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Lower Ordovician glauconite-bearing facies in the Holy Cross Mountains and their equivalents on the Małopolska Block (SE Poland): depositional environments and the relationship with eustatic changes in Baltica

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Glauconite-bearing siliciclastic lithofacies are widely distributed throughout the Lower Ordovician (upper Tremadocian–Floian) sedimentary record of Poland. They form a diachronous horizon composed of glauconitic sandstones that locally rest on a basal conglomerate, which occur on the Małopolska Block (including the southern Holy Cross Mountains) and the East European Platform. The Lower Ordovician facies architecture in the Holy Cross Mountains can be roughly correlated with the sea-level changes reconstructed in Baltoscandia, though the local tectonics contributed to some notable differences. The Lower Ordovician glauconitic interval reflects a major change of depositional environment on the Baltica and Małopolska shelves characterised by favourable conditions for stratigraphic and sedimentary condensation. It corresponds to a transgressive and early highstand depositional system encompassing the upper Tremadocian to lower Floian interval in the Holy Cross Mountains. On the East European Platform, an extremely condensed glauconitic horizon is associated with the Floian, although its basal conglomerates may be related to the latest Tremadocian. A low accumulation rate, including periods of sediment starvation, facilitated early diagenetic precipitation of a siliceous phase in tuffitic muds, resulting in bedded and nodular cherts in the upper Tremadocian of the southern Holy Cross Mountains.

Key words: Tremadocian, Floian, siliciclastics, glauconite, cherts, eustasy.

INTRODUCTION

A distinctive feature of the Lower Ordovician succession in the southern Holy Cross Mountains (HCM), located in SE Poland, is the widespread occurrence of upper Tremadocian to lower Floian siliciclastic deposits enriched in glauconite (Czarnocki, 1919; Turnau-Morawska, 1958, 1960; Bednarczyk, 1964, 1966; Chlebowski, 1971; Trela, 2001, 2022; and references therein). These deposits rest unconformably on Cambrian strata, mostly with a huge stratigraphic gap, and represent a sedimentary succession that developed after protracted tectonic deformation finished in the early late Furongian (see Trela et al., 2025; and references therein). This time-specific Lower Ordovician facies is also widespread across SE Poland (Tomczyk, 1962; Moryc and Nehring-Lefeld, 1997; Maksym et al., 2003) and the Polish segment of the East European Platform (Modliński, 1968, 1973, 1982; Szymański, 1973, 1984; Modliński and Szymański, 1997, 2005, 2008; Porębski and Podhalańska, 2019; Trela, 2022; references therein). Thus, the occurrence of the upper Tremadocian to Floian glauconite-bearing siliciclastic deposits in SE Poland (including the southern HCM) and the East European Platform appears to be a lithofacies proxy for their palaeogeographic proximity during this time, reflecting comparable sedimentary conditions and the influence of the same eustatic events.

To date, the stratigraphic and facies architectures of the Lower Ordovician siliciclastic succession in the HCM and SE Poland remain insufficiently recognised, particularly concerning the glauconite-bearing unit. This paper presents the results of sedimentological studies focusing on sedimentary processes and facies distribution of the Lower Ordovician siliciclastics in the southern HCM, and their relationship to eustatic changes reported in Baltica (see Nielsen, 2004). Furthermore, this is the first study providing insight into the temporal and spatial distribution of Early Ordovician facies associations and sedimentary environments in SE Poland.

Previous studies of the Lower Ordovician deposits in the southern HCM have primarily focused on palaeontology, stratigraphy, petrology and general tectonic aspects (Kozłowski, 1948; Tomczyk, 1954; Turnau-Morawska, 1958, 1961; Starmach, 1963; Bednarczyk, 1964, 1966, 1971, 1988, 1999; Bednarczyk et al., 1966; Chlebowski, 1971; Znosko and Chle-

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bowski, 1976; Szaniawski, 1980; Bednarczyk and Stupnicka, 2000; Holmer and Biernat, 2000). Preliminary approaches to the lithofacies and sedimentological issues of chert-bearing upper Tremadocian glauconitic mudstones and to Early Ordovician sedimentary environments were provided by Bednarczyk (1966), Chlebowski (1971) and Trela (2001). The mineralogical composition of upper Tremadocian mudstones, cherts, and conglomerates was studied by Turnau-Morawska (1958, 1960) and Chlebowski (1971).

GENERAL BACKGROUND

GEOLOGICAL SETTING AND PALAEOGEOGRAPHY

The HCM is a unique place on the geological map of Central Europe where two tectonic units of the Trans-European Suture Zone meet: the Małopolska Block in the south, and the Łysogóry Block in the north, separated by the Holy Cross Fault (Fig. 1). However, Żelaźniewicz et al. (2011, 2020) place the northern boundary of the Małopolska Block on the Chmielnik-Ryszkowa Wola Tectonic Zone, south of the HCM (Fig. 1). The geotectonic origin of these tectonic units has been debated for more than four decades, focusing on their relationship with either Baltica or Gondwana (Pożaryski, 1990; Lewandowski, 1993; Dadlez et al., 1994; Pharaoh, 1999; Malinowski et al., 2005, 2013, 2015; Nawrocki et al., 2007; Narkiewicz et al., 2011; Narkiewicz and Petecki, 2017; Walczak and Belka, 2017; Callegari et al., 2025; and references therein). Studies of detrital mica and zircon ages indicate that during the Cambrian, the HCM received detrital material from peri-Gondwanan fragments of the Cadomian orogen and Mesoproterozoic sources on Baltica (Belka et al., 2000, 2002; Nawrocki et al., 2007; Żelaźniewicz et al., 2020). According to Callegari et al. (2025), detrital zircons in the Cambrian strata of the HCM were derived from a continental arc developed along the Baltica margin that was an equivalent of the Cadomian Arc on the opposite side of the Mirovoi Ocean.

The Małopolska Block is regarded either as a proximal terrane of Baltica that was accreted to this palaeocontinent in the late Silurian to earliest Devonian (Dadlez et al., 1994) or even in the late Carboniferous (Lewandowski, 1993), or as an exotic terrane derived from the peri-Gondwanan Cadomian belt that collided with Baltica in the Furongian (late Cambrian; e.g., Belka et al., 2002; Walczak and Belka, 2017) or in the Early Devonian (e.g., Narkiewicz et al., 2011; Narkiewicz and Petecki, 2017). Deep seismic sounding experiments suggest the similarity of the crustal structure between the Małopolska Block and the East European Platform (Malinowski et al., 2005). In contrast, deep reflection seismic profiles in SE Poland reveal an Avalonia-type crust suggesting peri-Gondwanan affinity (Malinowski et al., 2013, 2015). According to Mazur et al. (2017), in SE Poland the Baltica-type crust extends probably southwest of the Teisseyre-Tornquist Zone, similarly to central and western Poland (Mazur et al., 2015). Cocks (2002) provided palaeontological arguments for the close affinity of the Małopolska Block with Baltica throughout the Early Paleozoic. In addition, palaeomagnetic data indicate that this area was located at its present position in relation to Baltica as early as the late Cambrian (Schätz et al., 2002; Nawrocki et al., 2007).

The Łysogóry Block – including the northern HCM and the Biłgoraj-Narol zone in the east – is interpreted as attenuated cratonic crust of Baltica (Malinowski et al., 2005). Dadlez et al. (1994) treated this tectonic unit as part of Baltica's passive margin. It is now considered as Baltica's proximal terrane (Narkiewicz and Petecki, 2017 and references therein), which is consistent with palaeomagnetic data (Nawrocki et al., 2007).

LOWER ORDOVICIAN STRATIGRAPHY IN THE HCM

The Lower Ordovician in the southern HCM consists of a glauconite-bearing siliciclastic sedimentary succession that unconformably overlies lower Cambrian strata (Czarnocki, 1939; Kozłowski, 1948; Tomczyk, 1962; Bednarczyk, 1966; Znosko and Chlebowski, 1976; Dadlez et al., 1994); however, in the eastern HCM it rests on upper Furongian deposits (Trela et al., 2025). This succession has been subdivided into five lithostratigraphic units showing significant lithological variability (see Trela, 2006).

The oldest part of the Lower Ordovician in the southern HCM is represented by thin- to medium-bedded glauconitic mudstones interbedded with bedded and nodular cherts, as well as siltstones/sandstones, which together form the Wysoczki Mudstone and Chalcedonite Formation (Fig. 2). This unit typically ranges in thickness from a few to about ten metres, locally reaching 30 m, and occurs mainly in the central part of study area, particularly within the Bardo syncline (Fig. 1). Conodont data indicate that the Wysoczki Formation corresponds to the upper Tremadocian *deltifer* Biozone (Szaniawski, 1980; Dzik and Pisera, 1994). Kozłowski (1948) described the graptolite fauna from chalcedony beds of the Wysoczki Formation which he considered to be younger than the early Tremadocian assemblage (see also Tomczyk, 1962). The age of this lithostratigraphic unit is further constrained by numerous lingulate brachiopods of the *Leptembolon-Thysanotos* assemblage including *Thysanotos siluricus* (Bednarczyk, 1964, 1971), *Eurytreta minor*, *Mamatia retracta*, *Siphonotretella popovi*, *Orbithele ceratopygarum* and *Leptembolon* cf. *lingulaeformis* (Holmer and Biernat, 2002). Bednarczyk (1999) and Mergl (2002) postulated that planktotrophic larvae of these lingulate brachiopods (*Leptembolon-Thysanotos* assemblage) could have been dispersed via oceanic gyres during the late Tremadocian to early Floian, migrating from Bohemia through the Małopolska Block to the Baltica margin. The Wysoczki Formation has also yielded numerous acritarch specimens, considered a reference assemblage for the late Tremadocian microphytoplankton (Górka, 1969; Szczepanik, 2003).

In the western and eastern localities, the upper Tremadocian succession is dominated by the Międzygórz Sandstone Formation, which locally rests on a conglomerate bed (5–40 cm thick) forming the Kędziorka Formation (Fig. 2). The stratigraphic position of the Międzygórz Formation is based on the presence of the brachiopod *Thysanotos siluricus* (Bednarczyk, 1964, 1971), however, other brachiopod taxa, like *Rosobolus robertinus*, *Celdobolus* and *Pidiobolus* cf. *minimus* indicate that the stratigraphic range of this unit may extend into the lower Floian (Bednarczyk and Stupnicka, 2000). In the east, the glauconitic sandstones of the Międzygórz Formation are interbedded with distinctive glauconitic conglomerates informally named the Chełm Conglomerate Member (Fig. 2) by Bednarczyk (1981). Mudstone clasts within these conglomerates have yielded chitinozoan taxa such as *Cyathochitina primitiva* (=*Euconochitina primitiva*) and *Lagenochitina* cf. *esthonica* (Chlebowski and Szaniawski, 1974), and graptolite fragments resembling *Dictyonema* species (see Znosko and Chlebowski, 1976), while thin mudstone intercalations contain acritarchs indicative of the late Tremadocian and early Floian (Szczepanik, personal information). In the Bardo syncline, the Międzygórz Formation appears to rest conformably above the Wysoczki Formation forming an interval no thicker than 3 m (e.g., Zalesie, see Czarnocki, 1919). In other localities of the southern HCM – such as Bukówka, Brzeziny-Zbrza, Szumsko and Lenarczyce (Fig. 1) – the total thickness of the Międzygórz Formation varies between 1 and 5 m, in contrast to the 20–30 m-thick successions present in the Międzygórz and

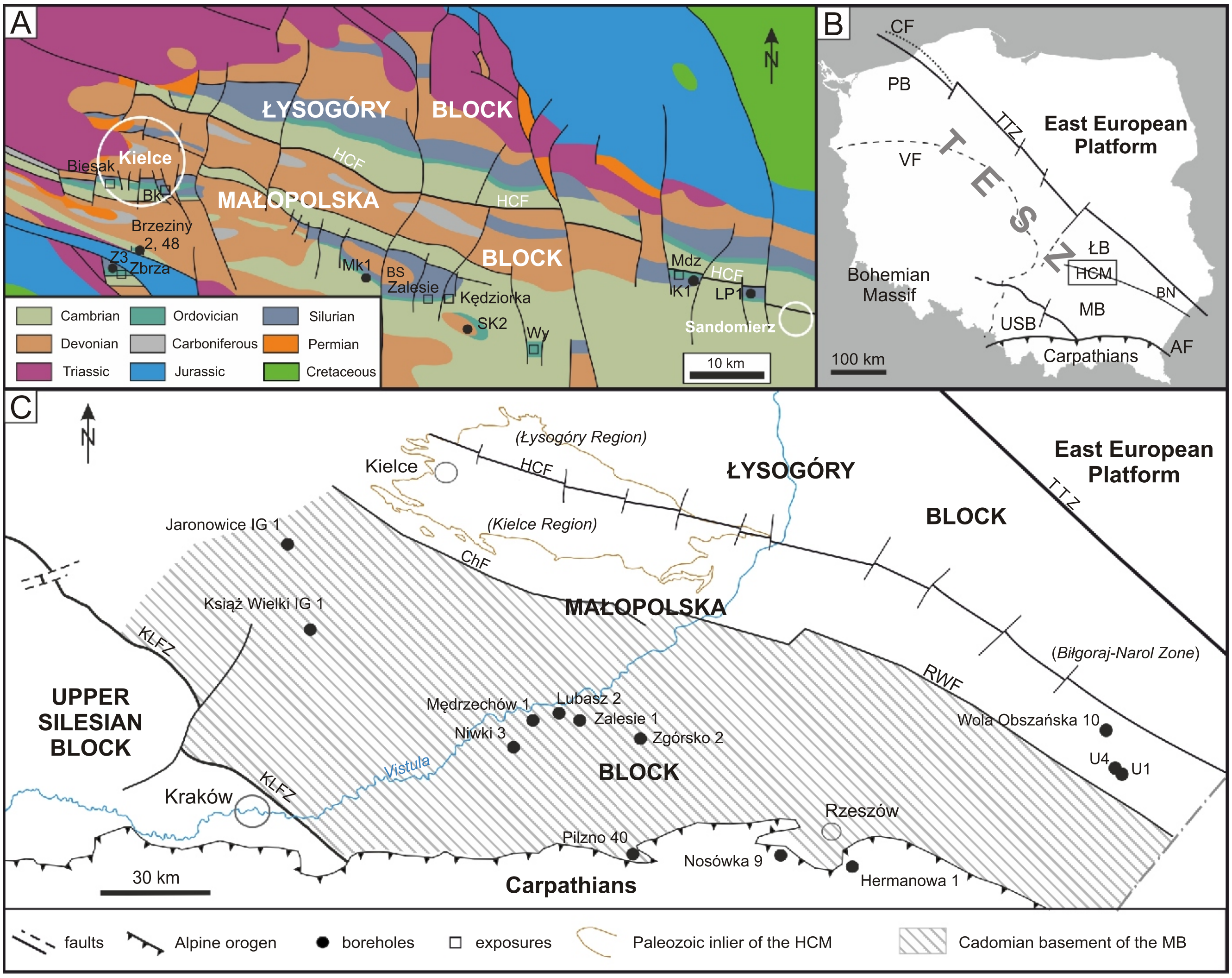

Fig. 1A – simplified map of the HCM (after the Geological Map of Poland at 1:1 000 000 scale; https://geologia.pgi.gov.pl/mapy/; Cenozoic deposits not included) showing the location of the sections studied; B – the main tectonic units of Poland beneath the Permian-Mesozoic and Cenozoic cover (after Pożaryski, 1990; Dadlez et al., 1994), rectangle – the HCM; C – location of boreholes penetrating the Lower Ordovician facies on the Małopolska Block

AF – Alpine front; BN – Biłgoraj-Narol Zone; Bk – Bukówka; BS – the Bardo Syncline; ChF – Chmielnik Fault; CF – Caledonian Front; HCF – Holy Cross Fault; K1 – Kleczanów 1 borehole; KLFZ – Kraków-Lubliniec Fault Zone; MB – Małopolska Block; MK1 – Mokradle 1 borehole; Mdz – Międzygórz; LP1 – Lenarczyce PIG 1 borehole; ŁB – Łysogóry Block; PB – Pomeranian Block; RWF – Ryszkowa Wola Fault; SK2 – Szumsko Kolonia 2 borehole; TESZ – Trans-European Suture Zone; TTZ – Teisseyre-Tornquist Zone; U1 – Uszkowce 1 borehole; U4 – Uszkowce 4 borehole; USB – Upper Silesian Block; VF – Variscan Front; Wy – Wysoki (Wysoczki); Z3 – Zbrza PIG 3 borehole

Biesak quarries, that are in the eastern and western HCM (Tomczyk, 1954, 1962; Bednarczyk, 1964; Bednarczyk et al., 1970; Bednarczyk and Stupnicka, 2000).

