¹. These waters are hosted in fracture-controlled reservoirs within sandstones and sandy claystones (Potfaj & Bodiš, 1987). Rock physical properties of the KLK-1 were studied by Dvořáková et al. (1989).

Simplified KLK-1 borehole profile (detailed description: Potfaj et al., 1986, p. 49; Potfaj & Bodiš, 1987)**:**

- **0–7.3 m:** Quaternary alluvium: brown sandy-clayey gravels and clays with sandstone pebbles.
- **7.3–75.6 m:** Svodnice Fm., Biele Karpaty Unit: alternating sandstones and claystones. The sandstones are predominantly fine-grained to silty, less commonly medium- to coarse-grained, with Ta, Tb, and Tc Bouma intervals. They are grey, laminated, contain muscovite, and show abundant plant detritus on lamination surfaces. Basal bed surfaces commonly exhibit bioglyphs. Bed thickness ranges from 1 to 250 cm. Claystones are grey, calcareous, occasionally dark grey, often with silty admixture. Dark grey claystones dominate within the deeper parts. The sandstone-to-claystone ratio is approximately 0.6, increasing to 0.8 at greater depths. Both sandstone proportion and bed thickness gradually increase with depth. At interval 25–25.5 m, a light grey marlstone to limestone occurs (so-called "treskúň" or "ruin marble"; Fig. 3; Marko et al., 2003). The succession is tectonically disturbed, with zones of slaty cleavage.
- **72.2–75.6 m:** Tectonic breccia composed of fine-grained laminated sandstones within a slaty clay matrix.
- **75.6–80.5 m:** Light grey calcareous muscovitic fine-grained sandstones, 5–20 cm thick, interbedded with grey to dark grey calcareous claystones, 5–10 cm thick. Sandstone-to-claystone ratio ~0.7.
- **80.5–84.3 m:** Tectonic breccia of strongly shaly grey calcareous claystones containing fragments of fine-grained laminated muscovitic sandstones and siltstones, with two beds of 15–20 cm thick fine-grained sandstones.
- **75.6–662 m:** Zlín Fm., Rača Unit: alternating sandstones and claystones. The dominant lithology is dark grey to brown silty calcareous claystones, 1–4 m thick. In the upper parts of cycles, thin 1–3 cm layers of bluish-green non-calcareous claystones occur. Rare pyrite streaks and nests are present in the brown claystones; contacts with grey-green claystones are usually bioturbated. The sandstones are represented by three types: a) greenish-grey glauconitic, fine-grained, with muscovite-rich laminae; b) light grey arkosic, displaying well-developed grading from coarse to fine-grained, some of which contain larger foraminifera, with bed thicknesses from a few cm up to 5.5 m; c) grey, poorly sorted, medium- to coarse-grained wacke sandstones up to 2 m thick. The sandstone-to-claystone ratio is ~0.3, locally higher in sandstone-dominated zones. Beds dip up to 40°, locally up to 75°. The succession is folded, with several overturned sequences; cores are cross-cut by calcite veins, and open fractures are present throughout the borehole.

Methods

Revision of KLK-1 was carried out as part of the geological mapping and research of the Biele Karpaty Mts. region during 2016–2020 (Pešková et al., 2021; Teťák et al., 2024) studying 48 core samples (Tab. 1). Samples were macroscopically examined and photographed. Two grey calcareous claystone samples from depths of 386.8 m and 482.2 m were analyzed for nannoplankton assemblages, while two quartzy glauconitic sandstone samples from depths of 197.0 m and 568.5 m were studied petrographically. Modal analysis of 500 grains per thin section was performed using an Eltinor 4 point-counting system.

Results

Based on the inspection of preserved core samples, we note a striking similarity in the macroscopic appearance of the glauconitic sandstones with the sandstones of the Bystrica Mb. (Tab. 1). We conclude that neither the presence of glauconitic sandstones nor a middle to late? Eocene age justify assignment to the Zlín Fm. (Vsetín Mb.) of the Rača Unit. In the upper part of the borehole, down to approximately 90 m, we agree with the assignment to the Svodnice Fm. of the Biele Karpaty Unit, consistent with the sequence observed in the vicinity of the borehole (Potfaj et al., 1986; Pešková et al., 2021).

Below the ~90 m, the borehole is reinterpreted as the Bystrica Mb. of the Bystrica Unit, characterized in core samples by abundant occurrence of larger not determined redeposited foraminifera in quartzy glauconitic sandstones and thick beds of dark grey claystones. In certain cases, the Svodnice Fm. of the Hluk succession of the Biele Karpaty Unit with glauconitic sandstones could be considered (cf. Teťák, 2016); however, its Paleocene to early Eocene age is older than the middle Eocene age determined for the sediments. The glauconitic sandstones from the borehole cores differ macroscopically indistinctly from those of the Vsetín Mb.

Nannoplankton analysis (Korábová in Pešková et al., 2020; Teťák et al., 2024) confirms a middle Eocene (NP17, Bartonian) age for samples at 386.8 m and 482.2 m. The assemblage, although low-diversity (Tab. 2), includes characteristic species typical of the middle Eocene: *Cyclicargolithus floridanus* (Roth & Hay) Bukry, *Reticulofe-*

Tab. 1

Macroscopic description of KLK-1 Klanečnica borehole core samples (explanations of abbreviations: cgs./mgs./fgs. – coarse-/medium-/fine-grained sandstone, Qks – quartz-carbonate sandstone, tectonics – tectonically fractured and calcite-healed).

