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A reappraisal of the terrane concept in the Holy Cross Mountains (Polish segment of the Trans-European Suture Zone) based on the Furongian (upper Cambrian) stratigraphy and facies in the Lenarczyce PIG 1 well

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ABSTRACT:

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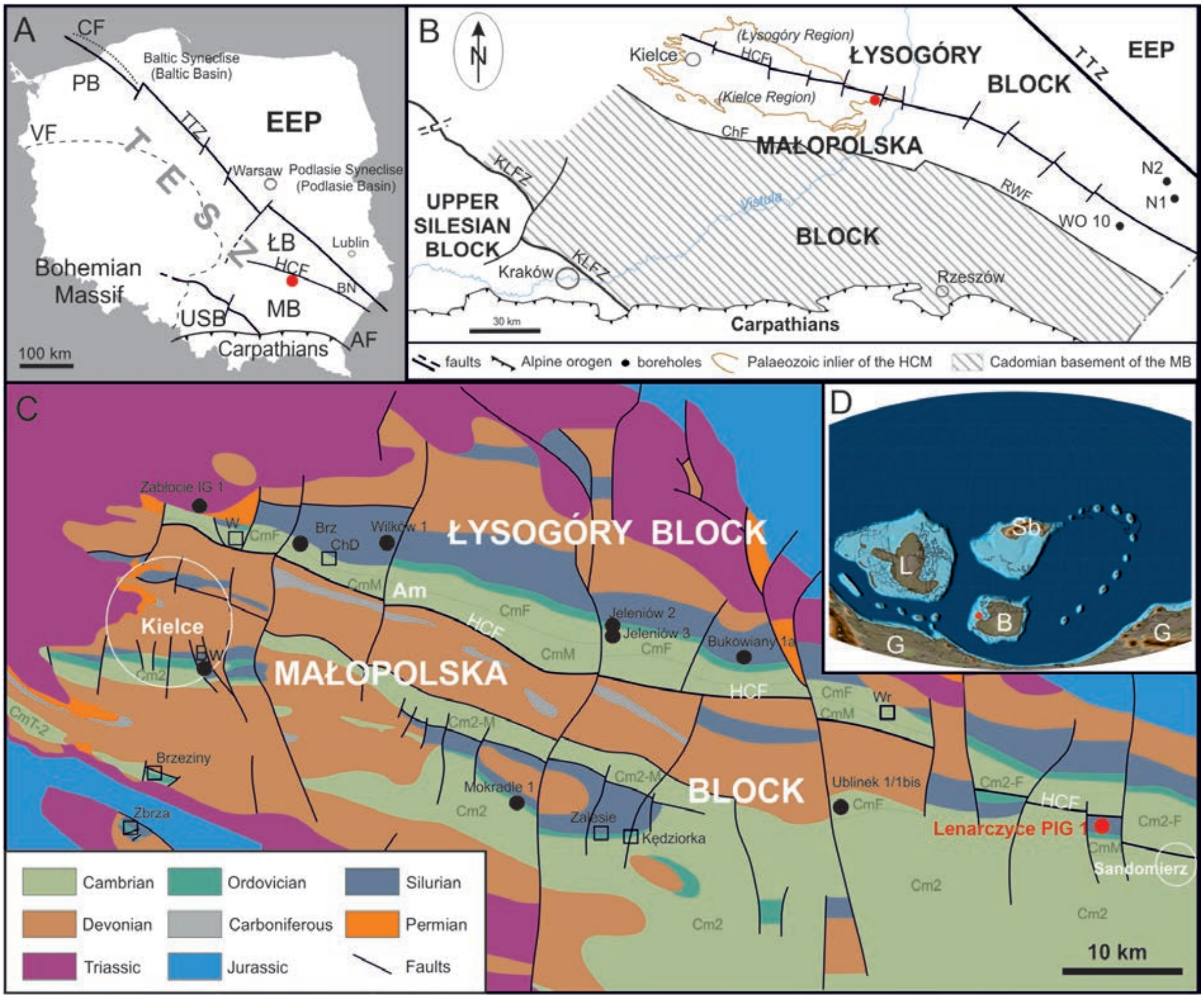
A wide stratigraphic gap spanning the middle Miaolingian to early Tremadocian in the succession of the northern Małopolska Block, exposed in the southern Kielce Region of the Holy Cross Mountains in south-central Poland, was hitherto indicated as the key argument for its different tectonic evolution compared to the adjacent northern Łysogóry Block. As these two blocks form part of the Trans-European Suture Zone, deciphering their early Palaeozoic history has profound impact on our understanding of the evolution of this major Central European tectonic domain. Based on data from the Lenarczyce PIG 1 well (Kielce Region), we analyse here the stratigraphy and sedimentary record of the upper Cambrian in the Holy Cross Mountains. Rich acritarch assemblages coupled with rare macrofossil specimens from this well indicate the presence of a Miaolingian and Furongian succession showing different tectonic styles and separated by a stratigraphic gap. The stratigraphic gap separating these successions spans the middle to late Miaolingian and the early to middle Furongian, and it has proved to be much narrower than previously considered. The upper Furongian siliciclastic succession recognised here can be defined as a shallow-water flood-dominated delta system, developed after the tectonic event responsible for the intense deformation of the lower and middle Cambrian strata. In the latest Furongian, this sedimentary system passed rapidly upwards into an offshore mud belt produced by a relative sea-level rise (transgressive event). The unconformity at the Cambrian–Ordovician boundary in the southern Holy Cross Mountains is shown to be of a complex nature resulting from pre-Furongian folding and thrusting, and post-Furongian changes of relative sea-level/accommodation space.

Key words: Furongian; Acritarchs; Sand lobes/bars; Offshore muds; Tectonic activity.