In the southwestern HCM (Brzeziny), the upper Tremadocian Międzygórz Formation grades upwards into lower Floian chamosite-rich glauconitic sandstones with mudstone intercalations of the Stokowa Hill Sandstone Formation (up to 15 m thick; Fig. 2). Tomczyk and Turnau-Morawska (1964) named them 'the chamositic horizon' and assigned them to the Middle Ordovician *murchisoni* graptolite Biozone, though no palaeontological evidence supports this stratigraphic classification. Notably, the chamosite-rich clastic deposits described by these authors in the Brzeziny 2 borehole are steeply dipping and occur on both sides of a small syncline documented by Mieczysławski (1962; and illustrated by Znosko, 2001), and corroborated by field data from a manmade trench (Trela, personal observations; sea also Trela, 2006).

These chamosite-rich sandstones and mudstones grade upwards (in the Brzeziny 2 borehole) into grey and greenish clayey mudstones and shales of the Brzeziny Mudstone Formation, reaching up to 40 m in thickness (Fig. 2; Trela, 2006). These deposits form the axial fill of a small syncline (Mieczysławski, 1962; Znosko, 2001). Their stratigraphic position has been determined based on a graptolite assemblage (Tomczyk and Turnau-Morawska, 1964) indicative of the lower/middle Floian – Dapingian (or even the lower Darriwilian) stratigraphic interval (Trela, 2022).

The Lower Ordovician in the northern (Łysogóry) part of the HCM is characterised by the Brzezinki Mudstone Formation (Fig. 2), which spans from the late Furongian to the upper Tremadocian (Trela, 2006; Trela et al., 2025). The age control of this succession is based on Furongian trilobite taxa (see Trela et al., 2005) and graptolite fragments of lower Tremadocian *Dictyonema* species (Tomczyk and Turnau-Morawska,

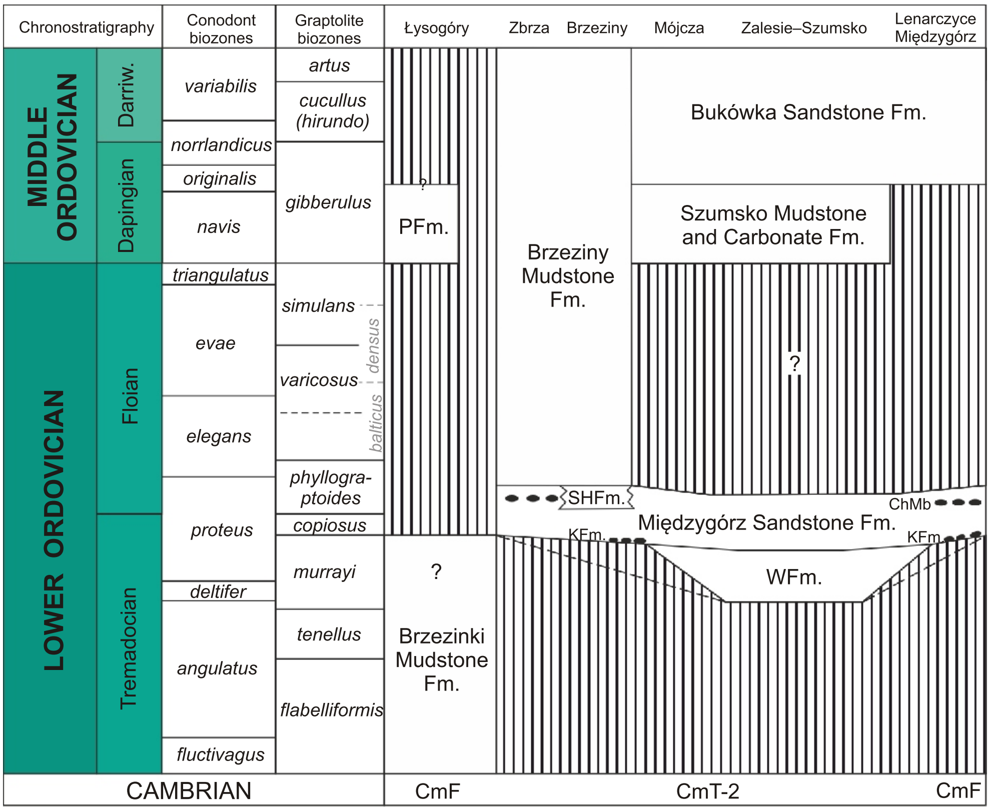

Fig. 2. Lithostratigraphy of the Lower-Middle Ordovician in the Holy Cross Mountains (after Trela, 2006; conodont and graptolite biozones after Cooper and Sadler, 2012)

ChMb – Chełm Conglomerate Member, CmF – Cambrian, upper Furongian, CmT-2 – Cambrian, Terreneuvian-Series 2, KFm. – Kędziorka Conglomerate Formation, PFm. – Pobroszyn Limestone Formation, SHFm. – Stokowa Hill Chamositic Sandstone Formation, WFm. – Wysoczki Mudstone and Chalcedonite Formation; dashed lines mark the possible lower stratigraphic extent of the Kędziorka and Międzygórz formations

1967). However, the occurrence of graptolite fragments resembling *Bryograptus* sp. (Tomczykowa, 1968) suggests that the upper stratigraphic range of the Brzezinki Formation extends into the upper Tremadocian, further supported by acritarch data (Trela et al., 2001). The upper boundary of this unit is marked by a discontinuity with a significant stratigraphic gap that includes the entire Floian Stage (Trela, 2022, and references therein).

LOWER ORDOVICIAN GLAUCONITIC UNIT IN THE EAST EUROPEAN PLATFORM – A BRIEF SYNTHESIS

The Lower Ordovician glauconitic facies in the East European Platform forms a diachronous horizon no more than 2 m thick, spanning the lower to upper Floian (Fig. 3; Modliński, 1968, 1973, 1982; Szymański, 1973, 1984; Modliński and Szymański, 1997, 2008; Kędzior et al., 2017; Skompski and Paszkowski, 2017; Porębski and Podhalańska, 2019; and references therein). It usually rests on middle Cambrian strata, but at some locations occurs above upper Cambrian (Furongian) or lower Tremadocian deposits (Fig. 3).

This distinctive interval comprises variable lithologies, including greyish- and reddish-green fine to coarse-grained glauconitic sandstones, carbonaceous glauconitic sandstones and mudstones, and subordinate thin limestone interbeds containing brachiopod, trilobite and ostracod fossils (Szymański, 1973, 1984; Kędzior et al., 2017; Skompski and Paszkowski, 2017). Locally, these deposits are replaced or underlain by thin conglomerate or breccia beds, up to 10–30 cm thick, composed of sandstone/siltstone, phosphorite and mudstone clasts up to 3 cm in diameter. Skompski and Paszkowski (2017) described, within the glauconitic interval, characteristic columnar calcite crystals, interpreted as marine phreatic palisade cements formed during the early transgressive phase. According to Kędzior et al. (2017), some clasts within this facies were derived from initial palaeosols (ferricretes and silcretes).

In the Podlasie area, the glauconitic sandstone and conglomerate lag deposits are distinguished as the Rajsk Formation (Fig. 3; Modliński and Szymański, 2008). In the Baltic area, they form the basal part of the Słuchowo Mudstone Formation in the west and the Pieszkowo Limestone Formation in the east (Modliński and Szymański, 1997). However, given its lithological characteristic, the glauconitic horizon across the entire East European Platform is assigned in this paper to the Rajsk Formation (Fig. 3). The age control of this interval in Podlasie is based on the brachiopods *Acrothele (=Orbithele) ceratopygarum* and *Lingulella.* cf. *insons* as well as the graptolites *Didymograptus deflexus* and *D.* cf. *extensus* identified from mudstone intercalations in the upper part of this unit (Znosko, 1964; Modliński, 1968; Szymański, 1973, 1984; Modliński and Szymański, 2008). These brachiopods are reported from upper Tremadocian and lower Floian strata (Popov and Holmer, 1994; Holmer and Biernat, 2002), while the graptolite specimens are indicative of the lower-middle Floian. Grey to greenish mudstones of the Słuchowo Formation (3–20 m thick) above the basal glauconitic sandstone bed are dated by graptolites of the Floian *phyllograptoides*, *balticus*, *densus* and *elongatus* biozones (Modliński and Szymański, 1997; Podhalańska, 2019). This

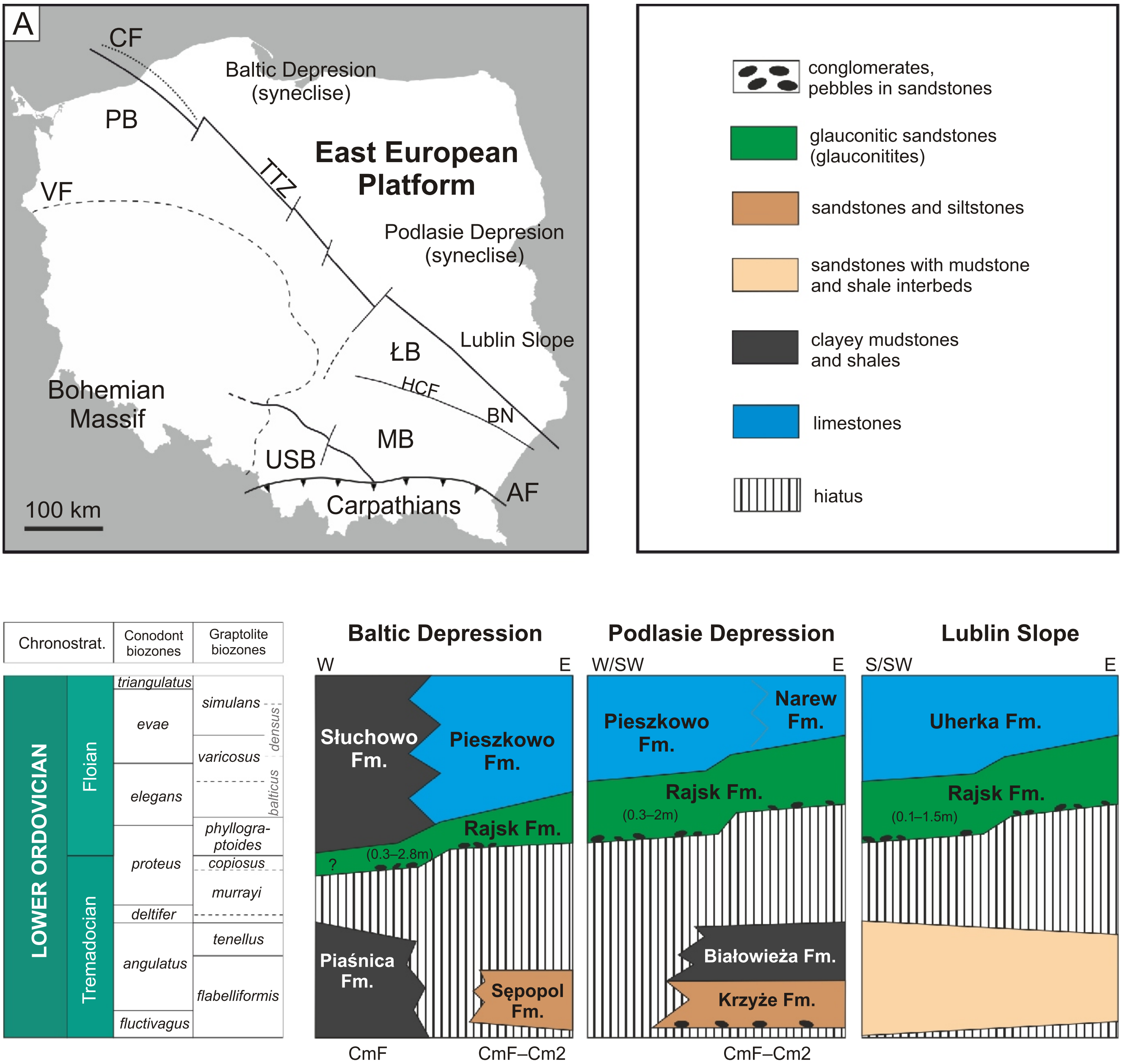

Fig. 3. Lithostratigraphy of the Lower Ordovician and distribution of the glauconitic unit on the East European Platform (after Modliński and Szymański, 1997, 2008; Porębski and Podhalańska, 2019; modified)

Abbreviations as on Figures 1 and 2

stratigraphic position indicates that the basal glauconitic sandstone in the western Baltic area corresponds to the lowermost Floian, while the basal conglomerate preserved in some locations may be even related to the uppermost Tremadocian. The glauconitic horizon in NE Poland (the Baltic Depression) has yielded a mixed conodont assemblage consisting of late Tremadocian and Floian taxa assigned to the *elegans* conodont Biozone (Bednarczyk, 1979). Moreover, the co-occurrence of Tremadocian and Floian conodonts in the glauconitic unit of the Podlasie area was documented by Nehring-Lefeld (1987), who interpreted them as representatives of the upper *proteus* Biozone. Bednarczyk (1985) reached a similar conclusion based on conodonts from carbonate intercalations in the glauconitic sandstones of the Lublin region. These biostratigraphic data indicate that the upper stratigraphic extent of the Rajsk Formation in the eastern locations reaches up to the *densus* graptolite Biozone (probably its middle part = the middle *evae* conodont Biozone; Fig. 3).

MATERIALS AND METHODS

Sedimentological studies were conducted at exposures located in Zalesie, Międzygórz, Biesak and in a trench at Brzeziny, as well as on the Zbrza PIG 3, Szumsko Kolonia 2 and Lenarczyce PIG 1 borehole cores (Fig. 1). Additionally, the study included Lower Ordovician strata from borehole cores located on the south and eastern Małopolska Block, namely the Hermanowa 1, Nosówka 9 and Wola Obszańska 10 boreholes (Fig. 1).

Sedimentological observations of each sample included the general lithology, primary stratification and preserved sedimentary, biogenic end erosional structures. The sedimentological observations were supplemented by analysis of 40 thin sections using standard petrographic techniques performed with a *Nikon Eclipse LV100POL* polarizing microscope to identify petrographic and microfabric features of the rock samples.

RESULTS – FACIES CHARACTERISTICS AND THEIR TEMPORAL-SPATIAL DISTRIBUTION

THE SOUTHERN HCM

The Lower Ordovician sedimentary facies in the southern HCM are characterised below in relation to the lithostratigraphic units and their regional distribution, to illustrate the stratigraphic and spatial variability of the facies architecture.

THE WYSOCZKI FORMATION

The facies association of the Wysoczki Formation is predominantly composed of bioturbated and massive tuffitic mudstones, intercalated with bedded and nodular cherts (chalcedony beds/nodules in Polish geological literature). Subordinate lithologies include siltstone and sandstone interbeds, as well as some beds showing composite characteristics, marked by the co-occurrence of deformed mudstones, sandstones and cherts (Fig. 4A–H).