Depth [m]	Lithology	Stratigraphy	Figure
17.4	fgs. Qks plant detritus, convolute and wavy laminated	Svodnice sst.	
25.2	limestone brownish-grey bioturbated	limestone	Fig. 3
25.8	fgs. Qks plant detritus, pyrite, laminated, + siltstone laminated, plant detritus	Svodnice sst.	
31.4	mgs.-(fgs.) Qks, plant detritus, massive, muscovite, tectonics	Svodnice sst.	
37.7	fgs. quartzy, dark green to glassy, laminated, a lot of glauconite	glauc. sst.	
48.6	fgs. Qks, plant detritus, laminated, (muscovite), tectonics	Svodnice sst.	
65.2	fgs. Qks, plant detritus, massive?, tectonics	Svodnice sst.	
77.2	fgs. Qks, plant detritus, cross bedded, muscovite, tectonics	Svodnice sst.	Fig. 4A
89.0	silty claystone hard grey calcareous, plant detritus, fissured (filled by fgs. Qks.), tectonics	Svodnice sst.	
92.8	fgs. quartzy greenish-grey, a lot of glauconite, muscovite, plant detritus, laminated	glauc. sst.	
108.6	silty claystone hard calcareous grey, fissured, plant detritus, tectonics (rusty a calcite veins)	claystone	
124.6	silty claystone brownish-grey calcareous, plant detritus, tectonics	claystone	
129.6	marlstone light grey, pyrite fills bioturbation), fissured, tectonics	claystone	
133.4	mgs. poorly sorted (?slump) massive, larger foraminifera, less glauconite, plant detritus, muscovite, tectonics	glauc. sst.	
142.6	silty claystone to siltstone light, plant detritus, tectonics	claystone	
144.8	siltstone light grey, plant detritus, muscovite, ?glauconite	claystone	
153.3	fgs. laminated, plant detritus, muscovite, medium glauconite, tectonics	glauc. sst.	
156.3	siltstone brownish-grey calcareous, plant detritus, muscovite, medium glauconite	glauc. sst.	
163.5	fgs. Qks laminated, muscovite, plant detritus, (?no glauconite)	Svodnice sst.?	
169.8	claystone light, soft, calcareous	claystone	
197.0	mgs. to fgs. Qks grey massive, a lot of glauconite, larger foraminifera, muscovite, plant detritus	glauc. sst.	Fig. 4B, 6
208.6	fgs. quartzy, a lot of glauconite, laminated, plant detritus, muscovite	glauc. sst.	Fig. 4C
211.7	siltstone dark brownish-grey, bioturbation (filled by fgs.), plant detritus, muscovite, (?glauconite), laminated	claystone	
212.4	silty claystone brownish-grey, plant detritus, muscovite, tectonics	claystone	
263.7	claystone dark grey, muscovite	claystone	
266.5	fgs. grey quartzy, a lot of glauconite, laminated, plant detritus, muscovite	glauc. sst.	
271.5	mgs. quartzy, medium glauconite, massive	glauc. sst.	Fig. 4D
279.3	fgs. quartzy, a lot of glauconite, tectonics, fissured	glauc. sst.	
285.5	claystone-siltstone claystone dark brownish-grey, bioturbated, plant detritus, (?glauconite)	claystone	
313.2	claystone-silty claystone dark brownish-grey calcareous, bioturb., plant detritus, (?glauconite)	claystone	
317.8	fgs. quartzy, a lot of glauconite, larger foraminifera, laminated, plant detritus	glauc. sst.	Fig. 4E
342.0	silty claystone grey, plant detritus	claystone	
383.5	fgs. quartzy, a lot of glauconite, laminated, tectonics	glauc. sst.	Fig. 4F
386.8	claystone grey calcareous plant detritus, muscovite	claystone	Fig. 5
425.0	mgs. to fgs. quartzy massive, a lot of glauconite	glauc. sst.	Fig. 4G

Tab. 1 – continued

Depth [m]	Lithology	Stratigraphy	Figure
436.5	fgs. quartzy, a lot of glauconite, larger foraminifera, massive	glauc. sst.	
441.2	claystone dark grey, plant detritus, tectonics	claystone	
469.5	fgs. quartzy, a lot of glauconite, massive, tectonics	glauc. sst.	Fig. 4H
482.8	claystone dark grey calcareous	claystone	Fig. 5
531.5	fgs. quartzy, a lot of glauconite, muscovite, plant detritus, laminated	glauc. sst.	
561.4	silty claystone dark grey, plant detritus, bioturbation (filled by glauconite fgs.)	glauc. sst.	
568.5	cgs. grey quartzy, larger foraminifera, massive, a lot of glauconite, (tectonics)	glauc. sst.	Fig. 4I, 6
580.5	silty claystone dark grey, plant detritus, bioturbation (filled by glauconite fgs.)	glauc. sst.	
608.5	mgs. to fgs. quartzy, a lot of glauconite, larger foraminifera	glauc. sst.	Fig. 4J
619.5	silty claystone dark grey, plant detritus, muscovite	claystone	
635.0	siltstone-(fgs.) laminated, plant detritus, a lot of glauconite, muscovite, tectonics	glauc. sst.	
660.0	silty claystone dark grey, plant detritus, muscovite, (laminated), tectonics	claystone	
661.0	fgs. quartzy, a lot of glauconite, (laminated), (plant detritus)	glauc. sst.	

nestra bisecta (Hay, Mohler & Wade) Roth, *R. hillae* Bukry & Percival, *R. lockeri* Müller. The samples contained *Helicosphaera compacta* Bramlette & Wilcoxon, *Coccolithus pelagicus pelagicus* (Wallich) Schiller, *Reticulofenestra* cf. *dictyoda* (Deflandre) Stradner, *Sphenolithus anarrhopus* Bukry & Bramlette, *S. moriformis* (Brönnimann & Stradner) Bramlette & Wilcoxon, *Coccolithus formosus* (Kamptner) Wise, and *Zygrhablithus bijugatus bijugatus* (Deflandre) Deflandre, as well. Potfaj et al. (1986) reports the similar assemblage from the depths 121 m, 184 m, 374 m and 552 m.

Tab. 2

Nannoplankton species determined in claystone samples from KLK-1 borehole.

386.8 m	482.2 m	Depth / Nannoplankton species
●	●	*Coccolithus formosus* (Kamptner) Wise
●		*Coccolithus pelagicus pelagicus* (Wallich) Schiller
	●	*Coccolithus* sp.
●	●	*Cyclicargolithus floridanus* (Roth & Hay) Bukry
●		*Discoaster deflandrei* Bramlette & Riedel
●	●	*Helicosphaera compacta* Bramlette & Wilcoxon
●		*Chiasmolithus grandis* (Bramlette & Riedel) Radomski
●		*Chiasmolithus* sp.
	●	*Pontosphaera multipora* (Kamptner) Roth
●	●	*Reticulofenestra bisecta* (Hay, Mohler & Wade) Roth
●		*Reticulofenestra* cf. *dictyoda* (Deflandre) Stradner
●	●	*Reticulofenestra hillae* Bukry & Percival
●		*Reticulofenestra lockeri* Müller
●		*Sphenolithus anarrhopus* Bukry & Bramlette
●		*Sphenolithus moriformis* (Brönnimann & Stradner) Bramlette & Wilcoxon
	●	*Zygrhablithus bijugatus bijugatus* (Deflandre) Deflandre
Middle Eocene NP17 Bartonian	Middle Eocene	Age

Petrographically analyzed sandstone samples from depths of 197.0 m and 568.5 m are medium- to coarse-grained, from moderately to well-sorted, and from slightly to very well-rounded, unidirectional, calcareous glauconitic sublitharenites to subarkoses (Tab. 3). Glauconite occurs both as intergranular cement and as oval grains. No chloritization was observed. Fossil organic fragments are variously represented by larger and small foraminifera, filaments, and, for example, red algae. Lithic fragments include carbonates (micro- to sparitic), felsite fragments, and less commonly sandstones, phyllites to gneisses, and granites are present. Calcite cement (sparite) binds the sandstones.