INTRODUCTION

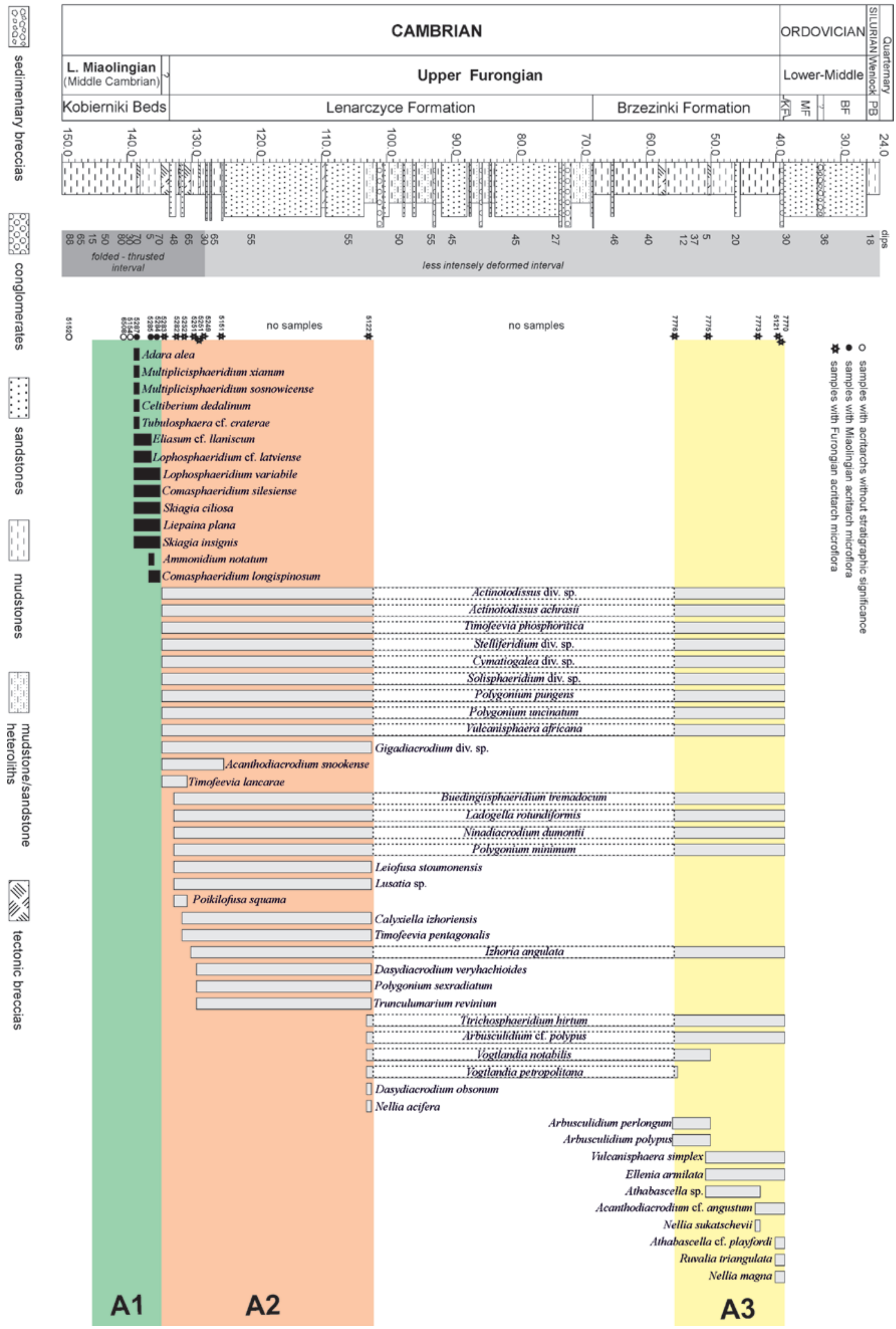
The Holy Cross Mountains in south-central Poland represent a small hilly area exposing Palaeozoic sedimentary rocks, located in the south-eastern part of the Trans-European Suture Zone (TESZ; Text-fig. 1A), a major tectonic domain between the Precambrian basement of the East European Platform, and the Variscan and Alpine tectonic belts of Western Europe (Pharaoh 1999). The Holy Cross Mountains area is



TText-fig. 1. Location of the Lenarczyce PIG 1 well (red circle) within the Polish TESZ segment (A), the Małopolska Block (B), and the Holy Cross Mountains (C; after the Geological Map of Poland without Cainozoic deposits. 1 : 1 000 000; modified after Dadlez *et al.* 2000), and its approximate palaeogeographic position in the Furongian (late Cambrian; D, after Scotese 2014). Abbreviations: AF – Alpine front; Am – Ameliówka; B – Baltica; BN – Biłgoraj-Narol Zone; Brz – Brzezinki wells; Bw – Bukówka; ChD – Chabowe Doły; ChF – Chmielnik Fault; CF – Caledonian Front; Cm – Cambrian (F – Furongian, M – Miaolingian, 2 – Series 2, T – Terreneuvian); EEP – East European Platform; G – Gondwana; HCF – Holy Cross Fault; KLFZ – Kraków-Lubliniec Fault Zone; MB – Małopolska Block; N1 – Narol IG 1 well; N2 – Narol PIG 2 well; L – Laurentia; ŁB – Łysogóry Block; PB – Pomeranian Block; RWF – Ryszkowa Wola Fault; Sb – Siberia; TESZ – Trans-European Suture Zone; TTZ – Teisseyre-Tornquist Zone; USB – Upper Silesian Block; VF – Variscan Front; W – Wiśniówka quarries; WO 10 – Wola Obszańska 10 well; Wr – Wąworków Quarry. Black circles indicate wells; black open squares indicate exposures and quarries.

crucial for the reconstruction of the geotectonic history of Europe as its southern and northern segments (Kielce and Łysogóry regions, respectively) are traditionally considered to be fragments of the Małopolska and Łysogóry lithospheric blocks (Text-fig. 1A, B). Their basement structure, geotectonic origin, and accretionary history are still a matter of debate. One of the key arguments so far for the different palaeogeographic and tectonic provenance of these blocks during the early Palaeozoic was the presence of an angular unconformity between the lower Cambrian and the upper Tremadocian, and a related huge stratigraphic gap in the southern Holy Cross Mountains, in contrast to the northern segment which is characterised by a continuous sedimentary succession across the Cambrian–Ordovician boundary.