The tuffitic mudstone beds are greenish-grey to green, and commonly show dark grey biodeformational structures of "mantle and swirl" type (Fig. 4A, B) as described by Lobza and Schieber (1999). Some beds are massive or display plastic deformation associated with the presence of coarse-grained material or chert nodules. Their lower boundaries are commonly deformed by load casts. In places, quartz and glauconite grains as well as tiny mudstone and chert clasts 'float' in a muddy groundmass. Distinctive components of the tuffitic mudstones are quartz grains, well-preserved plagioclases (orthoclases and albites), K-feldspars, unaltered biotite and muscovite (Chlebowski, 1971; Salwa and Trela, 2019). In some cases, fine detrital material in the mudstone beds shows microscale normal grading (Fig. 5 A, B). The matrix is usually composed of siliceous mud enriched in montmorillonite, with minor admixture of Fe-oxyhydroxides and phosphates (Turnau-Morawska, 1958, Chlebowski, 1971). Quartz forms monocrystalline and angular silt grains (Fig. 5C – pyrogenic quartz in Chlebowski, 1971), or weakly rounded polycrystalline granules of magmatic origin (Salwa and Trela, 2019).

The chert beds are generally massive with tiny glauconitic mudstone clasts scattered in places (Fig. 4F, G); however, locally they display discrete lamination enhanced by glauconite-rich laminae. They consist of cryptocrystalline quartz, finely crystalline mosaic microquartz and spherulitic chalcedony (Fig. 5D). A notable feature of the cherts is locally preserved siliceous clay patches with relicts of tuffitic mud (Fig. 5E, F) resembling devitrified volcanic ash. Detrital grains dispersed in the siliceous background include phosphate lingulate shell and graptolite fragments, glauconite and angular quartz grains, mica flakes, as well as subordinate ferruginous and phosphate granules (less than 100 μm), and clay lumps up to 50 μm in diameter (presumably relicts of volcanic ash). Furthermore, Turnau-Morawska (1958) and Chlebowski (1971) reported the presence of sponge spicules preserved within the chert beds.

Siltstones and sandstones are typically very fine- to fine-grained (in places even medium-grained), respectively, thin- to medium-bedded (5 to 15 cm) with sharp and erosive bases, and groove casts or tool marks locally preserved. They occur either as massive layers or as parallel to undulose-laminated beds, the latter locally exhibiting grain size variation between laminae and by an upwards coarsening trend (Fig. 4C, D). In places, internal erosional surfaces, subordinate ripple/flaser lamination, and burrows resembling dwelling structures filled with siliceous mud (or silica) are also present (Trela, 2001; and Plate I, fig. 5 therein). In addition, tiny current ripples occur at the tops of some sandstone and siltstone beds, and rare biogenic escape structures have also been reported (Trela, 2001; and Plate I, fig. 6; Plate III, fig. 3 therein). Sandstones, referred to as quartz arenites and wackes (Fig. 5A, B), are enriched in glauconite grains (0.02–0.1 mm) forming usually 5–10% of the mineral framework, though in some samples they may range up to 15–20% (Turnau-Morawska, 1958; Chlebowski, 1971). Besides occurring as grains, the glauconite phase can occur as irregular pore fillings and glauconitised biotites.

Beds with composite characteristics display soft-sediment deformation obscuring primary sedimentary structures (Fig. 4G, H). Some are liquefied or brecciated and contain various admixtures of small clasts.

In Zalesie, the Wysoczki Formation is a thin- to medium-bedded succession (~ 5.0 m thick; Figs. 6 and 7A) with thin pebbly sandstone at the base. In addition, this succession is exposed in numerous localities of the Bardo syncline (e.g. in the Choiny ravine at Kędziorka; Czarnocki, 1919, 1939; Bednarczyk, 1964, 1966; Chlebowski, 1971) as well as farther to the east in Wysoki (Wysoczki in Kozłowski, 1948; Figs. 1 and 7B).

Interpretation. This facies association indicates deposition of fairweather mud from suspension settlement, periodically interrupted by high-energy events introducing coarse-grained clastic sediment; however, some mudstones with tiny clasts seem to have originated from mudflows. The low-energy periods favoured colonization of the sediment by infaunal deposit feeders that destroyed primary sedimentary structures. The laminated sandstones are a sedimentary record of tractional transport in the upper flow regime (Harms et al., 1975), while the massive siltstone beds can be attributed to fallout from turbulent suspension (see Lowe, 1988). In addition, rapid depositional events are indicated by biogenic escape structures and load/slump structures resulting from soft-sediment instability, although internal deformation of beds can be also triggered by local seismic activity. Semi-consolidated silica and siliceous mud was subjected to reworking and winnowing by currents/flows.

THE KĘDZIORKA FORMATION

This lithostratigraphic unit is composed of clast-supported conglomerate forming a bed up to 40 cm thick with a slightly erosional base, which grades upwards into massive glauconitic sandstones (Fig. 8A). The conglomerate consists of poorly sorted, ellipsoidal and rounded pebbles ranging from 0.5 to 5 cm in length (Fig. 8A). The pebbles are composed of fine-grained sandstones with a phosphate or siliceous matrix, glauconitic siltstones and fine-grained sandstones, which are accompanied by well-rounded quartz grains (~0.5 cm in diameter; Fig. 8B, C). These are embedded within a poorly sorted, medium- to coarse-grained glauconitic sandstone matrix (Fig. 8B, C).

A typical conglomerate bed of the Kędziorka Formation occurs in the Lenarczyce PIG 1 borehole, were it marks the base of the Lower Ordovician succession above an erosional unconformity with the upper Furongian strata (Fig. 8A; Trela et al., 2025). A similar basal conglomerate lag was also noted in Kędziorka, Zbrza and the Biesak Quarry (Fig. 1), where it ranges from 5 to 30 cm in thickness (Czarnocki, 1939; Bednarczyk, 1964; Bednarczyk et al., 1970).

Interpretation. The conglomerate bed of the Kędziorka Formation is interpreted as a bedload of tractional deposition from storm-generated surges or cohesionless density flows (see

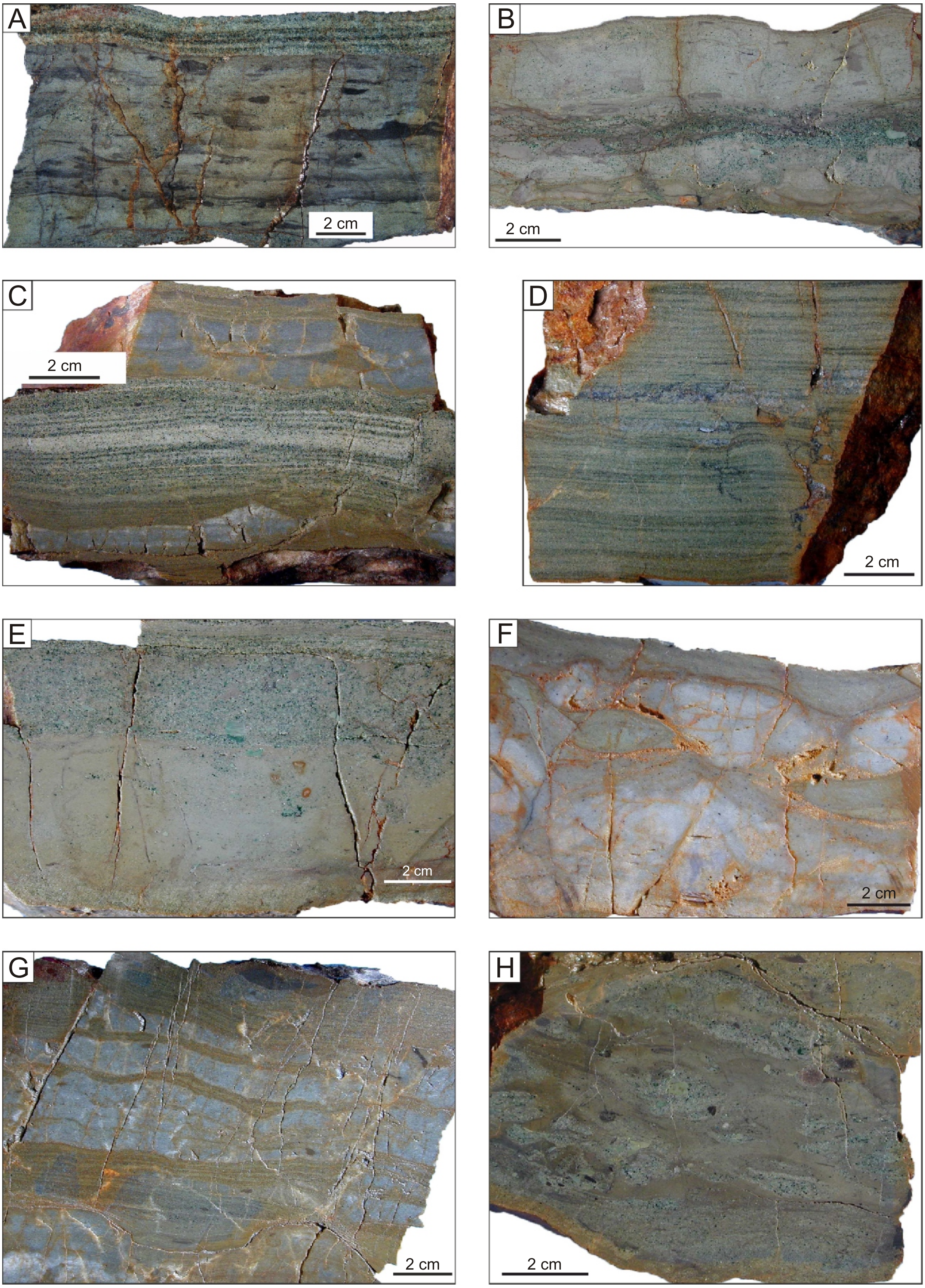

Fig. 4. Facies of the upper Tremadocian Wysoczki Formation from the Zalesie section

A – bioturbated tuffitic mudstones with "mantle and swirl" structures overlain by laminated sandstone; **B** – tuffitic mudstones with initial tiny chert nodules, admixtures of detrital material and sparse bioturbation; **C**, **D** – planar laminated sandstones with chert nodules overlain in C by a thin chert bed; **E** – weakly bioturbated siliceous mudstone overlain by fine-grained glauconitic sandstone with tiny clasts; note loading of detrital material in the mudstone bed; **F** – nodular chert interspersed with tuffitic mudstone; **G** – fine-grained sandstone intercalated with thin chert beds showing undulose bedding; **H** – composite bed composed of tuffitic and siliceous mudstones and sandstones displaying soft-sediment deformation and dispersed tiny clasts

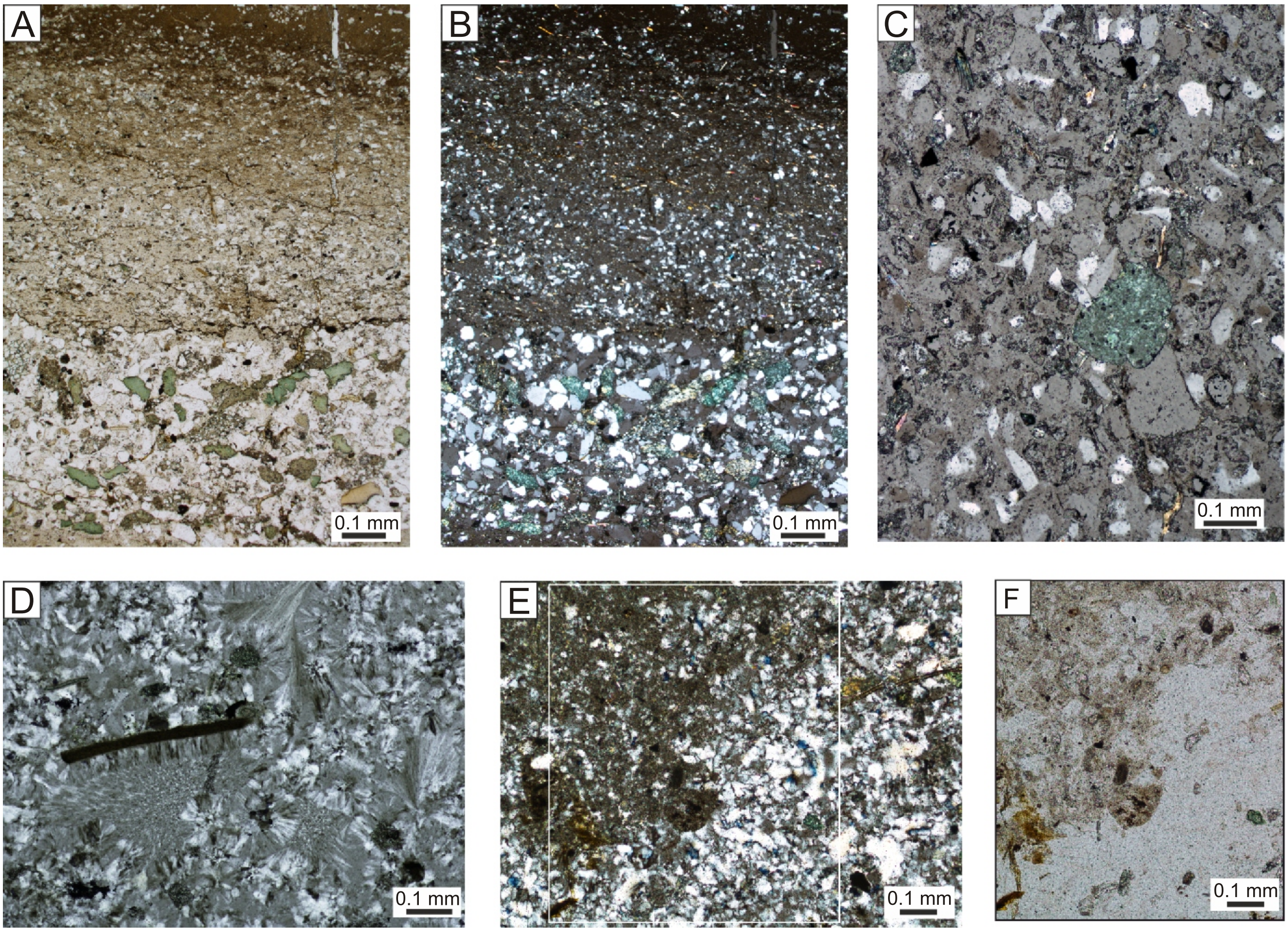

Fig. 5. Photomicrographs of tuffitic mudstones and cherts (chalcedony beds) forming the upper Tremadocian Wysoczki Formation

A, **B** – tuffitic mudstone showing normal grading with phosphatic mudstone at the top, underlain by a sandstone lamina containing glauconite grains (A – PPL, B – XPL); **C** – siliceous tuffitic mudstone with angular quartz grains and remnants of devitrified volcanic ash, XPL; **D** – spherulitic chalcedony and microcrystalline quartz in a chert (chalcedony) bed; note the isopachous chalcedonic overgrowth on a fossil remnant (probably a graptolite), XPL; **E**, **F** – remnant of tuffitic mudstone enclosed within a chalcedonic chert bed (E – XPL; F – PPL, marked by white rectangle on E). All photomicrographs are from samples collected at Zalesie

Walker, 1975; Nemec and Steel, 1984; Gruszczyński et al., 1993; Mulder and Alexander, 2001). Comparable conglomerate lags may be associated with the foreshore gravel produced by wave-ravinement erosion and redeposited by storms onto the shoreface (Siggerud and Steel, 1999; Leszczyński and Nemec, 2015; Larsen et al., 2024).