Fig. 3. Light brownish-grey marlstone to limestone (so-called "treskúň" or "ruin marble") from the 25–25.5 m interval.

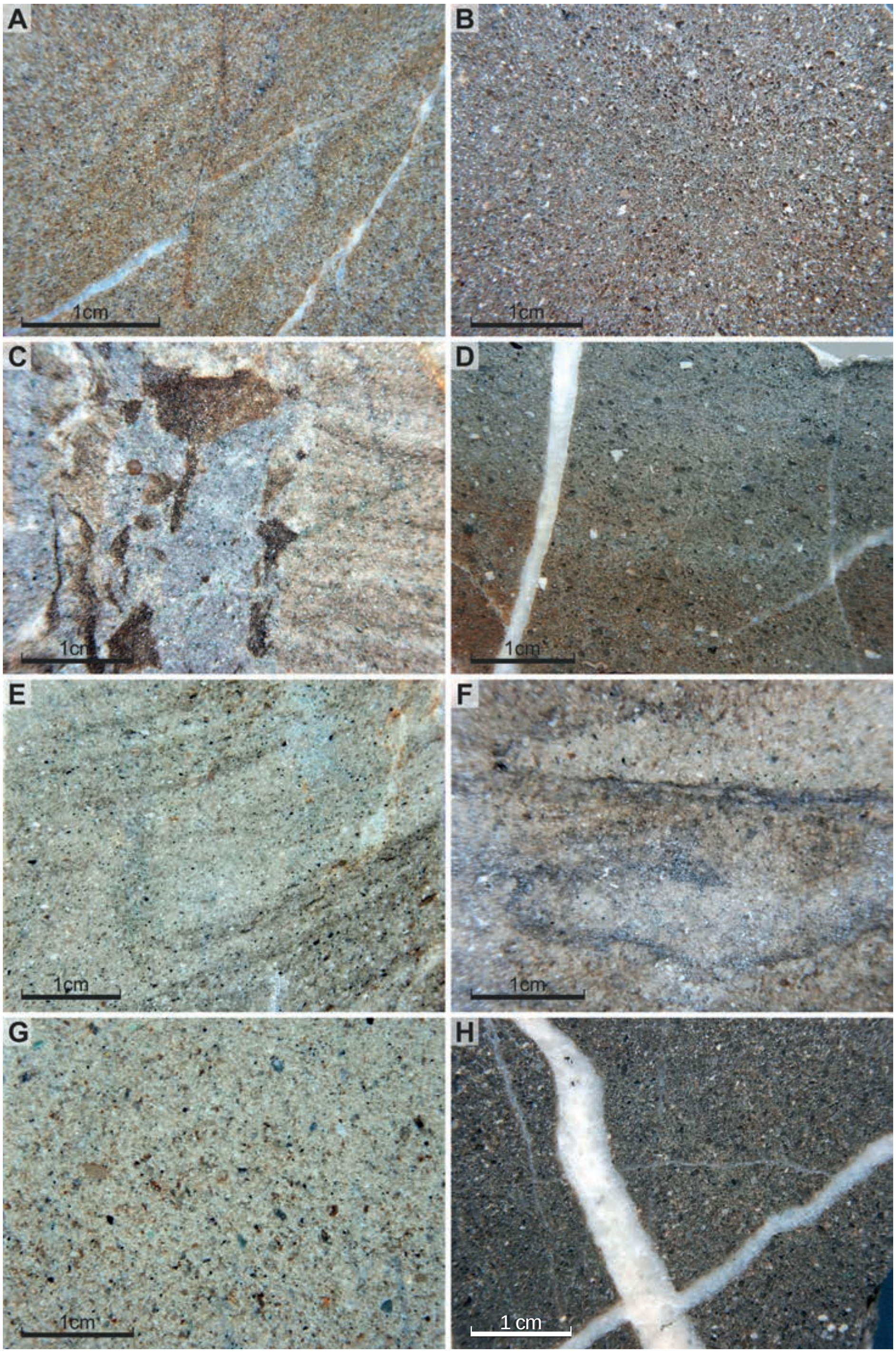


Fig. 4. Polished slabs from sandstone samples of the Klanečnica KLK-1 borehole: (A) laminated fine-grained quartz-carbonate sandstone with muscovite and plant detritus, tectonically fractured – depth 77.2 m (Svodnice Fm.); (B) grey, massive, medium- to fine-grained quartz–carbonate sandstone with muscovite, abundant glauconite, larger foraminifera, and plant detritus – depth 197.0 m (Bystrica Mb.); (C) laminated fine-grained quartzy sandstone with muscovite, abundant glauconite, and plant detritus – depth 208.6 m (Bystrica Mb.); (D) medium-grained quartzy sandstone, medium glauconitic, massive – depth 271.5 m (Bystrica Mb.); (E) laminated fine-grained quartzy sandstone with abundant glauconite and plant detritus – depth 317.8 m (Bystrica Mb.); (F) laminated fine-grained quartzy sandstone with abundant glauconite, tectonically fractured – depth 383.5 m (Bystrica Mb.); (G) massive medium- to fine-grained quartzy sandstone with abundant glauconite – depth 425.0 m (Bystrica Mb.); (H) massive fine-grained quartzy sandstone with abundant glauconite, tectonically fractured – depth 469.5 m (Bystrica Mb.); (I) massive coarse-grained grey quartzy sandstone with larger foraminifera and abundant glauconite – depth 568.5 m (Bystrica Mb.); (J) medium- to fine-grained quartzy sandstone with abundant glauconite – depth 608.5 m (Bystrica Mb.).