The absence of upper Cambrian strata in the southern Holy Cross Mountains, unlike in the northern (Łysogóry) segment, was commonly assumed to be the case until 2004 (see Szczepanik *et al.* 2004a)



Text-fig. 2. Stratigraphy, lithology, and tectonic features of Palaeozoic rocks in the Lenarczyce PIG 1 well with range chart of selected Cambrian acritarch taxa arranged in assemblages A1-A3. Abbreviations: BF – Bukówka Formation; KF – Kędziorka Formation; MF – Międzygórz Formation; PB – Prągowiec Beds.

Formal units	Description
Lenarczyce Sandstone, Mudstone and Conglomerate Formation (in short: Lenarczyce Formation) (Polish name: formacja piaskowców, mułowców i zlepieńców z Lenarczyc, in short: formacja z Lenarczyc)	Definition: sandstones intercalated by mudstones or alternating mudstone/sandstone complexes, locally with conglomerate interbeds. Origin of name: from the village of Lenarczyce located to the north-west of Sandomierz in the eastern Holy Cross Mountains (Kielce Region). Previous names: Lenarczyce Beds (Szczepanik *et al*. 2004a). Stratotype: Lenarczyce PIG 1 well in depth interval 68.2–133.5 m (see Table 2). Boundaries: lower boundary at a sharp contact of sandstones and pebbly sandstones with underlying mudstones of the Kobierniki Beds placed in Lenarczyce PIG 1 well at depth 133.5 m; upper boundary at the contact of a greenish grey sandstone bed with an overlying thin breccia bed delineating grey mudstones of the Brzezinki Formation located in Lenarczyce PIG 1 well at depth 68.2 m. Thickness: not more than 65.0 m. Detailed description: alternating sandstone- and mudstone-dominated intervals ranging from 2.0 to 20 m in thickness. Sandstones are fine- and medium-grained, massive or parallel to low-angle laminated with dispersed mudstone and sandstone pebbles. Pebbly massive sandstones and beds with putative hummocky cross-stratification occur as well. In places they are intercalated by conglomerate beds, up to several cm thick. Mudstone-dominated intervals consist of massive to discretely laminated clayey and silty mudstones, and mudstones/sandstone heteroliths intercalated by sandstone and rare conglomerate beds not more than 20-30 cm in thickness. Chrono- and biostratigraphy: upper Furongian based on acritarch specimens of the RA6 and RA7 zones coeval with the *Peltura* Superzone (this paper) Regional distribution and correlation: the Lenarczyce Formation was reported only in the stratotype section, in the southern Holy Cross Mountains (Kielce Region). Its age-equivalent is the Ameliówka Formation (as defined in this paper). Genetic interpretation: flood-related sand lobes deposited in the distal delta front and heterolithic sandstone-mudstone complexes associated with the proximal prodelta zone (detailed interpretation in this paper).
Ameliówka Mudstone and Sandstone Formation (in short: Ameliówka Formation) (Polish name: formacja mułowców i piaskowców z Ameliówki, in short: formacja z Ameliówki)	Definition: grey mudstones with thin intercalations of sandstones and subordinate thicker sandstone beds. Origin of name: from the small settlement of Ameliówka in the western part of the northern Holy Cross Mountains (Łysogóry Region) where deposits of the formation crop out in the eastern slope of Klonówka Hill within the Masłów Range. Previous names: Mąchocice Beds (Tomczykowa 1968), Klonówka Claystone Formation (Orłowski 1975, the formation revised herein corresponds to its lower part with sandstone interbeds). Stratotype: exposure known as Chabowe Doły located to the west along the road from Ameliówka to Mąchocice, on the eastern slope of Klonówka Hill in the northern Holy Cross Mountains (Łysogóry Region); hypostratotype: Wilków 1 well (depth interval 891.0–957.8 m) in the northern Holy Cross Mountains (Łysogóry Region). Boundaries: lower boundary is currently inaccessible but probably located at the sharp contact of mudstones with the underlying thick-bedded quarzitic sandstones of the Wiśniówka Formation; upper boundary is transitional with the overlying Brzezinki Formation (see below) and placed at the disappearance of sandstone intercalations (in the Wilków 1 well at the depth of c. 891.0 m). Thickness: c. 60 m accessible in the Wilków 1 well but not drilled through. Detailed description: predominantly grey to dark grey clayey mudstones alternating with laminae and thin beds of mudstones and siltstones to fine-grained sandstones. The lithotypes form heterolithic intervals in places characterised by a moderate intensity of bioturbation. They are intercalated by sandstone beds of various thickness ranging from 15 cm up to 1.0 m. Chrono- and lithostratigraphy: upper Furongian based on trilobite fauna indicative for the lower part of the *Peltura* Superzone (Żylińska 2002; Szczepanik *et al*. 2017; this paper). Regional distribution and correlation: this formation occurs in the northern Holy Cross Mountains (Łysogóry Region); besides the stratotype locality (Chabowe Doły) it is also present in the Lisie Jamy and Bęczków outcrops (Żylińska 2002) and numerous wells (Tomczykowa 1968). Genetic interpretation: transition from shoreface sands to distal shelf muds (Jaworowski and Sikorska 2006), referred to prodeltaic deposits.