THE MIĘDZYGÓRZ FORMATION

The facies types of the Międzygórz Formation include structureless (massive) sandstone and, less commonly, parallel-laminated sandstones, accompanied by subordinate pebbly and brecciated sandstones (Fig. 9A–H), which are locally intercalated with thin chert beds. The sandstones are greenish-grey, thin to medium bedded with typically sharp bases, fine- to medium-grained, but locally also coarse-grained. They are quartz arenites with a variable content of glauconite (typically 5 to 15%, and up to 30% in some laminae) forming grains with sizes ranging from 0.03 to 0.1 mm, rarely reaching 0.25 mm, or occurring as irregular infillings in the pore space (Fig. 9I, J). The sandstone succession of the Międzygórz Formation shows a significant variability of sedimentary features and thickness across different locations and therefore two facies associations – designated as FA1 and FA2 – are distinguished within this unit.

FA1 forms a relatively thin unit, usually ranging from 1.0 to 2.5 m in thickness, but locally reaching up to 5 m. This association is largely made up of massive and parallel-laminated sandstones (Fig. 9A–D), in places containing scattered small pebbles. The lamination displays a distinctive alternation of green glauconitic and grey quartz laminae, in places cut by small vertical burrows confined to individual laminae (Fig. 9B). Biogenic escape structures and bioturbation has also been observed in some beds (Fig. 9D). Sandstones of FA1 have been identified in several boreholes – Brzeziny 2, 48, Kleczanów 1, Lenarczyce PIG 1, Szumsko Kolonia 2 (Figs. 1, 8 and 10) and Zbrza 1, 2, 3 (Tomczyk and Turnau-Morawska, 1964, 1967; Deczkowski and Tomczyk, 1969; Trela et al., 2025). In addition, glauconite-bearing sandstones exposed in Zalesie (Czarnocki, 1919, 1928; Bednarczyk, 1966) are also assigned to FA1 in this study. At most locations, FA1 rests unconformably on lower Cambrian strata, except in the Lenarczyce and (?)Kleczanów areas where this facies overlies upper Furongian mudstones across an erosional unconformity (Figs. 2, 8 and 10). In the Brzeziny 2 borehole, glauconitic sandstones of FA1 are overlain by greenish grey mudstones and sandstones (~3.7 m) assigned in this paper to the Stokowa Hill Formation (Fig. 10; Tomczyk and Turnau-Morawska, 1964).

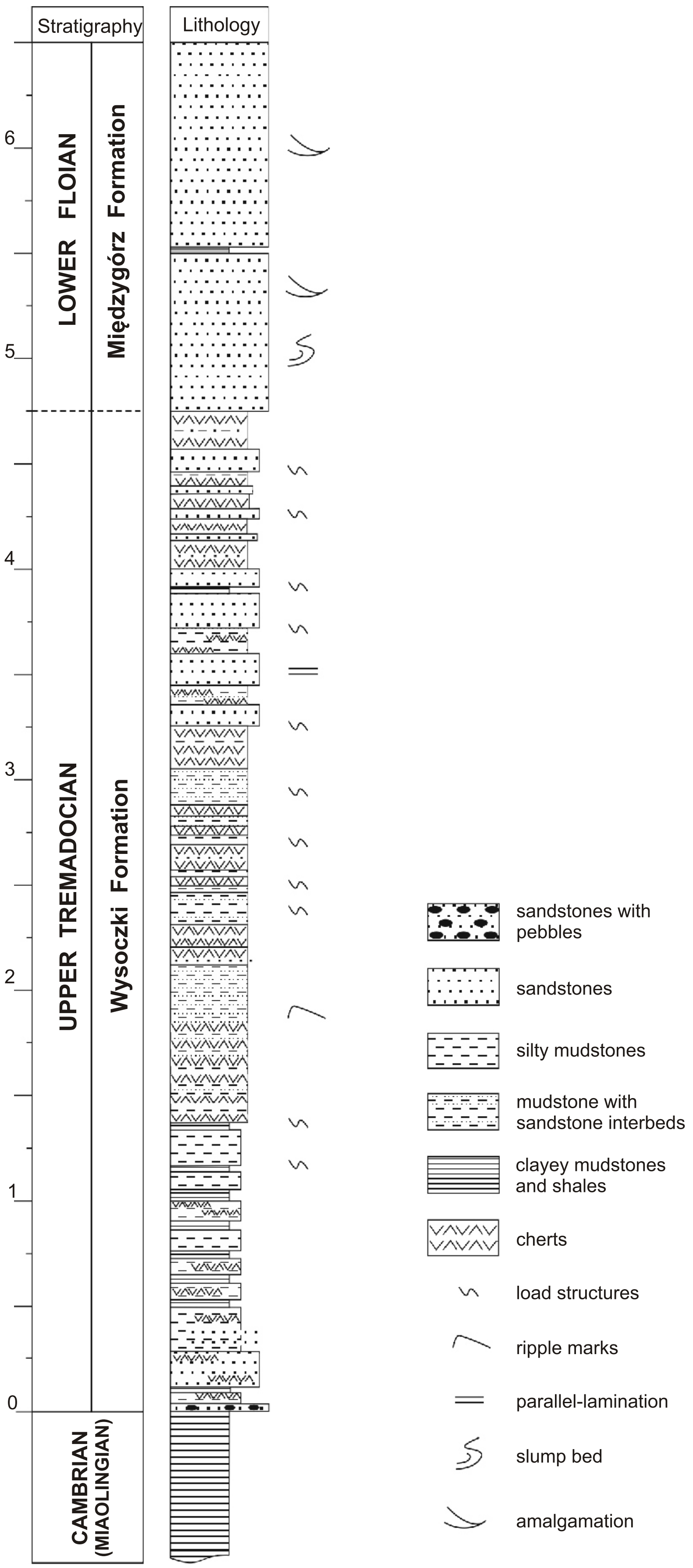

Fig. 6. Stratigraphy and lithology of the upper Tremadocian Wysoczki Formation in Zalesie

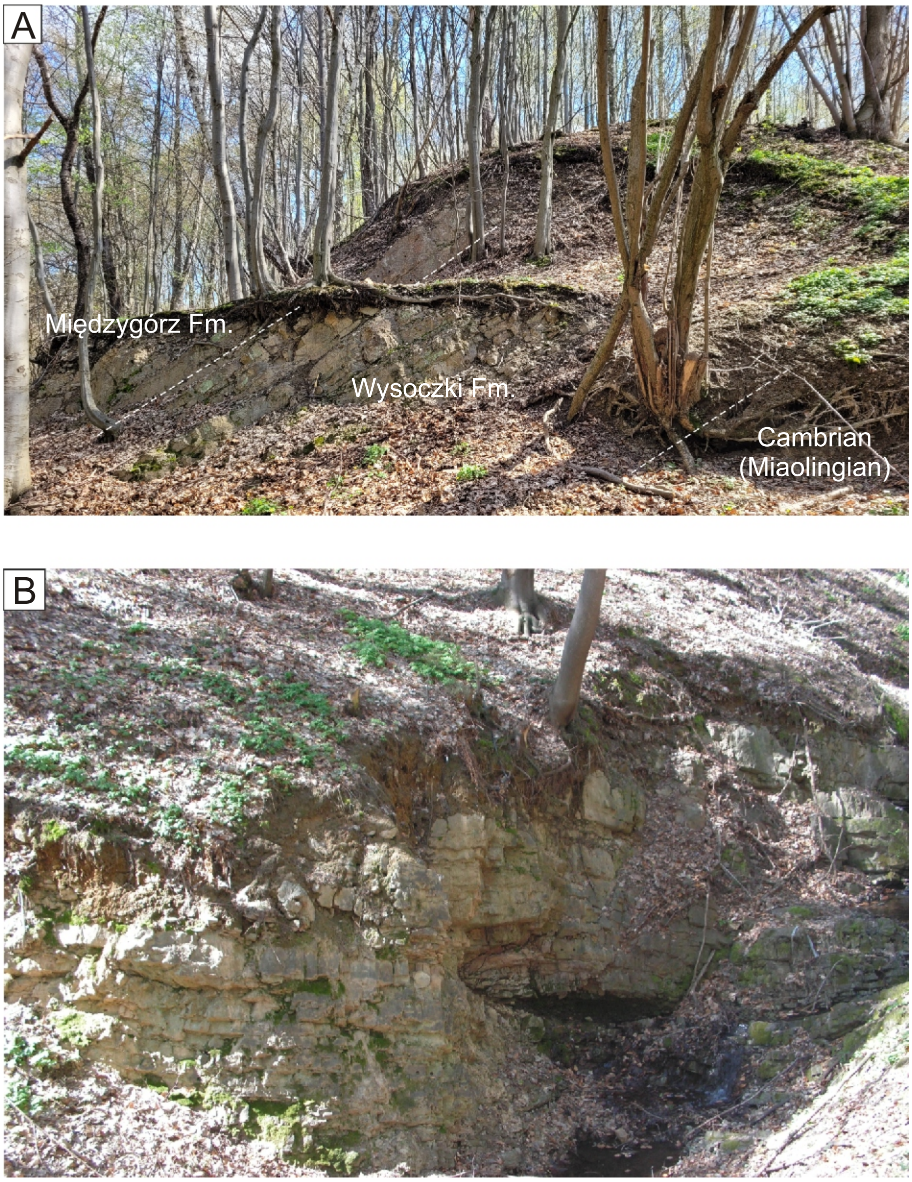

Fig. 7. Natural exposures of the upper Tramdocian Wysoczki Formation in Zalesie (A – the Wysoczki Fm. ~4.5 m thick) and Kędziorka (B – the Chojny ravine, exposure ~4 m)

FA2 forms a sedimentary succession exceeding 20 m in thickness, consisting mostly of massive and pebbly sandstones, locally parallel-laminated, and accompanied by pebbly conglomerates (Fig. 9A, E, F, J, K). These deposits are exposed in the Międzygórz Quarry, located in the Chełm ravine in the eastern HCM (Figs. 1, 11 and 12A; Tomczyk, 1954). Turnau-Morawska (1960) provided their detailed petrographic description, noting 4–9% glauconite grains in the quartz-dominated framework (quartz arenites; Fig. 9J). Bednarczyk and Stupnicka (2000) divided the Międzygórz Formation in the Chełm ravine into six tectonically separated packages (Fig. 11). The sandstones are medium- to thick-bedded with sharp contacts, and in places they are amalgamated (Fig. 12B). The pebbly and massive sandstones also infill scour-and-fill structures (up to 1.0 m wide and 30 cm thick), commonly marked by groove casts or tool marks at the base. Some sandstone beds of FA2 in the upper part of the quarry show normal grading characterised by a transition from a basal conglomerate with outsized pebbles (up to 2–3 cm in diameter) to overlying coarse-grained, structureless sandstones with dispersed small pebbles (Fig. 9E). Notably, small wave ripples and *Skolithos*-like burrows occur at the tops of some sandstone beds (Fig. 9G, H).

The middle portion of the Międzygórz Formation in the Chełm ravine comprises clast-supported conglomerates forming a package up to 5 m thick (the Chełm Member in Bednarczyk, 1981) composed of sharp-based planar to slightly undulose beds, each no more than 20 cm thick (Figs. 11 and 12A). The conglomerate pebbles are oval, slightly rounded to rounded, moderately to poorly sorted, and their length ranges from 0.5 to 5 cm (max. 10 cm; Fig. 9F). In some cases, the larger ellipsoidal pebbles are aligned parallel or inclined to the bedding. Pebble lithologies include fine-grained quartz arenites (with phosphate, ferruginous or siliceous matrix), glauconitic siltstones and subordinate dark mudstones (Fig. 9K), the latter containing fragments of Tremadocian graptolite and chitinozoan fossils (Turnau-Morawska, 1958; Znosko and Chlebowski, 1976). They are accompanied by large and well-rounded quartz grains, up to 0.5 cm in diameter. The conglomerate matrix is composed of fine- to medium-grained sandstones with no more than 6% of glauconite grains (Turnau-Morawska, 1960) and patches of tuffitic mudstone (Znosko and Chlebowski, 1976).

Outside the Chełm ravine, a thick sandstone succession (~30 m) of the Międzygórz Formation occurs in the Biesak Quarry, located in southern Kielce (Fig. 1; Bednarczyk et al.,

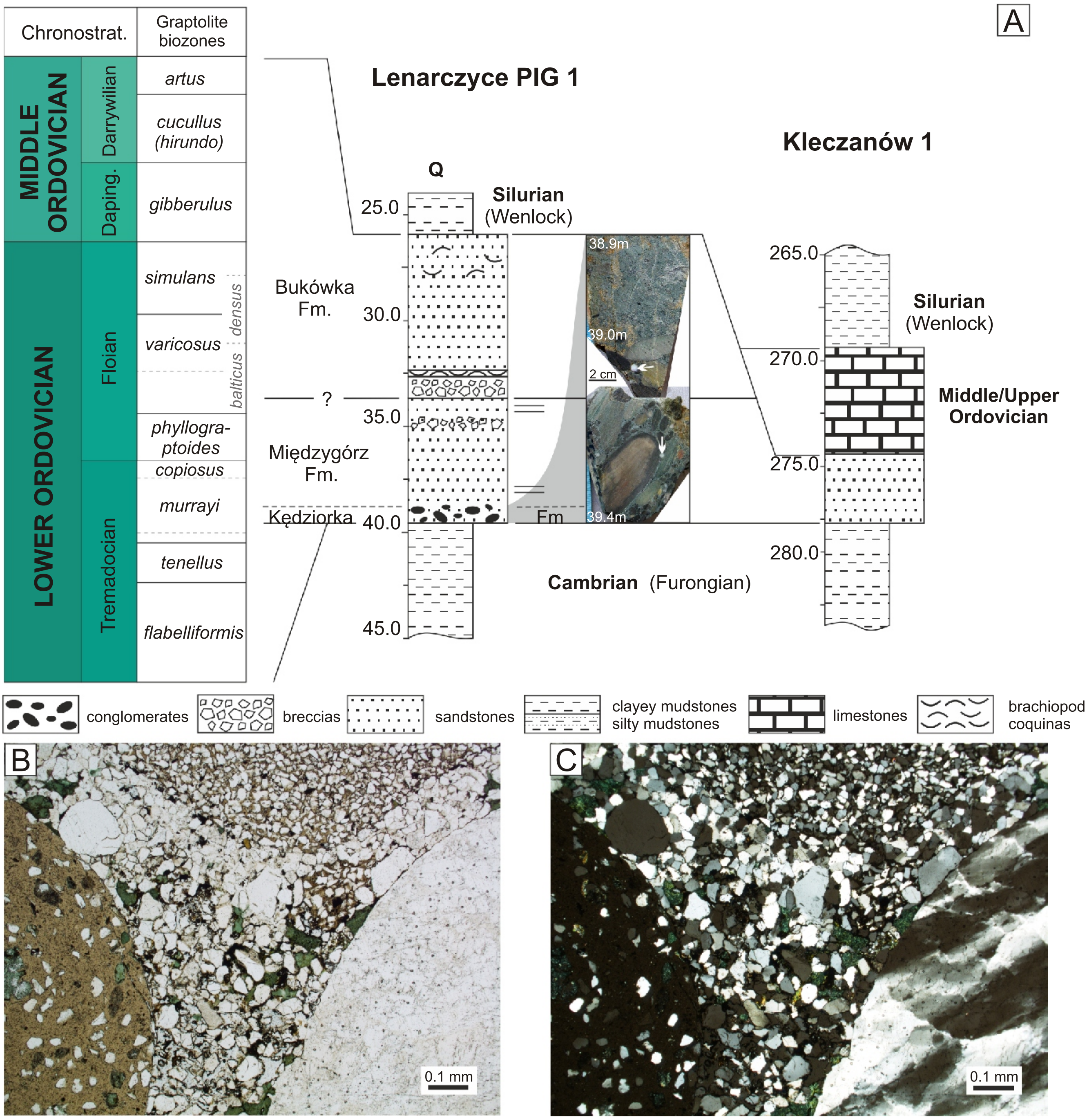

Fig. 8. Stratigraphy and lithology of the Lower Ordovician in the Lenarczyce PIG 1 and Kleczanów 1 boreholes (A). The photos show the transition from conglomerates of the Kędziorka Formation into sandstones of the Międzygórz Formation in the Lenarczyce PIG 1 borehole; note rounded pebbles of (dark) phosphatic and (green) glauconitic sandstones, and large quartz grains (arrows). B, C – photomicrographs of pebbles forming conglomerate of the Kędziorka Formation within a moderately sorted sandstone matrix with glauconite grains; note phosphate mudstone pebble on the left, fine-grained sandstone pebble with phosphate matrix at the top, and large polycrystalline quartz grain on the right (B – PPL; C – XPL)