Tab. 3

Modal composition of glauconitic sandstone samples of the KLK-1 borehole at depths of 197.0 m and 568.5 m. (Legend: Qm – monocrystalline quartz, Qp – polycrystalline quartz, Silicite – chert, Plg – plagioclase, Kfs – potassium feldspar, Ls – sedimentary rock fragments, Lc – carbonate rock fragments, Lm – metamorphic rock fragments, Lv – volcanic rock fragments, Ms – muscovite, Bt – biotite, Acc – accessory heavy minerals, Fos – fossils, Gl – glauconite, Mx – matrix, Cm – cement).

Depth	Qm	Qp	Silicit	Plg	Kfs	Ls	Lc	Lm	Lv	Ms	Bt	A	Fos	Gl	Mx	Cm
197.0 m	44.04	12.42	0.5	0.33	1.66	0.99	7.45	0.33	0.33	4.64	0	0.83	5.79	9.11	0	11.9
568.5 m	38.1	32.38	1.9	1.9	6.86	0.95	0.95	0.38	2.86	1.52	0.76	1.33	1.14	0.57	0	8.38

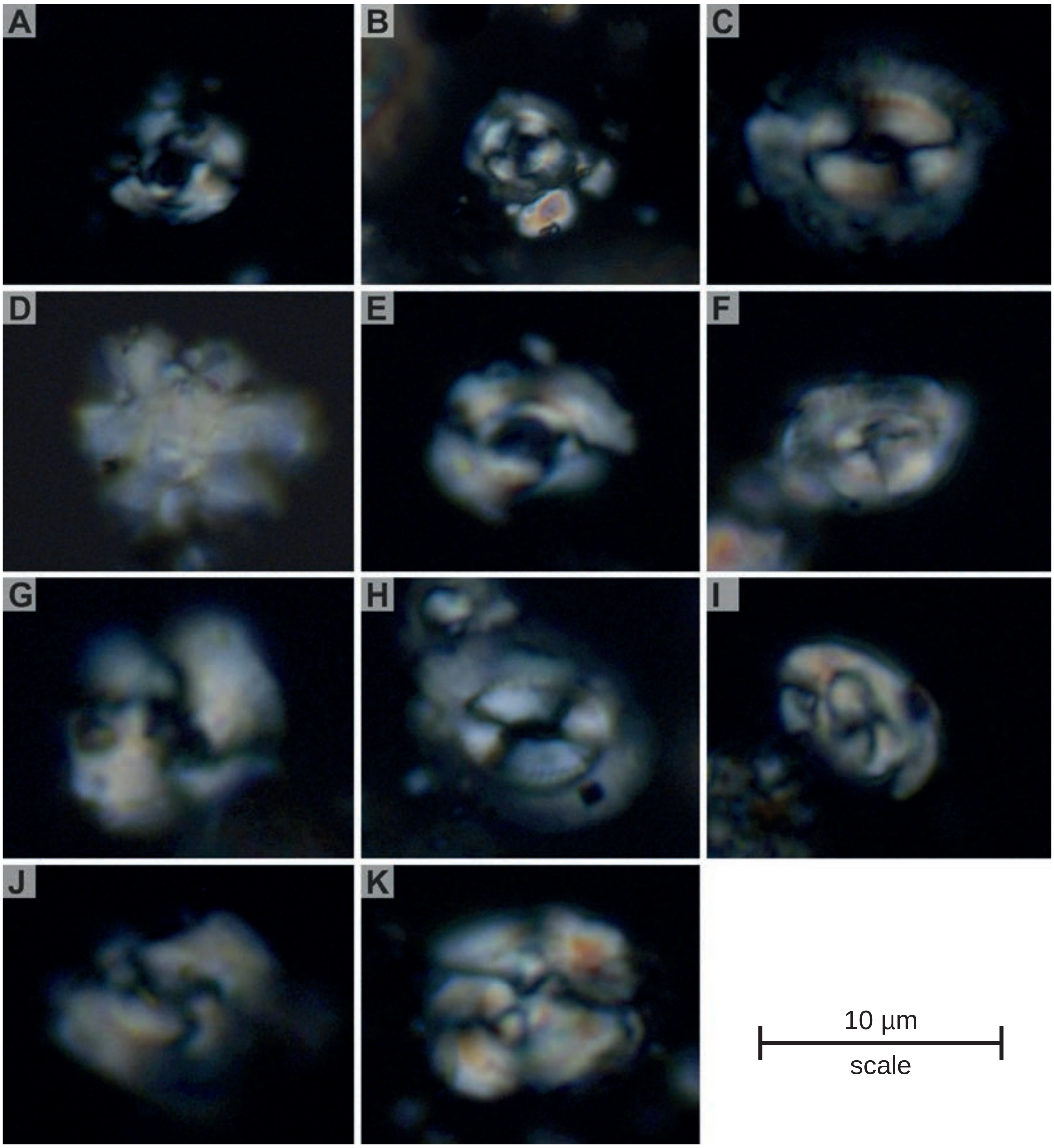
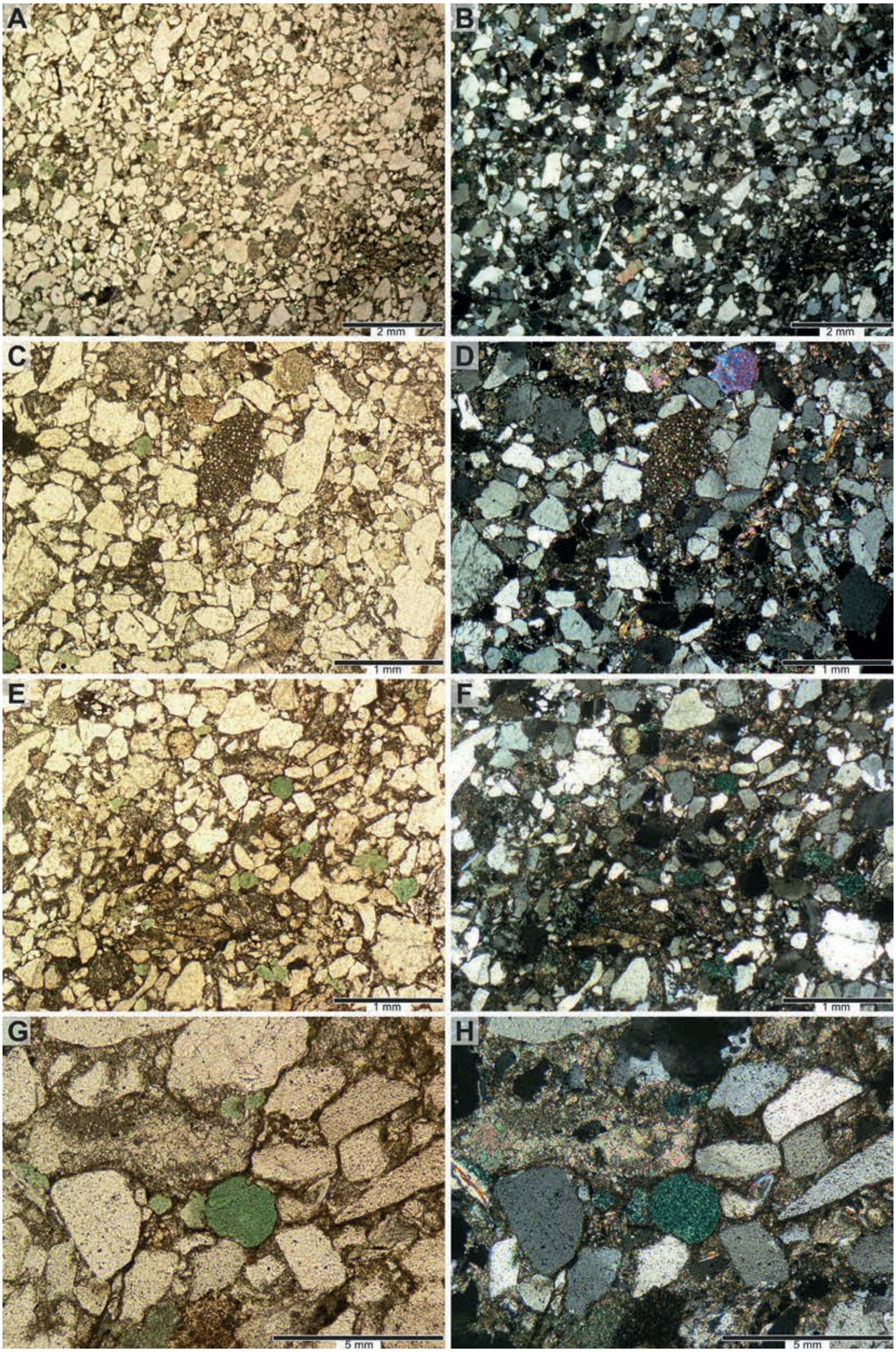