Formal units	Description
Brzezinki Mudstone Formation (in short: Brzezinki Formation) (Polish name: formacja iłowców i mułowców z Brzezinek, in short: formacja z Brzezinek)	<u>Definition</u>: grey and dark grey clayey mudstones with subordinate siltstone interbeds. <u>Origin of name</u>: from the village of Brzezinki where three boreholes (Brzezinki 1, Brzezinki 2 and Brzezinki 3) and shallow geological shafts reaching Cambrian grey mudstones are located (see Tomczykowa 1968; Central Geological Database at the website of the Polish Geological Institute – National Research Institute). <u>Previous names</u>: Łysogóry Beds (Tomczykowa 1968); Klonówka Claystone Formation (Orłowski 1975; the formation revised in this paper corresponds to its upper part); Brzezinki Claystone Formation [Trela 2006, referred only to the northern Holy Cross Mountains (Łysogóry Region)]. <u>Stratotype</u>: Wilków 1 well, depth interval 785.0–891.0 m; hypostratotype: Lenarczyce PIG 1 well, depth interval 39.4–68.2 m. <u>Boundaries</u>: in the southern Holy Cross Mountains (Kielce Region), the lower boundary corresponds to the upper boundary of the Lenarczyce Formation (new, this paper), i.e., at the sharp contact of a basal breccia of the mudstone succession with the underlying greenish grey sandstone bed at the top of the Lenarczyce Formation (new, this paper); in the northern Holy Cross Mountains (Łysogóry Region), the lower boundary corresponds to the upper boundary of the Ameliówka Formation (new, this paper). The upper boundary is placed at the sharp contract with the overlying Lower Ordovician conglomerates of the Kędziorka Formation or glauconitic sandstones of the Międzygórz Formation (southern Holy Cross Mountains – Kielce Region), or Middle Ordovician limestones of the Pobroszyn Formation (northern Holy Cross Mountains – Łysogóry Region; see Trela 2006) <u>Thickness</u>: from 30 m in the southern Holy Cross Mountains (Kielce Region) up to 150 m in the northern Holy Cross Mountains (Łysogóry Region). <u>Detailed description</u>: dark grey clayey mudstones and claystones are the predominating litofacies of this formation but locally they may also be calcareous. The mudstones and claystones are mostly massive, but locally discrete submillimetre lamination is also observed. Subordinate carbonate beds/?concretions were described in these deposits from some wells. Moreover, rare siltstone and fine-grained sandstone intercalations with a sharp lower boundary are present. They can be massive or parallel to low-angle laminated (comparable to hummocky cross-stratification). <u>Chrono- and biostratigraphy</u>: upper Furongian based on trilobite fauna of the *Peltura scarabaeoides* and *Acerocare sensu lato* zones (Żylińska 2001, 2002), i.e., lower part of the *Acerocarina* Superzone; local acritarch zones: M-XI, M-XII (Szczepanik 2009, 2010; this paper). <u>Regional distribution and correlation</u>: the entire area of the northern Holy Cross Mountains (Łysogóry Region) but also eastern localities of the southern Holy Cross Mountains (Kielce Region). Wells: Kajetanów 1, Wiśniówka 1, Brzezinki 1, Brzezinki 2, Brzezinki 3, Wilków 1, Jeleniów 2, Jeleniów 3, Bukowiany 1, Bukowiany 1a, Ublinek 1, Lenarczyce PIG 1 (see Tomczyk and Turnau-Morawska 1967; Tomczykowa 1968; Orłowski 1975; Michniak and Olkowicz-Paprocka 1976; Trela 2006). Tremadocian mudstones exposed in an artificial trench in Pobroszyn (eastern Holy Cross Mountains) are also included in this formation (Trela 2006). <u>Genetic interpretation</u>: open shelf setting with deposition of fine-grained clastics from hemipelagic suspension and mud flow periodically interrupted by high-energy storm events, as described in this paper.

Table 1. Revised lithostratigraphy of the upper Furongian in the Holy Cross Mountains – characteristics of formal units.

and utilised in palaeotectonic reconstructions. Interestingly, the occurrence of upper Cambrian rocks in the southern Holy Cross Mountains was already mentioned for the first time by Samsonowicz (1920, 1934), who noted sandstones of this age occurring in the village of Lenarczyce, westward of Sandomierz, but did not provide any palaeontological documentation. Furthermore, the presence of upper Cambrian deposits in the southern Holy Cross Mountains was suggested by Bednarczyk *et al*. (1970) for sandstones and mudstones in the depth interval 109.7–580.0 m of the Barwinek 1 well located in the southern part of Kielce city. However, such a stratigraphic position of these strata was questioned by Orłowski and Mizerski (1996), who provided lithostratigraphic arguments for their being of early Cambrian age; this notion was later supported by acritarch analysis (ZS, unpublished data). Undoubtedly, the presence of upper Furongian grey mudstones was documented in the eastern part of the Kielce region (Ublinek 1bis well; Text-fig. 1C) on the basis of acritarch microphytoplankton (Szczepanik 1996); the analysed strata were earlier considered to be of Tremadocian age (Michniak and Olkowicz-Paprocka 1976). Kowalczewski (1990) introduced the Ublinek Formation to encompass these mudstones in his proposed lithostratigraphic scheme for the Cambrian of southern Poland (including the Holy Cross Mountains), but did not provide a formal definition of the unit. Cambrian siliciclastic rocks including a Furongian succession were drilled in the Lenarczyce PIG 1 well located in the eastern part of the southern Holy Cross Mountains (Text-fig. 1C); they were described in general terms by Szczepanik *et al.* (2004a). That preliminary report shed new light on the tectonic and sedimentary evolution of the southern Holy Cross Mountains in the late Cambrian, but lacked a detailed stratigraphic approach, sedimentological and facies analysis, and related sedimentary settings, as well as a thorough analysis of the mutual relation of Furongian strata in both regions of the Holy Cross Mountains. In this paper we have undertaken an attempt to fill this interpretational gap, focusing on the Miaolingian to Furongian succession from the Lenarczyce PIG 1 well (Text-figs 1C and 2), and concentrating on a detailed sedimentological and facies analysis, and the late Cambrian evolution of the Holy Cross Mountains in a broader stratigraphic, regional and tectonic context. Moreover, in this report we present for the first time a comprehensive study of the characteristics of Furongian acritarch microphytoplankton assemblages in the northern part of the Małopolska Block and their stratigraphic aspects.