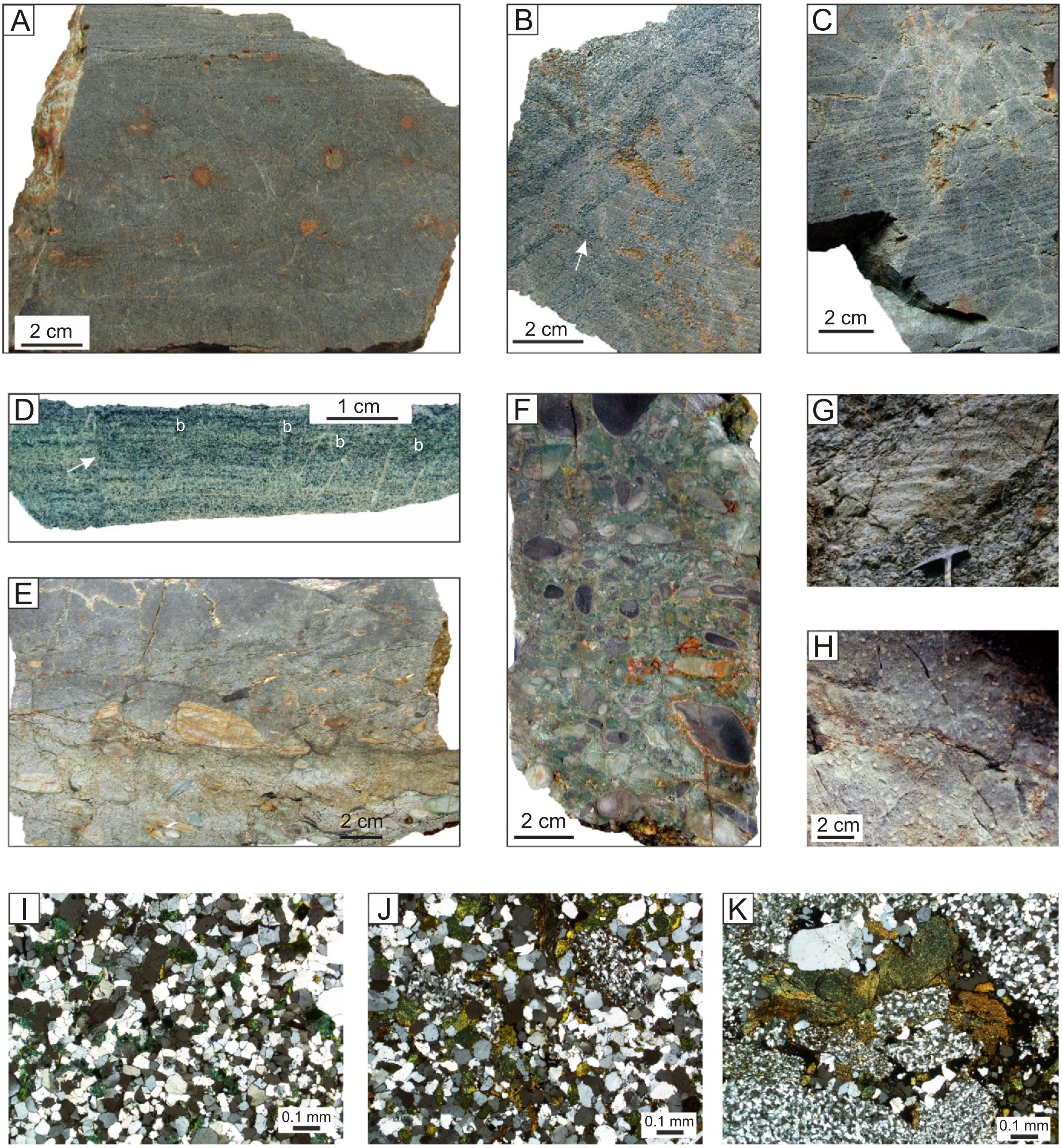

Fig. 9. Upper Tremadocian – lowermost Floian glauconite-bearing sandstones of the Międzygórz Formation

A, **B** – massive beds, in B note the presence of thick glauconite-rich and siliceous laminae interrupted by tiny burrows (arrow), above the massive sandstone; the Międzygórz Quarry (A) and Lenarczyce PIG 1 borehole (B); **C**, **D** – parallel laminated sandstones from the Lenarczyce PIG borehole (C) and Szumsko Kolonia 2 borehole (D; arrow – ?synsedimentary fault, b – bioturbation); **E** – massive sandstone bed with dispersed sandstone pebbles (also glauconite-bearing) in the basal part; note outsized pebble in the central part of the bed; the Międzygórz Quarry; **F** – conglomerate bed of the Chełm Member with well-rounded sandstone pebbles (dark – with phosphatic matrix, green – glauconite-bearing, grey – with siliceous cement); **G** – ripple marks on the top of a sandstone bed from the Międzygórz Quarry; **H** – *Skolithos* burrows on the top of a sandstone bed from the Międzygórz Quarry; **I** – photomicrographs of arenitic sandstone of the Międzygórz Formation from the Lenarczyce PIG 1 borehole showing dispersed glauconite grains (XPL); **J** – glauconite-bearing sandstone with scattered siltstone pebbles from the Międzygórz Quarry; **K** – pebbles in the conglomerate bed of the Chełm Member, including siltstone and fine-grained sandstones, glauconitised mudstone clasts, and a large quartz grain; sample from the Międzygórz Quarry

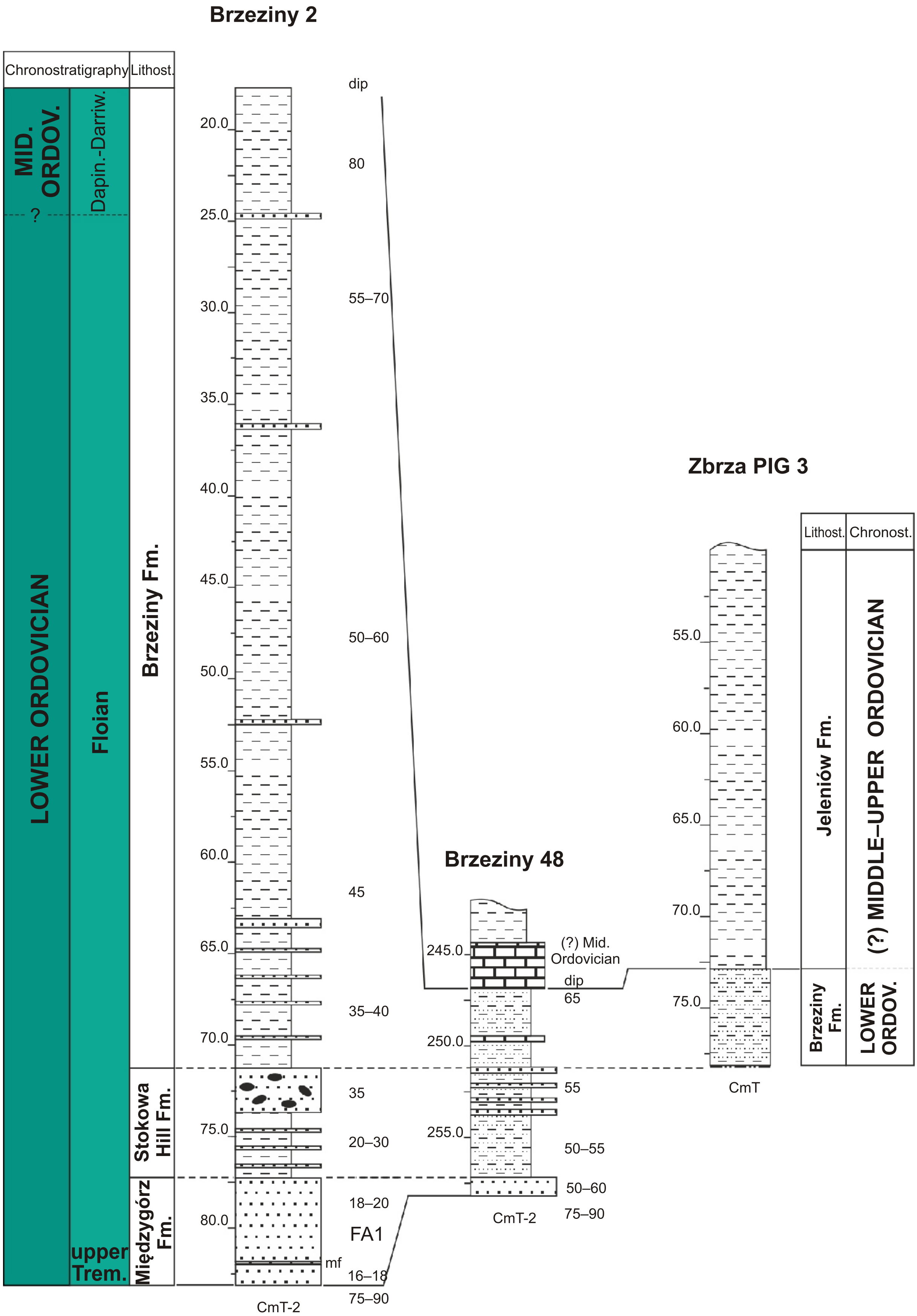

Fig. 10. Stratigraphy and lithology of the Lower Ordovician in the Brzeziny 2, Brzeziny 48 and Zbrza PIG 3 boreholes (lithology of the Brzeziny boreholes reinterpreted after Tomczyk and Turnau-Morawska, 1964)

FA1 – facies association 1; CmT-2 – Cambrian, Terreneuvian – Series 2; lithology as on Figure 8

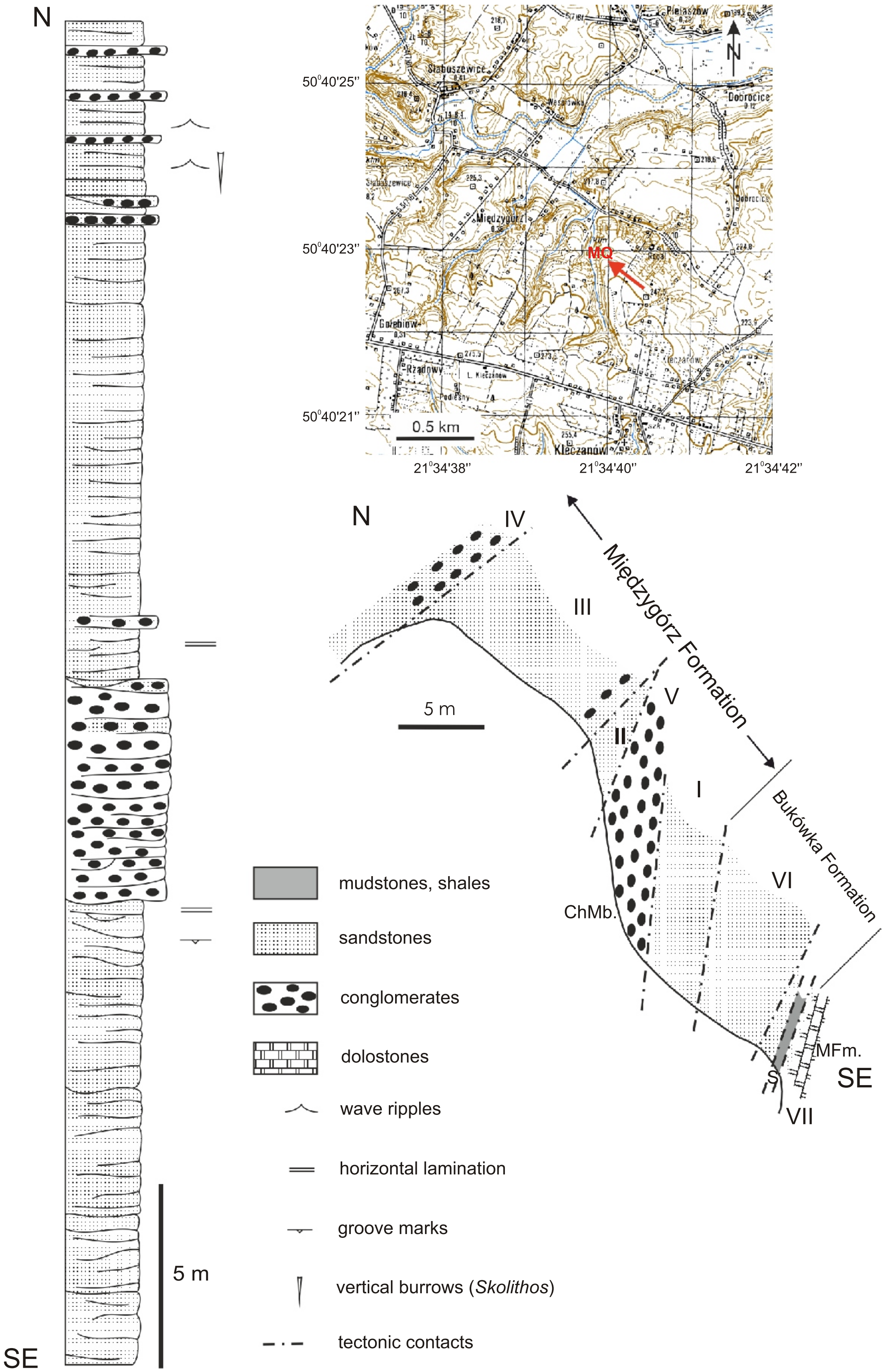

Fig. 11. Lithology of the upper Tremadocian-lower Floian sandstone-conglomerate succession in the Międzygórz Quarry (the Chełm ravine)

General quarry layout and tectonic packages (I–VII) after Bednarczyk and Stupnicka (2000); ChMb. – Chełm Conglomerate Member, MFm. – Mokradle Formation, S – Silurian; MQ – Międzygórz Quarry