Fig. 5. Representative nannoplankton species from claystone samples of the Klanečnica KLK-1 borehole, observed under crossed nicols, Bystrica Mb. of Zlín Fm. Scale bar = 10 µm: (A) *Cyclicargolithus floridanus* (Roth & Hay) Bukry, depth 482.2 m; (B) *Coccolithus formosus* (Kamptner) Wise, depth 386.8 m; (C) *Coccolithus pelagicus pelagicus* (Wallich) Schiller, depth 386.8 m; (D) *Discoaster deflandrei* Bramlette & Riedel, depth 386.8 m; (E) *Cyclicargolithus floridanus* (Roth & Hay) Bukry, depth 386.8 m; (F) *Helicosphaera compacta* Bramlette & Wilcoxon, depth 386.8 m; (G) *Cyclicargolithus floridanus* (Roth & Hay) Bukry, depth 386.8 m; (H) *Coccolithus pelagicus pelagicus* (Wallich) Schiller, depth 386.8 m; (I) *Helicosphaera compacta* Bramlette & Wilcoxon, depth 482.2 m; (J) *Reticulofenestra* cf. *lockeri* Müller, depth 386.8 m; (K) *Reticulofenestra bisecta* (Hay, Mohler & Wade) Roth, depth 482.2 m.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2 mm
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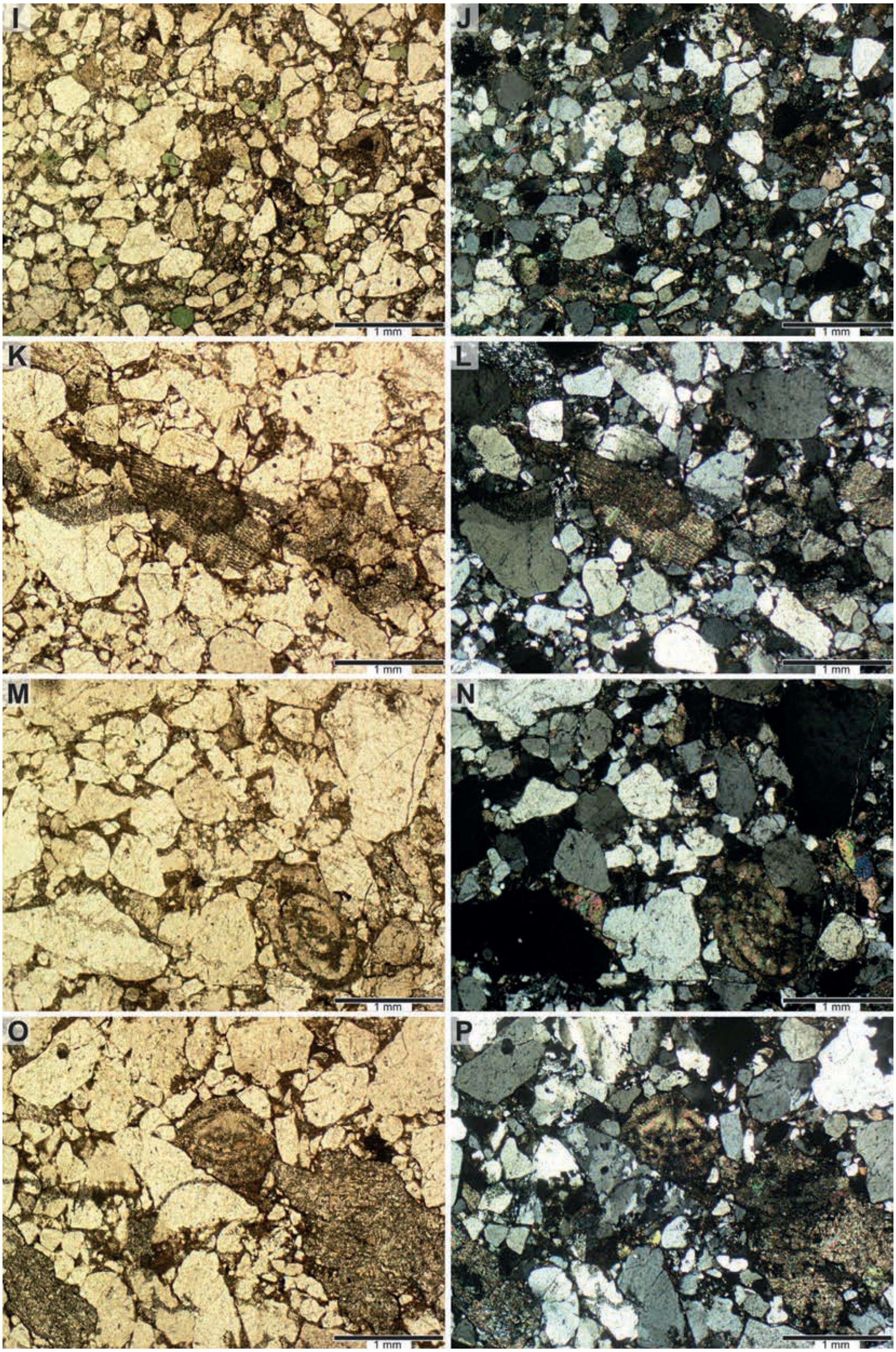