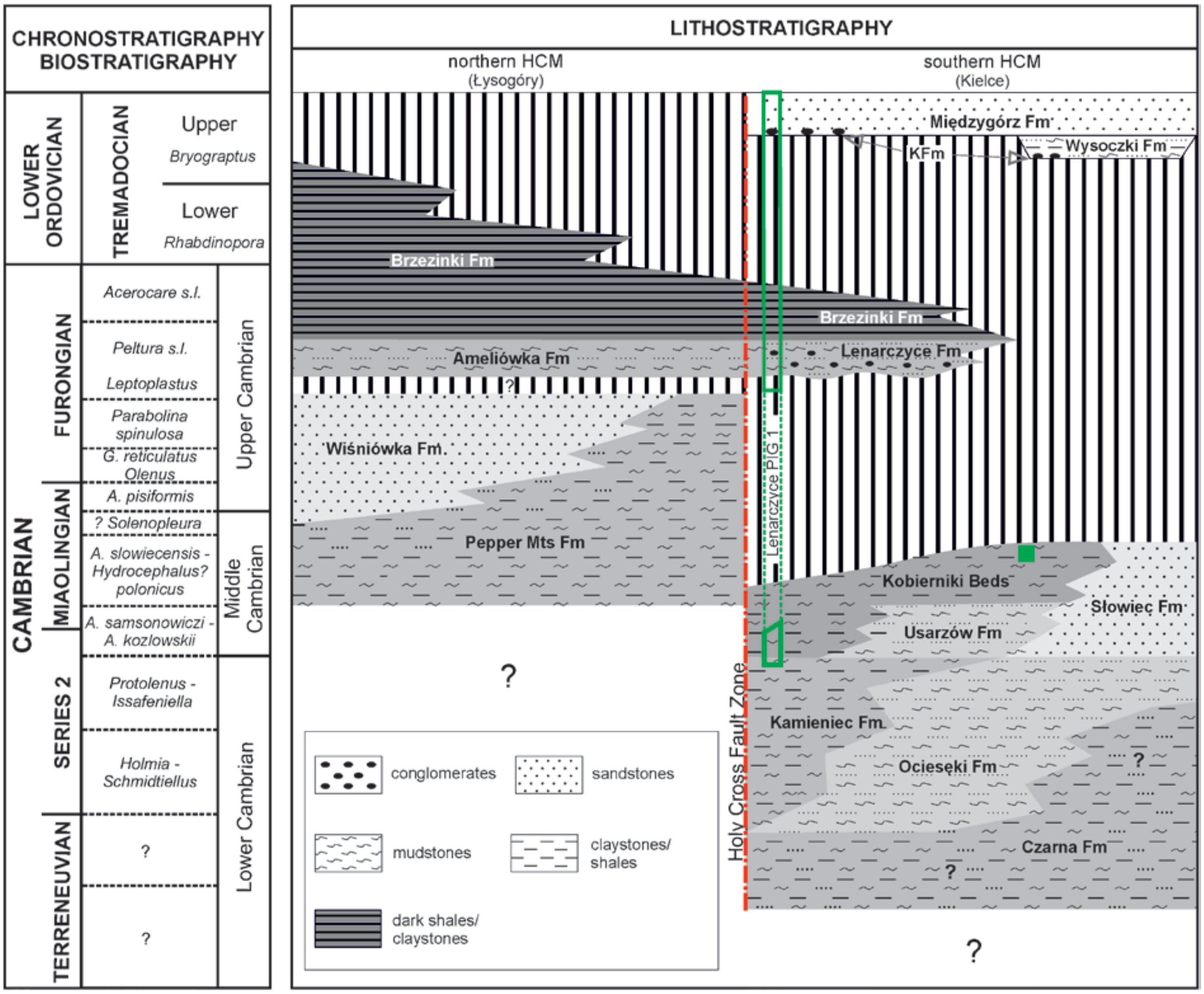
GEOLOGICAL SETTING

The sedimentary succession of the Palaeozoic in the Holy Cross Mountains is developed on a so far undrilled but geophysically recognised basement composed of variously interpreted crustal fragments included in the TESZ (see overviews in Pożaryski 1990; Pharaoh 1999; Nawrocki 2015; Aleksandrowski and Mazur 2017; Mazur *et al.* 2017; Narkiewicz and Petecki 2017; Walczak and Belka 2017). The Palaeozoic succession was exposed from underneath a Permian–Mesozoic cover following the Late Cretaceous–Early Paleogene tectonic inversion and uplift (Kutek and Głazek 1972; Krzywiec *et al.* 2009).