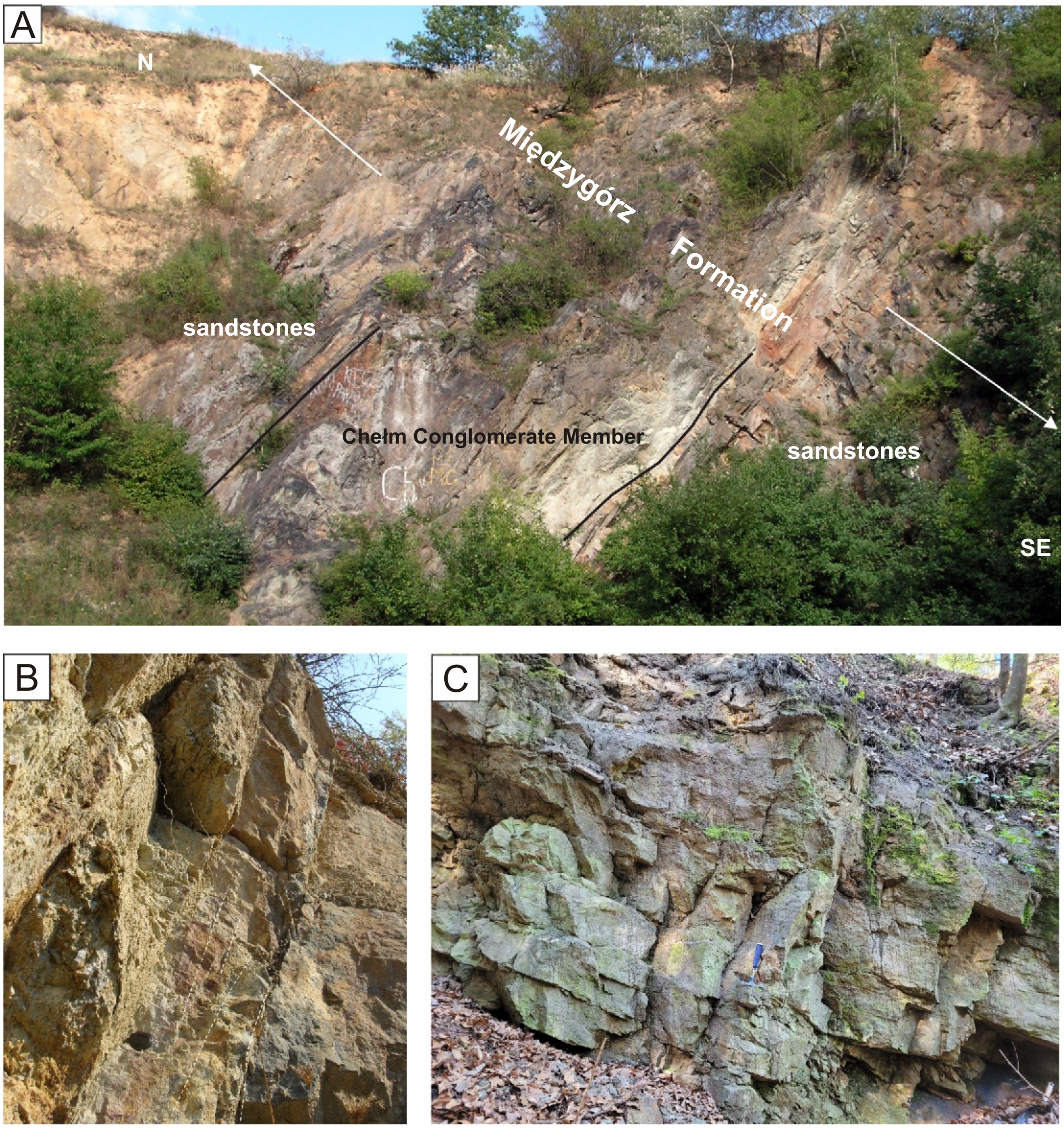

Fig. 12. Sandstones and conglomerates of the Międzygórz Formation exposed in the Chełm ravine at Międzygórz (A, B; Chełm Conglomerate Member, ~5 m thick) and the Biesak quarry (C). Note amalgamation of sandstone beds in the Międzygórz quarry (B) marked with white dashed lines

1970). It consists of medium- to thick-bedded massive sandstones forming sharp-based sheet-like beds (Fig. 12C). Some of beds display faint parallel lamination, although tectonic overprinting hampers detailed sedimentological interpretation.

Interpretation. The sedimentary characteristics of the Międzygórz Formation indicate deposition from the suspended sand load of turbulent flows and unidirectional flows, represented by massive and planar-laminated sandstone beds, respectively (cf. Allen, 1982; Harms et al., 1982). The stratification type, lack of burrows, and argillaceous interlayers in FA1 imply perennial winnowing and sediment reworking under high-energy conditions, such as a wave-reworked environment (see Hampson, 2000). Locally observed biogenic escape structures imply rapid sediment deposition. The erosional events in FA2 are recorded by scour-and fill structures produced by high-velocity flows/currents depositing clastic sediment rapidly after losing transport competence. Periodic intense reworking produced amalgamated beds. The conglomerates and sandstones with outsized pebbles in FA2 display sedimentological characteristics of cohesionless debris flows (see Walker, 1975; Lowe, 1982, 1988; Postma et al., 1988) delivering the phosphate siltstone and sandstone pebbles from an extrabasinal source. The wave ripples and *Skolithos* burrows at the top of some sandstone beds in the Międzygórz Quarry (top part) indicate a high-energy marine setting with oscillatory wave motion and colonisation by filter-feeding organisms.

THE STOKOWA HILL FORMATION

The main facies type comprises massive, green-grey (yellow when weathered), fine-grained sandstones (Fig. 13A) locally intercalated with greenish and red (hematitic) clayey mudstones and shales (Tomczyk and Turnau-Morawska, 1964). The sandstone beds are sharp-based and typically 10–15 cm thick, mostly massive, although some display subtle, irregular parallel lamination. A detailed petrographic characteristic of these facies, including also preliminary geochemical analyses, was provided by Turnau-Morawska (see Tomczyk and Tur-

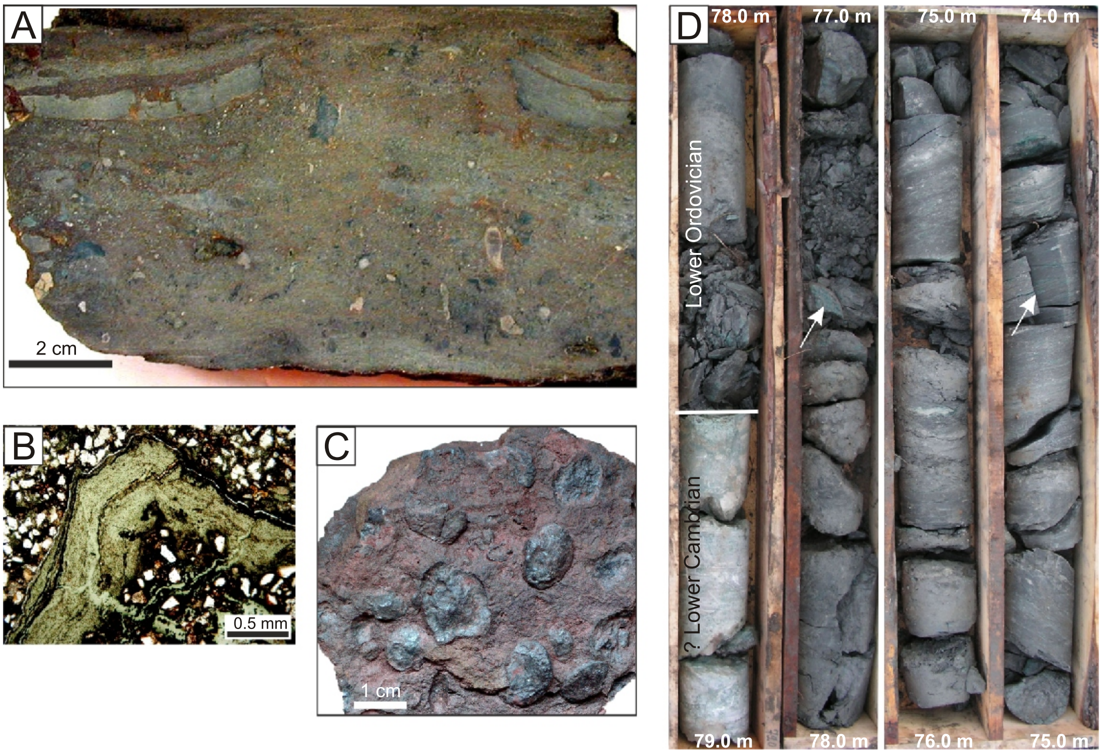

Fig. 13. Lower Floian sedimentary facies of the Stokowa Hill and Brzeziny formations

A – sandy mudstone with scattered large clasts of green glauconitic sandstones, dark grey siltstones and carbonates; the Stokowa Hill Formation in Brzeziny; **B** – photomicrograph of distorted chamosite crust in fine-grained sandstone of the Stokowa Hill Formation; Brzeziny; **C** – fine-grained ferruginous sandstone with hematitic concretions; the Stokowa Hill Formation in Brzeziny; **D** – dark mudstones of the Brzeziny Formation with glauconite grains scattered or concentrated in discontinuous laminae or lenses; the Zbrza PIG 3 borehole

nau-Morawska, 1964). The sandstone framework is composed of angular to poorly rounded quartz grains (~0.08–0.16 mm) cemented by a silty to muddy matrix containing scattered Fe-oxyhydroxides and pyrite aggregates. A distinctive feature of this facies is the presence of a chamosite-type mineral phase occurring as dispersed coated grains or crusts, commonly distorted (Fig. 13B), and locally as the pore-filling matrix accompanied by a siderite phase (see Tomczyk and Turnau-Morawska, 1964). Subordinate components include disseminated glauconite grains (~0.06–0.18 mm, up to 0.25 mm), lingulid brachiopod shells, and clasts of various lithologies (ranging from 0.5 to 1.0 cm) including phosphatic, glauconitic and chamositic mudstones. Hematitic ribbons and small nodules/concretions (Fig. 13C) as well as red hematitic sandy mudstones are also present in places (Tomczyk and Turnau-Morawska, 1964). The chamosite content in some sandstone and mudstone beds ranges from 16 to nearly 44% of the total mineral composition (Tomczyk and Turnau-Morawska, 1964).

The Stokowa Hill Formation forms a succession up to 15 m thick occurring in Brzeziny (the southwestern HCM), where it rests on sandstones (FA1) of the Międzygórz Formation (Fig. 10). In the Brzeziny 2 borehole, the uppermost part of this unit comprises a sandstone package 2.3 m thick containing numerous phosphate pebbles (Fig. 10). There is a gradual transition of the Stokowa Hill Formation into the overlying mudstones of the Brzeziny Formation manifested by the sandstone interbeds in the basal part of the latter unit (Fig. 10).

Interpretation. Massive sandstones were deposited from the sand suspended load of turbulent flows, while mudstone beds indicate the accumulation of fine-grained sediment from suspension fallout and mud flows (in the case of the silty mudstones with tiny clasts). A distinctive feature of the Stokowa Hill Formation is glauconitic siltstone, chamosite and hematite clasts indicating erosional events preceding the final deposition of sandy sediment.

THE BRZEZINY FORMATION

The main facies in this formation are green-grey clayey mudstones with sparse dark grey shale laminae (no more than 1 cm thick), which are accompanied by sandstone beds 3–10 cm thick with sharp bases, although beds up to 30 cm thick occur subordinately. The sandstone interbeds are fine-grained and typically massive, though some show indistinct parallel lamination. They are usually enriched in glauconite grains dispersed in a sandy background or concentrated in irregular laminae. Locally, a dark grey subfacies dominates, composed of structureless clayey mudstones with numerous disseminated glauconite grains locally forming small concentrations (Fig. 13D). This facies may also contain millimetre-sized mudstone and siltstone clasts.

This facies association is present in the southwestern part of the HCM, where it forms the Brzeziny Formation, reaching a thickness of ~40 m in the Brzeziny 2 borehole (Figs. 1 and 10; Tomczyk and Turnau-Morawska, 1964). There is sedimentary continuity between this sedimentary succession and the underlying chamositic sandstones and mudstones of the Stokowa Hill Formation (Fig. 10). The dark grey subfacies has been noted only in the Zbrza PIG 3 borehole (Figs. 1 and 10).

Interpretation. The facies characteristics indicate a predominantly low-energy environment where fine-grained sediment accumulated mainly from suspension settlement, but deposition from mudflows also operated as can be inferred from tiny clasts within a massive muddy background. These conditions were periodically interrupted by high-energy events, likely storm-induced, that deposited the sandstone interbeds attributed to distal tempestites (*sensu* Aigner, 1985; Myrow and Southard, 1996).

SOUTH-EASTERN POLAND

The upper Tremadocian–Floian facies in SE Poland occur locally in boreholes located on the Małopolska (outside of the southern HCM) and Łysogóry blocks.

On the Małopolska Block, the main lithological components of this stratigraphic interval are glauconitic sandstones, documented in the Jaronowice IG 1, Książ Wielki IG 1, Mędrzechów 1, Lubasz 2, Zalesie 1, Zgórsko 2, Niwki 3, Nosówka 9, Zagorzyce 1, Hermanowa 1, Wola Obszańska 10 and Uszkowce 4 boreholes (Figs. 1C and 14; Tomczyk, 1962; Jurkiewicz, 1976, 1991; Moryc and Nehring-Lefeld, 1997; Kowalska et al., 2000; Maksym et al., 2003; Trela, 2022). The presence of rare brachiopod specimens represented by *Obolus* species and *Lingulella lepis* (Jurkiewicz, 1976; Moryc and Nehring-Lefeld, 1997) supports correlating this sandstone unit with the upper Tremadocian–lower Floian transition. Its thickness varies from 3.0 to >30.0 m. In the Jaronowice IG 1 borehole, fine-grained sandstones are underlain by clayey mudstones containing glauconite-rich laminae/lenses and thin sandstone intercalations, resting unconformably on Ediacarian-lower Cambrian deposits (Fig. 14; Jurkiewicz, 1976; Buła, 2000). Locally, the sandstone beds contain fine mudstone (and possibly chert) clasts as well as skeletal detritus, mainly phosphatic linguliform brachiopods (Jurkiewicz, 1976; Maksym et al., 2003). In the Hermanowa 1 borehole, glauconite-bearing sandstones (glauconite content ~ 10%) form a ~10 m-thick interval grading upwards into mudstones or mudstone/sandstone alternations overlain by a pure sandstone package up to 4 m thick (Fig. 14; Maksym et. al., 2003). A similar lithofacies transition was noted in the Mędrzechów 1 borehole where mudstones above the glauconitic sandstones are dated by the lower Dapingian graptolite *Isograptus gibberulus* (Fig. 14; Tomczyk, 1962). As with the Jaronowice area, the upper Tremadocian glauconitic sandstones in the Hermanowa 1 and Mędrzechów 1 boreholes rest on Ediacarian deposits (Maksym et al., 2003). However, on the eastern Małopolska Block (Wola Obszańska), these sandstones are placed above the upper Cambrian mudstones (Fig. 14; Kowalska et al., 2000), similarly to the Lenarczyce PIG 1 bofrehole in the eastern HCM (see Trela et al., 2025).

The upper Tremadocian–lower Floian glauconite-bearing sandstones are fine- to medium-grained, but coarse-grained beds occur as well. Their sedimentological features include massive beds, with normal grading as well as cross-bedded and parallel- to undulatose-laminated layers (Fig. 15A–H). The glauconite occurs as allochtonous grains concentrated in some laminae or disseminated within the quartz-dominated sandstone background (Fig. 15 I, J). Small mudstone and sandstone clasts are scattered in massive sandstones (Fig. 15A, I, J), while the undulose lamination in sandstones is enhanced by mud drapes. Some sandstone beds reveal the presence of trace fossils (e.g., *Teichichnus* isp.), bioturbational mottling, biogenic and water (pillar) escape structures (Fig. 15F, G, H). In the Hermanowa 1 borehole, sedimentary cycles showing normal grading are present, and each cycle consists of a basal coarse-grained sandstone with tiny pebbles passing upwards into a massive medium- to fine-grained sandstone unit (Fig. 15B; Maksym et al., 2003).

On the Łysogóry Block, the upper Tremadocian–Floian facies occur in the northern part of the HCM (Trela, 2022) and the Biłgoraj-Narol zone (Modliński and Szymański, 2005). In the northern HCM, the upper Tremadocian mudstones with thin sandstone interbeds, documented in Pobroszyn, belong to the Brzezinki Formation, characterised by a wide stratigraphic range including also the upper Furongian (Fig. 2; Trela et al., 2001, 2025; Trela, 2006). In turn, the Floian stratigraphic interval in the Biłgoraj-Narol zone is dominated by a mudstone succession forming the Tanew Formation (dated by graptolites of the *phyllograptoides* to *hirundo* biozones), which rests on an erosional surface on lower Tremadocian strata (Fig. 14; Modliński and Szymański, 2005). The base of this succession is marked by a thin bed (up to 10–15 cm thick) consisting of mixed glauconite and quartz grains accompanied by phosphorite clasts and lingulid brachiopod shells. Additionally, glauconite grains are dispersed in the lower part of the Tanew mudstones or form irregular laminae and lenses (Modliński and Szymański, 2005).