Fig. 6. Quartzy glauconitic sandstones of the Bystrica Mb. from samples of the Klanečnica KLK-1 borehole (IIN and XN pairs): (A–J) grey, massive, medium- to fine-grained quartz-carbonate sandstone with muscovite, abundant glauconite, larger foraminifera, and plant detritus – depth 197.0 m; (K–P) massive, coarse-grained, grey, quartzy sandstone with abundant glauconite and larger foraminifera – depth 568.5 m.

Discussion

Pesl (1968), who introduced the Vsetín Mb., points out that the Vsetín Mb. is very similar to the Bystrica Mb., with the most important diagnostic feature distinguishing the Bystrica Mb. from the Vsetín Mb. being "the presence of hard bluish-grey, whitish, and yellowish-weathering marlstones to limestones and marls with shell-like prismatic disintegration – the so-called Łącko marls". Potfaj et al. (1986) document claystones to marls with thicknesses up to 300 cm in the interval 84.3–141 m in their borehole description.

Another distinguishing feature may be the lithological variability of the sandstones. Even a macroscopic inspection of the sandstone samples from the borehole suggests an affinity to the Bystrica Mb. It is notably lithologically and texturally diverse, with abundant shells of larger foraminifera. Teťák et al. (2016) emphasize the lithological diversity of glauconitic sandstones of the Bystrica Mb. from the Orava region, explaining it by the spatially and temporally varied character of the source area and transport. They distinguish five main types of sandstones, including slump and debris flow bodies observed also in the KLK-1 borehole.

The increased occurrence of larger foraminifera in the glauconitic sandstones of the Bystrica Mb. has been mentioned in several studies (Köhler & Salaj, 1999; Buček & Teťák, 2020). Köhler & Salaj (1999), based on apparently redeposited material from the Bystrica Mb. at the Škaredá locality west of Bytča, assign the described assemblage with *Orbitoclypeus douvillei douvillei* (Schlumberger), *O. varians angoumensis* Less, and *Asterocyclina stellata adourensis* Less to the early Lutetian. Buček & Teťák (2020) studied larger foraminifera in more detail from the Javorníky and Orava localities. Older species, from the Ypresian to Bartonian, were redeposited into the sediments. The age of the sediments can be represented by the youngest species of the Lutetian SBZ 13–16 to the younger Bartonian SBZ 18. The occurrence of larger foraminifera in the Vsetín Mb. is reported but not so typical.

Potfaj et al. (1986) reported the age of sediments from the deeper part of the borehole, based on nannoplankton assemblages, as at least late middle Eocene, possibly even late Eocene. This age does not exclude correlation with either the Vsetín or Bystrica members. The described assemblage includes: *Coccolithus pelagicus* (Wallich) Schiller, *C.* cf. *eopelagicus* (Bramlette & Riedel) Kamptner, *Reticulofenestra umbilica* (Levin) Martini & Ritzkowski, *R.* cf. *coenura* (Reinhardt) Roth, *Chiasmolithus grandis* (Bramlette & Riedel) Radomski, *Ch. expansus* (Bramlette & Sullivan) Gartner, *Ch.* cf. *gigas* (Bramlette & Sullivan) Radomski, *Nannotetrina fulgens* (Stradner) Achuthan & Stradner, *N.* cf. *pappii* (Stradner) Perch-Nielsen, *Discoaster saipanensis* Bramlette & Riedel, *D. tani nodifer* Bramlette & Riedel, *D. barbadiensis* Tan, and *Cyclicargolithus floridanus* (Roth & Hay) Bukry. At present, this assemblage can be considered of middle Eocene age (NP15). Based on the youngest species, *Reticulofenestra umbilica* (NP16–NP22), the sediments can be assigned at most to the upper part of the middle Eocene. However, this would not exclude the Vsetín Mb.

Potfaj et al. (1986) interpret the lower boundary of the Biele Karpaty Unit at the base of the tectonic breccia zone at a depth of 72.2 to 75.6 m. Furthermore, the sandstone samples from depths of 77.2 and 89.0 m are clearly quartz–carbonate sandstones, more characteristic of the Biele Karpaty Unit. Another zone of tectonic breccias occurs at a depth of 80.5–84.3 m. The nearest sandstone core sample from 92.8 m already belongs to glauconitic sandstones. Therefore, we estimate the tectonic interface slightly lower than previously assumed, at approximately 90 m.

The sandstone sample from 163.5 m, based on macroscopic examination, can be classified as quartz-carbonate sandstones typical for the Svodnice Fm. Potfaj et al. (1986) document occasional sandstones without glauconite, or sandstones containing carbonate fragments, as well. Such sandstones were observed in the same stratigraphic position in co-occurrence with glauconite sandstones, in smaller quantities, at several places on the surface in the southernmost part of the Bystrica Unit in the Púchovská dolina Valley (Teťák, 2024), which may indicate that the borehole intersected the southernmost tectonic slices of the Bystrica Unit.

The Bystrica Mb. crops out as well in the southernmost tectonic slice of the Rača Unit in Javorníky Mts., up to a thickness of 450 m (Mello et al., 2005). At the time of drilling the KLK-1 borehole, this position was not known.