Breaks in the stratigraphic record within the Palaeozoic succession are marked both by stratigraphic gaps and angular unconformities, but the number, magnitude, and lateral extent of the hiatuses vary over the area. The presence of some of these discrepancies and facies differences had led Czarnocki (1919, 1950) to sub-divide the Palaeozoic inlier (Palaeozoic core in older literature) into two facies regions: the northern Łysogóry Region and the southern Kielce Region. These regions correspond to the Łysogóry Fold Zone and the Kielce Fold Zone, respectively, of the Holy Cross Mountains Fold Belt (see Konon 2008), and are separated by the WNW-ESE trending Holy Cross Fault (Text-fig. 1B). This fault has been interpreted as either a border between the Małopolska Block (with the Kielce Region in its northernmost part) and the East European Platform (with Łysogóry located on its south-western margin), or as the boundary between the Małopolska and Łysogóry terranes or blocks (Pożaryski 1990; Dadlez *et al.* 1994; Aleksandrowski and Mazur 2017; Narkiewicz and Petecki 2017; Text-fig. 1B). Therefore, the regions are understood either as tectono-stratigraphic domains, or palaeogeographic units of proximal *vs.* exotic provenance in relation to the Baltica palaeocontinent (e.g., Pożaryski 1990; Lewandowski 1993; Dadlez *et al.* 1994; Belka *et al.* 2000, 2002; Nawrocki *et al.* 2007; Narkiewicz and Petecki 2017; Walczak and Belka 2017). According to Żelaźniewicz *et al.* (2011, 2020), the northern boundary of the Małopolska Block is delineated by the Chmielnik-Ryszkowa Wola Fault Zone, along which it is in contact with the Holy Cross Mountains Fold belt (Text-fig. 1B).

The Cambrian System in the Holy Cross Mountains is developed as a thick, generally shallow marine, siliciclastic succession encompassing distal offshore to shoreface facies, and sub-divided into formal and informal lithostratigraphic units (see Text-fig. 3 and Table 1) that reveal a high degree of tectonic deformation (e.g., Orłowski 1975; Kowalczewski 2000; Gągała 2005; Kowalczewski *et al.* 2006). Comparison of these units between the southern (Kielce) and northern (Łysogóry) parts of the Holy Cross Mountains is impossible in the case of the lower Cambrian since rocks of this interval have not been recognised so far in Łysogóry due to a thick cover of stratigraphically younger strata. Stratigraphic, facies and tectonic comparisons can only be made for the lower Miaolingian and upper Furongian rocks, largely represented by shallow shelf sandstones and mudstones, which occur in both regions of the Holy Cross Mountains (Text-fig. 3).

Several angular unconformities have been identified in the Palaeozoic succession of the Holy Cross Mountains. Deformation related to the two older unconformities has been noted only in the Terreneuvian to lower Miaolingian of the Kielce Region, because the age-equivalent rock succession is not exposed to the north of the Holy Cross Fault. The two younger unconformities (Variscan and Alpine) have been documented in the entire Holy Cross Mountains area and its vicinity. The lowermost unconformity, attributed to the mid-Cambrian Holy Cross deformation phase (Tomczyk 1964) and so far recognised



Text-fig. 3. Lithostratigraphy of the Cambrian in the Holy Cross Mountains (after Orłowski 1975 and Kowalczewski *et al.* 2006, modified) with the succession depicted in the Lenarczyce PIG 1 well marked by a vertical green bar; green square marks the Miaolingian deposits cropping out in Lenarczyce village. Abbreviations: KFm – Kędziorka Formation.

only in the Kielce Region (Szczepanik *et al.* 2004a; Salwa *et al.* 2006), is discussed in detail herein. The succeeding unconformity is attributed to the Sandomierz (or Sandomirian) deformation spanning the Cambrian–Ordovician boundary (Samsonowicz 1934). In the southernmost part of the Holy Cross Mountains, upper Tremadocian strata rest directly on sandstones and mudstones spanning Cambrian Series 2 and the lower Miaolingian (Text-fig. 3). The stratigraphic gap attributed to this unconformity narrows gradually northeastwards to the Holy Cross Fault, where in its direct vicinity upper Tremadocian conglomerates overlie upper Furongian mudstones (Szczepanik *et al.* 2004a; Salwa *et al.* 2006; Text-fig. 3).

GEOTECTONIC PROVENANCE OF THE MAŁOPOLSKA AND ŁYSOGÓRY BLOCKS – A BRIEF SYNTHESIS

The geotectonic origin of the Małopolska and Łysogóry blocks – being part of the TESZ in Poland – has been discussed for over three decades. Based on detrital mica and zircon ages, deep-seismic experiments, and palaeomagnetic data, a relationship with Baltica or conversely Gondwana has been postulated (e.g., 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).

Dadlez *et al*. (1994) treated the Łysogóry Block as part of the passive margin of Baltica, a notion that has been supported by recent deep-seismic soundings indicating the similarity of the crystalline crust between these areas (Malinowski *et al*. 2005). Therefore, this unit is currently considered as a proximal terrane of Baltica (e.g., Narkiewicz and Petecki 2017), which is in agreement with palaeomagnetic data (Nawrocki *et al*. 2007).

In turn, the Małopolska Block is considered as, either: 1) a proximal terrane of Baltica that was dextrally relocated and accreted to this palaeocontinent in the late Silurian to earliest Devonian times (Dadlez *et al*. 1994) or even in the late Carboniferous (Lewandowski 1993), or 2) 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). Based on deep-seismic sounding experiments, Malinowski *et al*. (2005) postulated the similarity of the crustal structure between the Małopolska Block and the East European Platform. However, data from deep reflection seismic profiles in south-eastern Poland were used as argument for the peri-Gondwanan affinity of the Małopolska Block, characterised by the presence of an Avalonia-type crust (Malinowski *et al*. 2013, 2015). Remarkably, Mazur *et al*. (2017) speculated a continuation of Baltica's crust to the south-west of the Teisseyre-Tornquist Zone similarly as in central and western Poland (Mazur *et al*. 2015).