DEPOSITIONAL ENVIRONMENTS AND EARLY ORDOVICIAN EUSTATIC CHANGES

The upper Tremadocian–lower Floian glauconite-rich siliciclastic facies on the Małopolska Block represents a transgressive to highstand sedimentary succession, which in the southern HCM is locally underlain by a basal conglomerate lag forming the Kędziorka Formation. The lower contact of this distinctive horizon is referred to as a transgressive ravinement surface and related erosional event, responsible for the removal of the Furongian and lower Tremadocian deposits in the southern HCM (Trela et al., 2025, reference therein). The original presence of these deposits was argued by Znosko and Chlebowski (1976) based on graptolite fragments preserved in chacedony beds of the Wysoczki Formation and mudstone clasts in conglomerates of the Chełem Member. Alternatively, Trela et al. (2025) suggested that the late Tremadocian transgression might have encroached onto the upper Furongian strata in the northeast and deformed lower-middle Cambrian rocks exposed in the south.

Glauconite-rich units generally form during transgressive events under conditions of sufficiently low accumulation rate, reduced detrital input and sediment winnowing/reworking favorable for stratigraphic and sedimentary condensation (Odin and Matter, 1981; Amorosi, 1995, 1997, 2012; Fölmi, 2016, and references therein). Glauconite precipitates as an authigenic mineral during early diagenesis near the sediment-water interface under weakly reducing conditions (Odin and Matter, 1981; Fölmi, 2016; López-Quirós et al., 2019, and references therein). This mineral accumulates on the shelf and upper slope but is also noted in marginal marine (lagoonal, estuarine) and continental settings (Odin and Fullagar, 1988; Giresse and Wiewióra, 2001; El Albani et al., 2005; Huggett and Cuadros, 2010; Cuadros et al., 2011; Baldermann et al., 2013; Fölmi, 2016; López-Quirós et al., 2019).

Biostratigraphic data indicates that the late Tremadocian transgression entered the southern HCM in the time span corresponding to the *deltifer* conodont Biozone, as documented in the Wysoczki Formation, in contrast to Znosko and Chlebowski (1976) who argued for its correlation with the early Floian (early Arenigian) flooding. This transgressive event corresponds to a high sea-level in the upper Tremadocian part of the Ordovician third-order eustatic curve reconstructed by Haq and Schutter (2008), and seems to be coeval with the Hagastrand Drowning Event in Baltoscandia (Nielsen, 2004; Fig. 16). The facies characteristics of the Wysoczki Formation indicate intermittent sand and fine gravel accumulation interrupting fairweather mud deposition in the upper offshore zone. The presence of biogenic

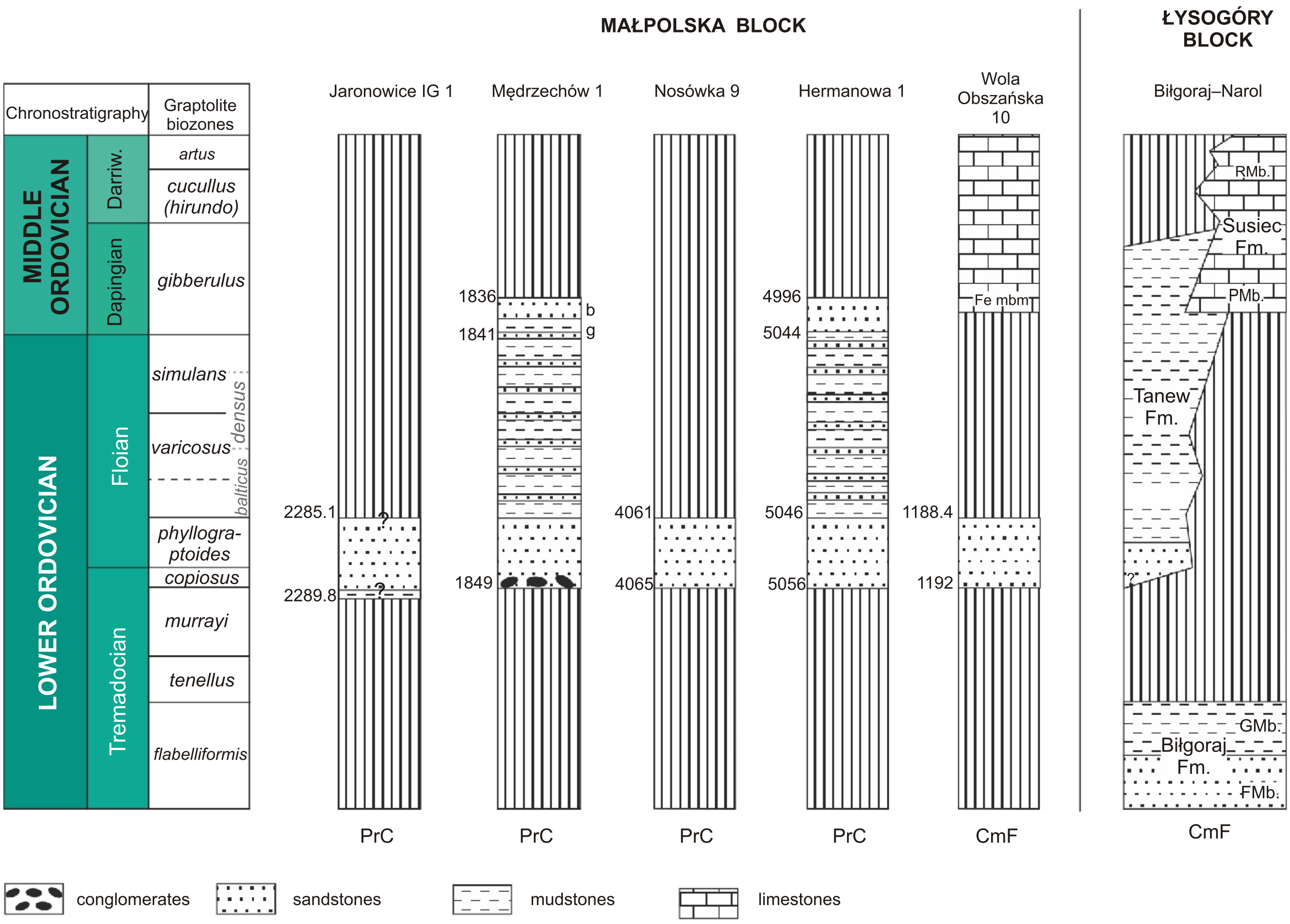

Fig. 14. Correlation of Lower Ordovician lithofacies on the Małopolska Block and the Biłgoraj-Narol Zone of the Łysogóry Block

CmF – Cambrian, Furongian; b – brachiopods; g – graptolites; FMb. – Frampol Member; GMb. – Goraj Member; PMb. – Paary Member; RMb – Rebizanty Member; Fe mbm – Fe microbialites; PrC – Proterozoic (Ediacaran)

escape structures in sandstone and siltstone beds point to rapid deposition of coarse-grained material (Trela, 2001). In turn, the "mantle and swirl" structures in the mudstone beds suggests soup-ground conditions and periods of non-deposition favourable for biogenic activity. Rapid emplacement of dense coarse-grained sediment was also responsible for the composite beds with load structures and internal deformation structures. Alternatively these beds might have been related to seismic-induced events that in some cases resulted in sediment liquefaction. The bottom sediment was inhabited by endobenthic or semi-endobenthic lingulid brachiopods that burrowed within the unconsolidated substrate (see Mergl, 2002). The oval and elongated structures noted in siltstones and sandstones of the Wysoczki Formation (see Trela, 2001: Plate I, fig. 5, therein) may be traces of their activity. Periods of clastic starvation facilitated early-diagenetic chert formation, preserved as thin beds and nodules revealing the selective replacement of the clay background (with relicts of volcanic ash) by spherulitic chalcedony and microquartz. Thus, it seems plausible that devitrification of volcanic glass and clay transformation were likely silica sources for the upper Tremadocian cherts in the southern HCM, as suggested earlier by Turnau-Morawska (1958). In addition, early diagenetic precipitation of silica facilitated the preservation of cyanobacterial structures (see Starmach, 1963). The pyroclastic origin of the parent sediment is supported by the presence of pyrogenic quartz grains, well-preserved feldspars, plagioclases, muscovite and biotite preserved in tuffitic mudstones and cherts (Chlebowski, 1971; Salwa, Trela, 2019). The temporal and spatial distribution of the upper Tremadocian facies and their sedimentary characteristics indicate that the Wysoczki Formation was deposited in a restricted marine setting (embayment or lagoon) favorable for the formation of authigenic glauconite, which was subject to periodic winnowing and redeposition.

The western and eastern localities in the southern HCM (that is Bukówka, Zbrza, Brzeziny, Kleczanów and Lenarczyce; Figs. 2, 10 and 17) are dominated by condensed glauconitic sandstones of FA1 forming the Międzygórz Formation. The lower boundary of this unit may be slightly diachronous relative to the Wysoczki Formation, as inferred from its stratigraphic position within the Tremdocian-Floian transition. This suggests that the base of FA1 can be correlated with the latest Tremadocian Copiosus Drowning Event in Baltoscandia (Nielsen, 2004), as well as the third-order sea-level rise indicated in the Ordovician eustatic curve reconstructed by Haq and Schutter (2008; Fig. 16). This view contrasts with that of Znosko and Chlebowski (1976), who considered the glauconitic sandstones in the HCM as a lithofacies and stratigraphic equivalent of the Arenigian (Floian) glauconites on the East European Platform.

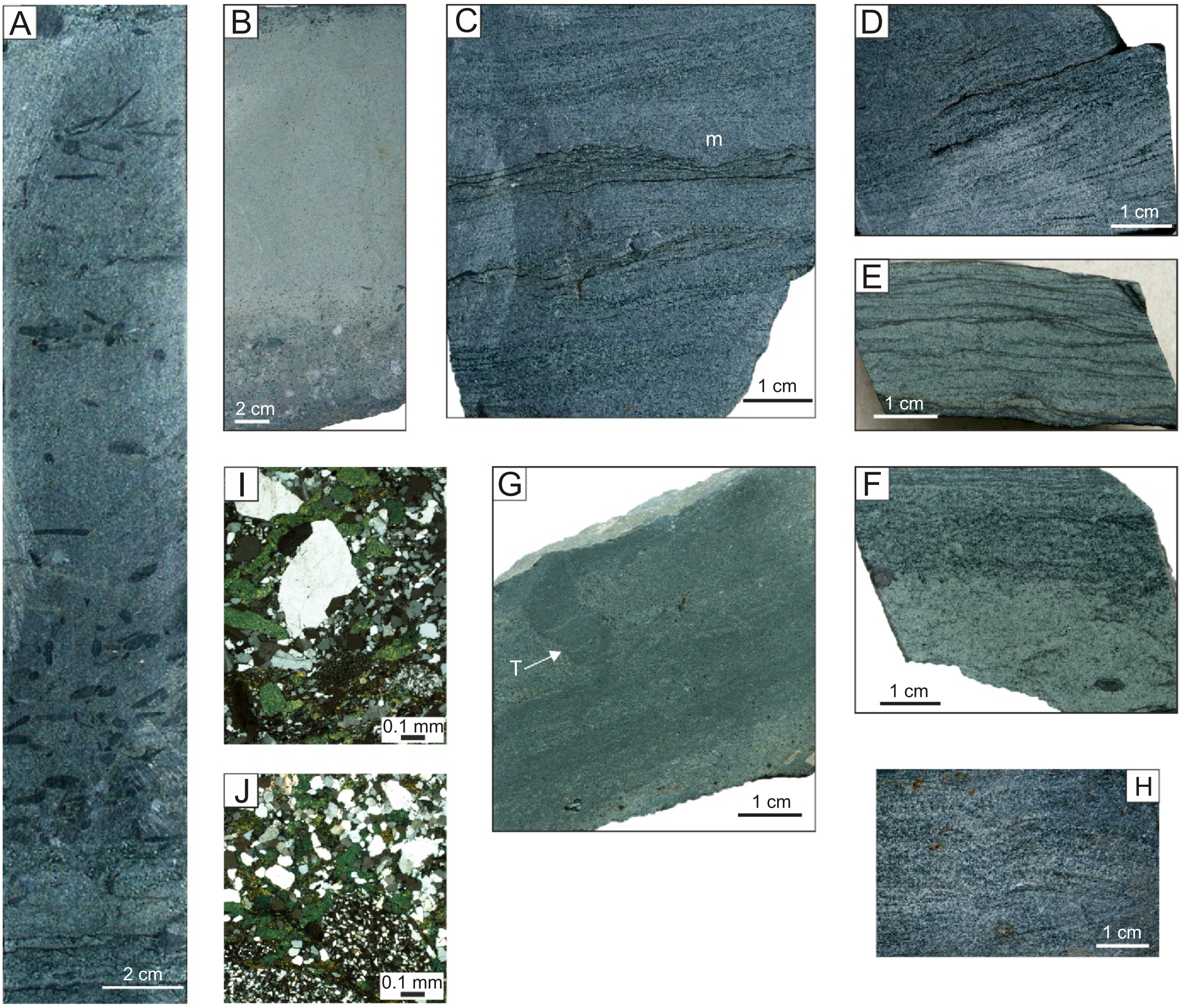

Fig. 15. Upper Tremadocian–lower Floian glauconitic sandstones from boreholes located in the Małopolska Block

A – tiny siltstone and mudstone pebbles dispersed in a massive sandstone, note dispersed large quartz grains (light); Wola Obszańska 10 borehole; **B** – normal grading from coarse-grained sandstones with large quartz grains and tiny clasts to massive medium-to fine-grained sandstone; coarse-grained deposit of the overlying bed visible at the top; Hermanowa 1 borehole; **C** – sandstone bed showing low-angle cross bedding intercalated with massive intervals; Wola Obszańska 10 borehole; **D** – cross-bedded sandstone; Wola Obszańska 10 borehole; **E** – sandstone with undulose lamination; Nosówka 9 borehole; **F** – bioturbated sandstone with parallel lamination preserved at the top; Nosówka 9 borehole; **G** – sandstone bed with indistinct undulose laminae and tiny clasts at the base, and *Teichichnus* isp. (T) at the top; Nosówka 9 borehole; **H** – biogenic escape structure in a sandstone bed; Wola Obszańska 10 borehole; **I**, **J** – photomicrographs of glauconitic sandstones from the Hermanowa 1 (I) and Wola Obszańska 10 (J) boreholes (XPL). Note fine-grained sandstone pebbles and large quartz grains

The sedimentary features of FA1 – such as stratification type, scarce burrows and subordinate mudstone interbeds - imply the accumulation of sandy sediment associated with frequent winnowing and reworking triggered by high-energy events (e.g., permanent wave action or storms) facilitating sedimentary condensation and localised glauconite concentrations. The conglomerate bed of the Kędziorka Formation and sandstones of FA1 represent transgressive lag and condensed onlap deposits (see Kidwell, 1991) grading upwards into early highstand deposits of the nearshore zone.