Since the Vsetín Mb. occurs in the northern (external) part of the Rača Unit, it is unlikely that the Biele Karpaty Unit would rest on the external part of the Rača Unit without the central part of unit with the Babiše Mb. and the southern part with the Kýčera Mb., as well as the Bystrica Unit with the Bystrica Mb., being preserved at the surface.

At the surface, the Bystrica Unit essentially ends at the Nezdenice Faults, which are among the most prominent neotectonically active transverse faults of the Flysch Belt. This was already pointed out by Potfaj & Bodiš (1987). The Bystrica Unit crops out southwest of the Nezdenice Faults only in minor occurrences near the Vlčnov municipality. The continuation of the Bystrica Unit in the subsurface of the Vienna Basin and the Rhenodanubian region has not been proven (Stráník et al., 2021). The Klanečnica borehole was one of the arguments for terminating the Bystrica Unit at the Nezdenice Faults in the subsurface.

It can therefore be assumed that the Bystrica Unit may continue subsurface to a limited extent further west,

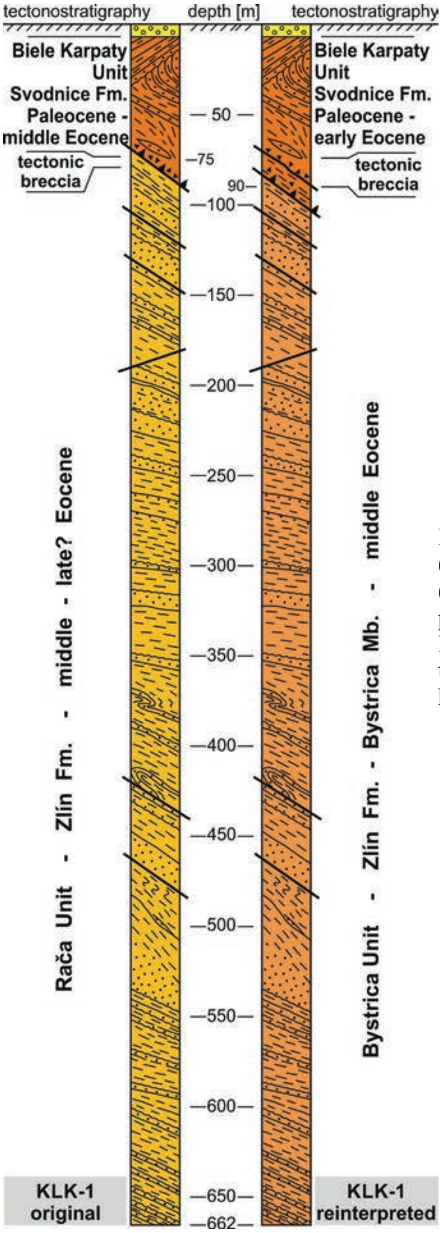

Fig. 7. Original (Potfaj et al., 1986) (left) and reinterpreted (right) lithological profile of the KLK-1 borehole.

where the outer margin of the Biele Karpaty Unit crops out; the sediments of its upper middle Eocene and younger parts have not been preserved, and it is likely that folding had already begun in this part of the Magura Basin in connection with the Rhenodanubian Zone (Teťák et al., 2019).

A detailed technical report with a thorough evaluation of the KLK-1 core is not available in the Geofond archive, nor is the drilling project, which later studies refer to (Kysela, 1984 in Potfaj & Bodiš, 1987). Only preliminary brief information from Potfaj et al. (1986), Potfaj & Bodiš (1987), and Dvořáková et al. (1989), as well as a few preserved core samples, can be used. Based on these data, we assign the deeper part of the borehole to the Bystrica Mb. of the Bystrica Unit and estimate the boundary between the Biele Karpaty and Bystrica units at approximately 90 m depth.

In the near-surface part of the Magura Nappe, we agree with the conclusion of Potfaj (1993): "… *we could look for the Bystrica Unit in the rear part of the Rača Unit in a 'scar' position (i.e., forming only a narrow, steeply inclined zone at the southern boundary of the Rača Unit)*." However, according to our conclusions, the Bystrica Unit may have locally significant volumes at greater depths underlying the Biele Karpaty Unit.

Conclusions

The KLK-1 borehole, drilled northwest of Moravské Lieskové village in 1986 as part of hydrocarbon exploration of the Drietoma Structure, reached a total depth of 662 m. The upper 90 m of the succession confirmed the presence of the Svodnice Fm. (Biele Karpaty Unit). The succession below the tectonic breccia at approximately 90 m, previously assigned to the Zlín Fm. (Rača Unit), is here reinterpreted as the Bystrica Mb. (Bystrica Unit). This interval is characterised by quartz-rich glauconitic sandstones with abundant redeposited larger foraminifera, and thick beds of dark grey silty claystones to marls.

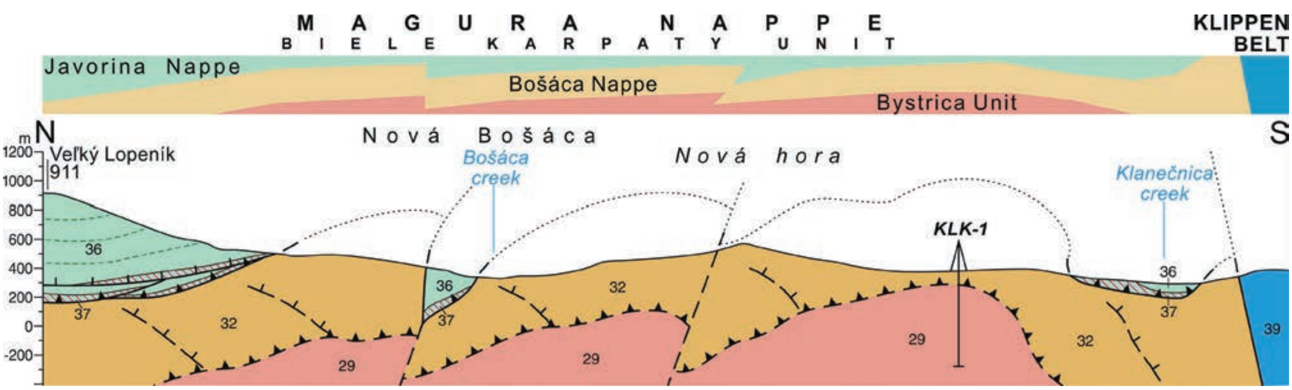

Fig. 8. The geological cross-section with the Bystrica Unit interpreted in the complex structural elevation beneath the Bošáca Nappe in the KLK-1 borehole (based on Pešková et al., 2021). A few minor backthrusts dislocate the structure. (Bystrica Unit: 29 – Bystrica Mb.; Biele Karpaty Unit: 32 – Svodnice Fm., 36 – Javorina Mb., 37 – Ondrášovec Mb.; 39 – Klippen Belt in general).