According to Żelaźniewicz *et al*. (2020), the Cambrian sedimentary succession of the Kielce and Łysogóry regions of the Holy Cross Mountains was deposited in a narrow, fault-controlled, shallow shelf basin that developed over the thinned Baltica margin (Jaworowski and Sikorska 2006). In the Cambrian, both areas received detrital material from the peri-Gondwanan fragments of the Cadomian orogen and the Mesoproterozoic sources on Baltica (Belka *et al*. 2000, 2002; Nawrocki *et al*. 2007; Żelaźniewicz *et al*. 2020). The most recent interpretation of the isotopic composition of the detrital zircons in the Cambrian sediments of the Holy Cross Mountains suggests that, similarly as in Podolia (Ukraine), they were sourced from a continental arc established on the Baltica margin being an equivalent of the Cadomian Arc on the opposite side of the Mirovoi Ocean (Callegari *et al*. 2025).

MATERIALS AND METHODS

Multidisciplinary geological studies conducted on samples from the Lenarczyce PIG 1 core included biostratigraphic analysis based on acritarch phytoplankton assemblages, coupled with trilobite and brachiopod data, as well as sedimentological and facies analysis.

Depth interval [m]	Stratigraphy				Lithology
	System	Series	Stage/Substage	Lithostratigraphy	
24.0–26.0	Silurian	Wenlock		Prągowiec Beds (after Tomczyk 1962; Tomczykowa and Tomczyk 1981)	grey graptolite shales
26.0–32.7	Ordo-vician	Middle Ordovician		Bukówka Formation (after Trela 2006)	greenish grey sandstones and calcareous sandstones
32.7–33.5					sandstone breccia
33.5–38.9		Lower Ordovician	lowermost Floian/ upper Tremadocian	Międzygórz Formation (after Trela 2006)	glauconitic sandstones
38.9–39.4			upper Tremadocian	Kędziorka Formation (after Trela 2006)	glauconitic pebbly sandstones and conglomerates
39.4–68.2	Cam-brian	Furongian	Stage 10	Brzezinki Formation (this paper)	dark grey clayey mudstones with subordinate intercalations of siltstones and fine-grained sandstones (Text-figs 2, 3; Table 1)
68.2–133.5			?Jiangshanian	Lenarczyce Formation (new, this paper)	sandstone intervals separated by mudstone-sandstone heterolithic intervals with conglomerate interbeds (Text-figs 2, 3; Table 1); lowermost part disturbed by tectonic breccias
133.5–150.0		Miaolingian	?Wuliuan	Kobierniki Beds (after Szczepanik *et al.* 2004a)	mudstones with thin siltstone interbeds interrupted by tectonic breccia (Text-figs 2, 3)

Table 2. Chrono- and lithostratigraphy of the Lenarczyce PIG 1 well with depth intervals and characteristic lithologies.

A total of 18 samples were collected for palynological testing, including 11 samples from depth interval 128.0–150.0 m and 7 samples from depth interval 39.6–128.0 m (Text-fig. 2). All samples were subjected to classical palynological maceration. Approximately 100 g of sample were firstly treated in cold hydrofluoric acid, then in hot hydrochloric acid, filtrated on 15 µm mesh membranes, and finally macerated again in cold hydrofluoric acid. The obtained residue was then centrifuged in heavy liquid. Glyceryne-gelatine micoscope slides were prepared and analysed with bright field microscopy (Olympus BX51 microscope) at magnifications between ×300 and ×1200. The identified acritarch specimens were documented as graphic files using a microcamera connected to a computer. All slides are housed in the Holy Cross Branch of the Polish Geological Institute – National Research Institute in Kielce.

The studied core was examined at a centimetre-scale for lithological and sedimentological features. The observations were concentrated chiefly on grain size, rock colour, thickness, sedimentary and erosional structures, ichnofabric and trace fossils, and contacts between individual lithological units. Selected samples (30 thin sections) were analysed using standard microscopic techniques to recognise petrographic features and the microfabric of the studied rocks. The core was also examined for macrofauna. All specimens of macrofauna are housed in the Stanisław Józef Thugutt Museum of the Faculty of Geology, University of Warsaw (collection of Anna Żylińska, MWGUW ZI/66).

LITHOSTRATIGRAPHY AND TECTONICS OF THE LENARCZYCE PIG 1 WELL

The Palaeozoic succession in the Lenarczyce PIG 1 well occurs under a Quaternary loess cover (24 m thick), and comprises Silurian, Ordovician and Cambrian clastic rocks (Text-fig. 2 and Table 2). The Cambrian succession consists of lower Miaolingian, referred to as the Kobierniki Beds, and upper Furongian strata. The upper Furongian succession of the entire Holy Cross Mountains is sub-divided in this work into three formal lithostratigraphic units (Table 1) comprising the Lenarczyce Formation (new), Ameliówka Formation (new), and Brzezinki Formation (emended). The formations are defined according to the classification of the International Commission on Stratigraphy under the auspices of IUGS.