Locally, the glauconite-bearing sand formed sedimentary successions exceeding 20 m in thickness, with a significant admixture of gravel, as shown by FA2 of the Międzygórz Formation exposed in the Międzygórz and Biesak quarries. The massive character and plane-parallel lamination of sheet-like sandstone beds displaying planar and undulose stratification indicate rapid sand deposition from turbulent suspension and tractional transport in the upper flow regime, respectively. The presence of amalgamated beds and wash and scour structures reflect erosional events in a high-energy environment. The sedimentary features of FA2 sandstones can be attributed to wave-worked shoreface deposits affected by frequent storm action. Pebbly conglomerates in FA2 are interpreted as products of beachface erosion by storm waves and subsequent seaward transport of gravel by storm-generated rip-surge density currents or high-energy stream floodwater (see Leckie and

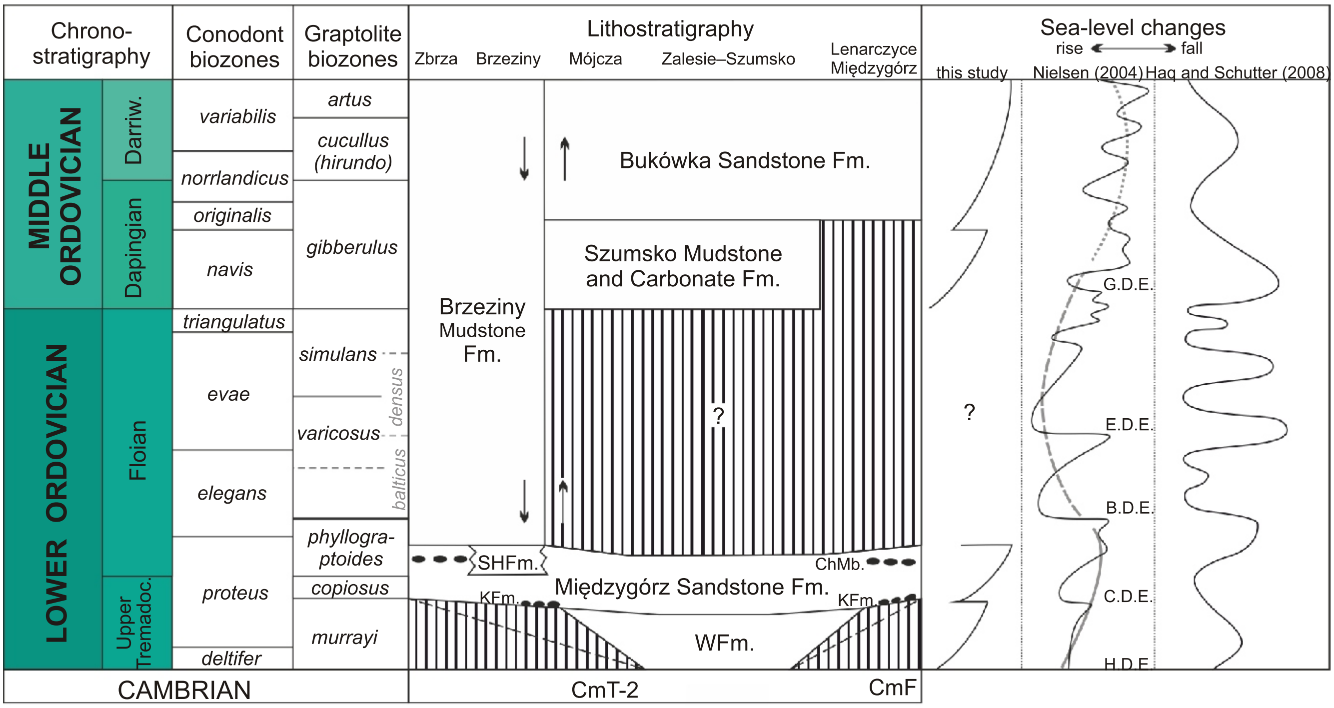

Fig. 16. Lower Ordovician lithostratigraphic units in the southern HCM and their correlation with the Ordovician sea-level curve of Baltoscandia (Nielsen, 2004) and eustatic changes reconstructed by Haq and Schutter (2008)

Chrono- and lithostratigraphic abbreviations as on Figure 2. Black arrows on the lithostratigraphic scheme indicate local tectonic mobility; black dashed lines mark the possible lower stratigraphic extent of the Kędziorka and Międzygórz formations. Grey lines on Nielsen's sea-level curve indicate the L. Tremadoc–E. Arenig Lowstand Interval (continuous line), the Mid Arenig Highstand Interval (dashed line) and the L. Arenig–E. Llanvirn Lowstand Interval (dotted line). H.D.E – Hagastrand Drowning Event, C.D.E – Copiosus Drowning Event, B.D.E – Billingen Drowning Event, E.D.E – Evae Drowning Event, G.D.E – Gärdlösa Drowning Event

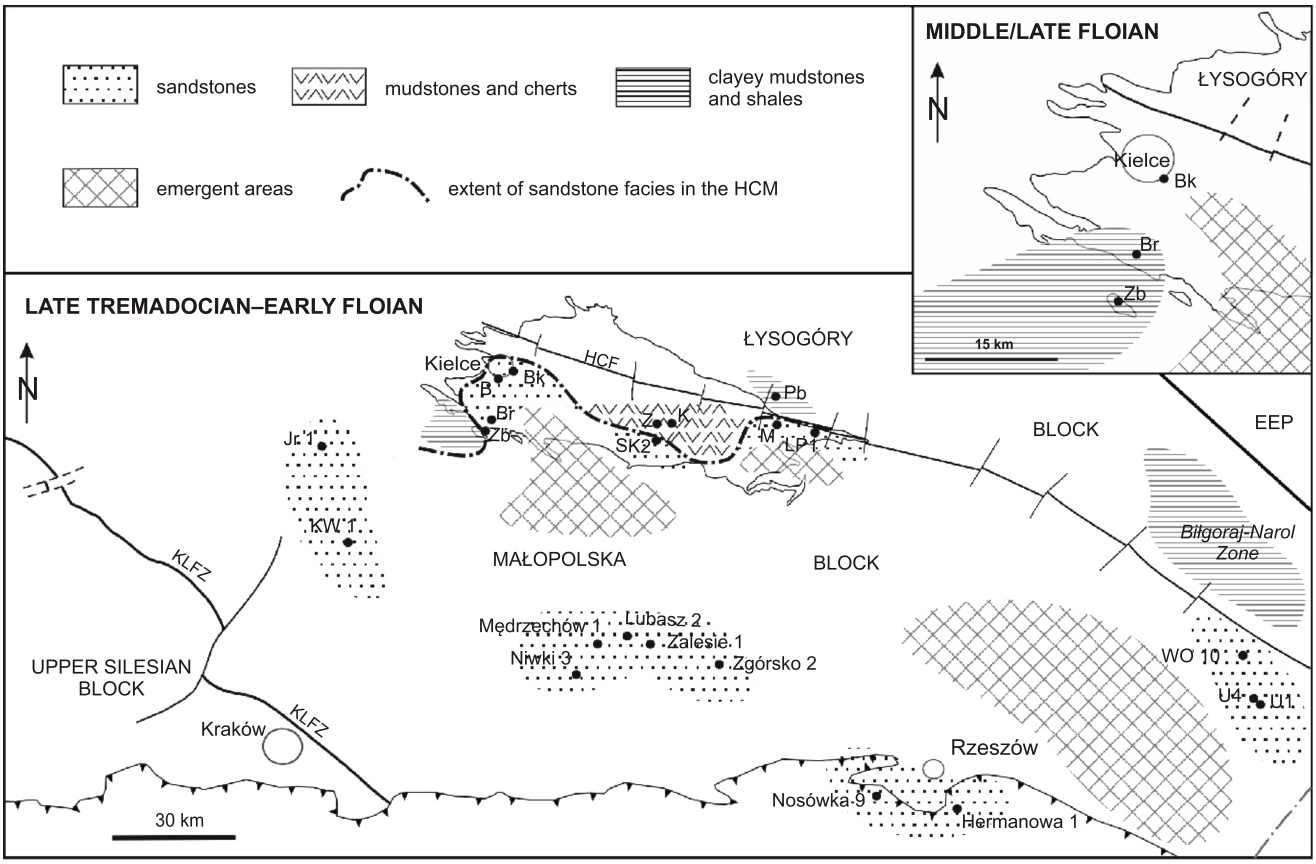

Fig. 17. Distribution of sedimentary facies on the Małopolska and Łysogóry blocks during the late Tremadocian–middle/late Floian

Abbreviations as on Figure 1 and B – Biesak, Br – Brzeziny, EEP – East European Platform, Jr 1 – Jaronowice IG 1 borehole, K – Kędziorka, KW1 – Książ Wielki IG 1 borehole, M – Międzygórz, Pb – Pobroszyn, WO10 – Wola Obszańska 10 borehole, Z – Zalesie, Zb – Zbrza

Walker, 1982; Nemec and Steel, 1984; Gruszczyński et al., 1993). The facies succession of FA2 in the Międzygórz Quarry displays an overall regressive trend, indicated by wave ripples, shallow water filter-feeders (*Skolithos* isp.) and lenticular gravels at the top indicating deposition above the fairweather wave base, probably within the upper shorface. This thick sandstone-conglomerate succession with a wave-worked top can be interpreted as a littoral bar developed along a topographic scarp, probably originated from post-Furongian block faulting (the Sandomirian tectonic activity) differentiating the basin morphology in the HCM (Trela et al., 2025). The brachiopod fauna identified in Międzygórz (Bednarczyk and Stupnicka, 2000) provides biostratigraphic arguments for the correlation of this regression with the early Floian sea-level lowstand noted in Baltoscandia (Fig. 16) preceding the Billingien Transgressive Event (see Nielsen, 2004). The sandstone unit (~3 m thick) in Zalesie above the Wysoczki Formation (Czarnocki, 1919; Bednarczyk, 1964, 1966) seems to correspond to the same eustatic event (Trela, 2022) likewise the chamosite-rich clastic deposits of the Stokowa Hill Formation with the topmost pebbly sandstone package in the Brzeziny 2 borehole (Fig. 16). However, in the latter location the reconstruction of facies architecture and relative sea-level changes at the Tremadocian–Floian transition is hampered by the tectonic disturbance of the Lower Ordovician succession.

A continuous transition from the Stokowa Hill Formation to the mudstone-dominated Brzeziny Formation in the Brzeziny-Zbrza area indicates a relative sea-level rise initiated in the middle Floian *balticus* Biozone, corresponding to the Billingen Transgressive Event (Fig. 16) in Baltoscandia (Nielsen, 2004; see also Haq and Schutter, 2008). The Brzeziny Formation represents a sedimentary succession developed in the upper offshore mud belt, where hemipelagic settling was interrupted by high-energy pulses of suspension fallout from turbulent storm-induced flows. This sedimentary setting extended probably farther southwest and south (Fig. 17), as inferred from greenish mudstones with sandstone intercalations in the Jaronowice IG 1 and Mędrzechów 1 boreholes. The Floian dark mudstones of the Brzeziny Formation in the Zbrza PIG 3 borehole are enriched in glauconite grains similar to the Słuchowo Formation in the Baltic Depression of the East European Platform and the Tanew Formation in the Biłgoraj-Narol zone of the Łysogóry Block (see Modliński and Szymański, 1997, 2005; Trela, 2022). They represent an oxygen-deficient deeper shelf setting in contrast to the Brzeziny area located in a shallower and better ventilated environment. The mud deposition in Brzeziny lasted until the early Darriwilian, as indicated by graptolite biostratigraphy, which was a result of increased accommodation space driven by regional tectonic activity (Trela, 2022).

The spatial distribution of the late Tremadocian–lower Floian facies on the Małopolska Block indicates that glauconite-bearing sandstones formed the wide sandy shelf of an epeiric sea, possibly with uplifted or even emergent areas (Fig. 17). Facies records from the Nosówka 9, Hermanowa 1, and Wola Obszańska 10 boreholes suggest depositional conditions similar to those of the Międzygórz Formation in the HCM. Sedimentary processes included the deposition from turbulent flows with suspended sand (massive and normally graded beds, which can be attributed to high-density turbidity currents, *sensu* Lowe, 1982), unidirectional flows of the upper flow regime (planar laminated beds) and migrating bedforms (cross-bedding). The presence of *Teichichnus* burrows and escape trace fossils indicates the activity of feeding infaunal organisms and sudden sediment deposition events, respectively.

As on the Małopolska Block (including the southern HCM), the condensed glauconitic unit in the Lower Ordovician is widespread in the Polish segment of the East European Platform as the Rajsk Formation (Modliński and Szymański, 1997, 2008), as well as on the Narol-Biłgoraj part of the Łysogóry Block (Modliński and Szymański, 2005), and extends farther northeastwards into Estonia and the St. Petersburg region (Drovov, 2005; Löfgren et al., 2005; Viira et al., 2006, and references therein). Znosko and Chlebowski (1976) argued for the isochronous nature of this horizon and confined it to the lower Arenigian (Floian). However, it is commonly accepted that this distinctive lithological horizon is a diachronous unit related to a transgressive event initiated in northeastern Poland during the time span corresponding to the Floian *balticus* graptolite Biozone and lasting until the *elongatus* Biozone (Modliński, 1968, 1973, 1982; Szymański, 1973, 1984; Bednarczyk, 1985; Modliński and Szymański, 2008; Modliński and Podhalańska, 2010). Biostratigraphic data from mudstones of the Słuchowo and Tanew formations (located in the western Baltic Depression and Biłgoraj-Narol zone, respectively), which overlie this horizon, indicate that the transgression started as early as the earliest Floian (*phyllograptoides* Biozone) or possibly even in the latest Tremadocian (Figs. 3 and 14; see Trela, 2022). The *proteus* and *elegans* conodont biozones in the eastern Podlasie Depression and the Baltic Depression, respectively, contain mixed assemblages including taxa redeposited from the upper Tremadocian (Bednarczyk, 1979; Nehring-Lefeld, 1987). According to Bednarczyk (1979) the mixed conodont assemblage in the glauconitic unit of the eastern Baltic Depression resulted from the redeposition of taxa from eroded deposits of the late Tremadocian–earliest Floian transition. This is consistent with conodont studies in Estonia that provided evidence of four successive depositional phases in glauconitic sandstones of the same stratigraphic interval, responsible for redeposition of older conodont elements (Löfgren et al., 2005; Viira et al., 2006). From a regional perspective, the glauconitic unit on the East European Platform appears to represent a landward migrating condensed onlap horizon produced by a series of flooding/reworking events responsible for its complex microstratigraphic pattern and physical amalgamation (see Kidwell, 1991). In this scenario, the deposition of the glauconitic Rajsk Formation in the western (basinal) segment of the East European Platform appears to be related to the early Floian transgressive event coeval with the *phyllograptoides* Biozone; however, its correlation with the latest Tremadocian Copiosus Drowning Event cannot be excluded, at least for the basal conglomerate lag (Fig. 3; Trela, 2022). The glauconitic horizon reached its maximum extent in the eastern East European Platform during the middle or even late Floian (Modliński and Szymański, 1997, 2008).

CONCLUSIONS

This work provides insight into the sedimentary environment of the upper Tremadocian–Floian glauconite-bearing siliciclastic succession in SE Poland and its relationship with relative sea-level changes in Baltica. In the southern HCM this succession is made up of tuffitic mudstones with chert and sandstone interbeds forming the Wysoczki Formation, and sandstones of the Międzygórz Formation, which are locally exposed and also recognised in several boreholes. These deposits represent a transgressive to highstand system tract, locally underlain by a basal conglomerate lag. The sedimentary facies of the Wysoczki Formation are interpreted as deposits of the upper offshore zone where deposition of fairweather mud was intermittently interrupted by the accumulation of sand and fine gravel. Frequent clastic starvation facilitated early diagenetic chert formation due to selective replacement of tuffitic mud by spherulitic chalcedony and microquartz. In turn, sandstones of the Międzygórz Formation represent nearshore sediments deposited under frequent winnowing triggered by high-energy events favourable for the concentration of glauconite. Locally, these sandstones formed littoral bars developed along a topographic scarp related to Early Ordovician tectonic block faulting. Biostratigraphic data (conodonts, brachiopods) allow correlation of the Lower Ordovician sedimentary facies in the southern HCM with eustatic events recognised in Baltoscandia, even accounting for the influence of local tectonic activity. This tectonic activity was responsible for increased accommodation space in the southwestern HCM and the associated deposition of mud (the Brzeziny Formation) from the early/middle Floian up to the Dapingian–Darriwilian transition.

The upper Tremadocian–lower Floian glauconite-bearing sandstones formed a wide sandy shelf on the Małopolska Block, probably with uplifted or even emergent areas, as inferred from their distribution in boreholes across SE Poland. Their sedimentary environment and depositional conditions were similar to those of the Międzygórz Formation in the HCM.

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