Examination of preserved core material, together with analyses of selected samples (nannoplankton and sandstone petrography), indicates that the occurrence of glauconitic sandstones and a middle to possibly late Eocene age alone are insufficient to justify assignment of these sediments to the Vsetín Mb. (Rača Unit) or to the Bystrica Mb. (Bystrica Unit).

The KLK-1 borehole may represent one of the few known occurrences of the Bystrica Unit west of the Nezdenice Faults. The unit continues beneath the Biele Karpaty Unit, indicating that its western extent is not terminated by the faults.

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Alternatívna interpretácia bystrickej jednotky vo vrte KLK-1 Klanečnica (magurský príkrov)

Hlboký vrt na preskúmanie podložia flyšového pásma a potenciálnych akumulácií uhľovodíkov v oblasti Starého Hrozenkova a Drietomy, ktorý navrhoval Leško (1980), mal dosahovať až 6 500 m. Oblasť Drietomy bola vybraná kvôli jej predpokladanej elevácii podložia, „drietomskej štruktúre“ alebo „hrozenkovskej elevácii“. Gravimetrické a seizmické údaje (Tomek, 1976; Němec, 1978, 1980) v tejto oblasti naznačovali prítomnosť telies s nízkou hustotou pod flyšovými a vnútrokarpatskými jednotkami. Potfaj (1986a, b) neskôr zhrnul geofyzikálne údaje a zdôraznil nejednoznačnosť pri interpretácii takejto elevácie. Hlboký vrt, plánovaný na rok 1981 (Leško, 1980), sa neuskutočnil.

Vrt KLK-1 bol realizovaný v roku 1986 (cca 48,862 36°; 17,760 45°) a dosiahol hĺbku 662 m. Projektová dokumentácia a podrobné vyhodnotenie vrtu sa v archíve geofondu nezachovali. Existujú len stručné charakteristiky (Potfaj et al., 1986; Potfaj a Bodiš, 1987). Potfaj et al. (1986) interpretovali najvrchnejších 75 m vrtu ako svodnické súvrstvie bielokarpatskej jednotky (paleocén až starší eocén) a pod intervalom brekcií považovaným za násunovú plochu bielokarpatskej jednotky bolo interpretované zlínske súvrstvie račianskej jednotky. V tektonickej brekcii v hĺbke 75 m boli zaznamenané emisie metánu, v hĺbke 118 m, 134 m, 216 m, 318 m a 505 m zas prílev Na–Cl–HCO_3–I–Br vody bohatej na metán s maximálnym prietokom 0,1 až 3,5 $l \cdot s^{-1}$ a teplotou do 16 °C. Koncentrácia jódu dosiahla približne 27 $mg \cdot l^{-1}$ (Potfaj a Bodiš, 1987).

Na základe makroskopickej prehliadky zachovaných vzoriek jadier sme zaznamenali výraznú podobnosť vo vzhľade glaukonitových pieskovcov z vrtu s pieskovcami bystrických vrstiev (tab. 1). Dospeli sme k záveru, že ani prítomnosť glaukonitových pieskovcov, ani vek stredný až neskorý eocén nedokazujú zaradenie k vsetínskym vrstvám zlínskeho súvrstvia račianskej jednotky. V hornej časti vrtu, približne do hĺbky 90 m, súhlasíme so zaradením k svodnickému súvrstviu bielokarpatskej jednotky. Je to v súlade s horninami pozorovanými v blízkosti vrtu (Potfaj et al., 1986; Pešková et al., 2021).

Pod hĺbkou asi 90 m vrt reinterpretujeme ako bystrické vrstvy bystrickej jednotky. Naznačuje to hojný výskyt väčších foraminifer a hrubé vrstvy tmavosivých ílovcov vo vzorkách jadra v kremitých glaukonitových pieskovcoch. Podľa litofaciálnej podobnosti by sa dalo uvažovať aj o svodnickom súvrství hluckého vývoja bielokarpatskej jednotky s glaukonitovými pieskovcami (Teťák, 2016). Jeho paleocénny až ranoeocénny vek je však starší ako strednoeocénny vek stanovený v prípade sedimentov z vrtu. Podobne, keďže sa vsetínske vrstvy vyskytujú len v severnej (externej) časti račianskej jednotky, je málo pravdepodobné, že by bielokarpatská jednotka ležala priamo na vonkajšej časti račianskej jednotky bez prítomnosti internejších častí magurského príkrovu, ktoré vystupujú na povrchu.

Glaukonitové pieskovce z vrtu sa od pieskovcov vsetínskych vrstiev makroskopicky líšia len nevýrazne. Rozlišovacím znakom môže byť litologická a textúrna variabilita pieskovcov spolu s hojnými schránkami väčších foraminifer. Teťák et al. (2016) zdôrazňujú z Oravy litologickú pestrosť glaukonitových pieskovcov bystrických vrstiev a vysvetľujú ju priestorovo a časovo rozmanitým charakterom zdrojovej oblasti a transportu. Rozlišujú päť hlavných typov pieskovcov vrátane sklzov a úlomkotokov, ktoré boli pozorované aj vo vrte KLK-1.

Analýza nanoplanktónu (Korábová in Pešková et al., 2020; Teťák et al., 2024) potvrdzuje vek vzoriek z hĺbky 386,8 m a 482,2 m stredný eocén (NP 17, bartón). Potfaj et al. (1986) uvádzajú podobné spoločenstvo z hĺbky 121 m, 184 m, 374 m a 552 m.

Preskúmanie zachovaného horninového materiálu naznačuje, že samotný výskyt glaukonitických pieskovcov a stredný až možno neskorý eocénny vek nie sú dostatočné na zaradenie týchto sedimentov k vsetínskym vrstvám (račianska jednotka), ale ani k bystrickým vrstvám (bystrickej jednotky). Vrt KLK-1 môže predstavovať jeden z mála známych výskytov bystrickej jednotky západne od nezdenických zlomov. Bystrická jednotka pokračuje pod bielokarpatskou jednotkou, čo naznačuje, že jej západný rozsah sa týmito zlomami nekončí.

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