A preliminary tectonic analysis of the Cambrian succession in the Lenarczyce PIG 1 well was presented by Szczepanik *et al.* (2004a) and Salwa *et al.* (2006) and is summarised herein. Two tectonically different intervals were recognised: 1) the intensely folded and thrusted Kobierniki Beds and the lowermost part of the Lenarczyce Formation (below the depth of 127.8 m), and 2) the less deformed Lenarczyce Formation (above the depth of 127.8 m) and the Brzezinki Formation (Text-fig. 2). The tectonic style of the Koberniki to lowermost Lenarczyce interval is characterised by: 1) bedding dips showing a significant variability along relatively short sections, from subhorizontal (5–15º) to nearly vertical (70–88º), 2) thrust-related faults oriented obliquely at low angles to the bedding planes with usually constant angular relationship, 3) concentric or similar folds associated with low-angle thrusts that sometimes form up to 10 cm thick ductile-brittle shear zones, and 4) younger strike-slip faults showing almost horizontal tectonic slickensides, but with indeterminable directions of displacement (Salwa *et al.* 2006). In turn, the characteristics of the remaining part of the Lenarczyce Formation and the overlying Brzezinki Formation include: 1) bedding dips in the range of 32–50º, exceeding 55º only in narrow and severely deformed zones, 2) absence of folds and occurrence of brecciated zones in the lowermost part of this interval, 3) small-scale thrusts identified on the boundaries of complexes showing different lithologies, and 4) less common strike-slip faults cutting the bedding planes at low angles (Salwa *et al*. 2006).

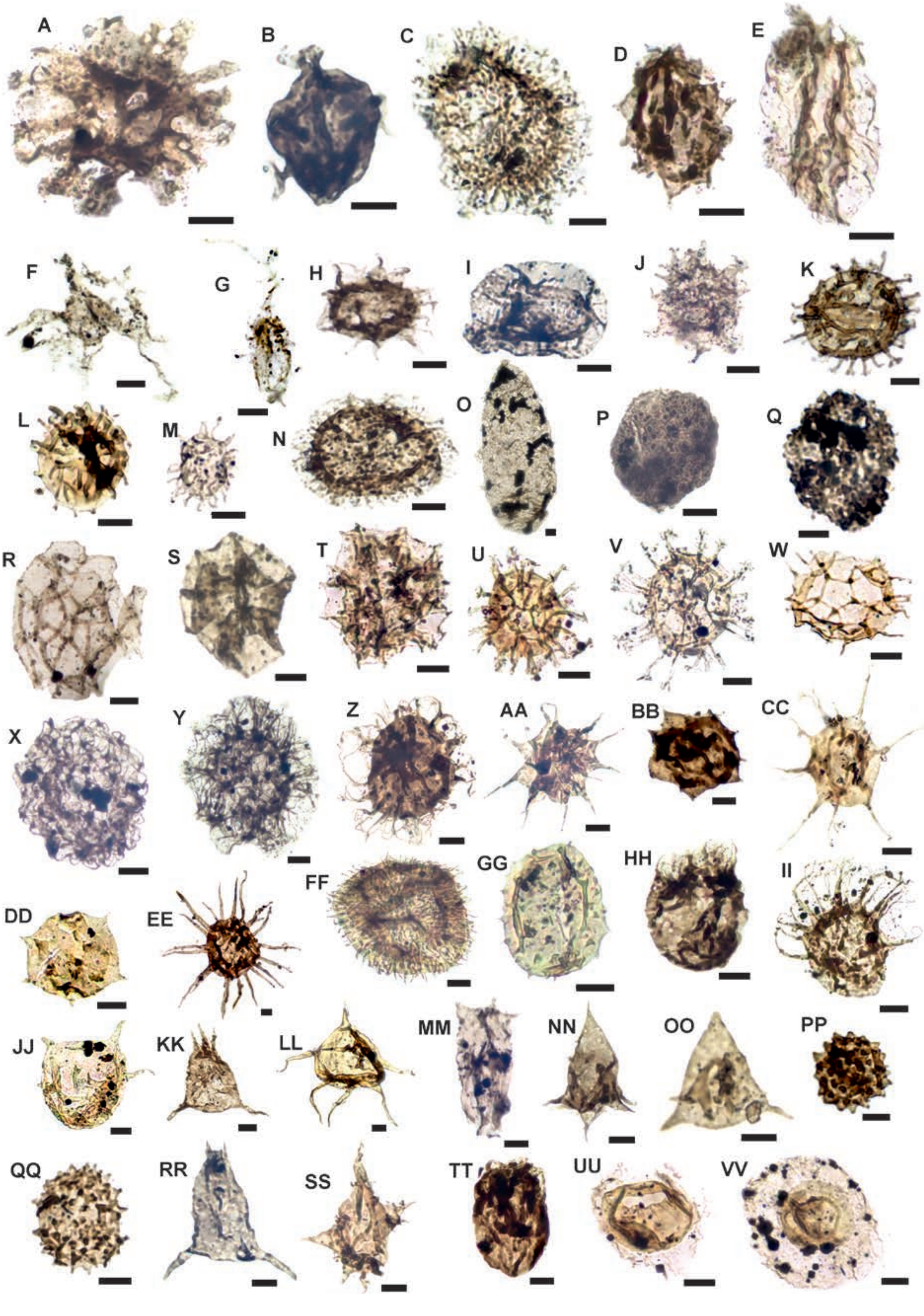
The overlying Ordovician and Silurian rocks reveal a tectonic pattern similar to the underlying Lenarczyce (above 127.8 m) and Brzezinki formations (Szczepanik *et al*. 2004a; Salwa *et al*. 2006). Worth noting is the lack of difference in the dip angle between the Furongian and Ordovician strata which are separated by an erosional unconformity with a stratigraphic gap including the lower Tremadocian (Text-fig. 2).

BIOSTRATIGRAPHY OF THE CAMBRIAN SUCCESSION

Acritrach assemblages and palynostratigraphy

The oldest acritarch assemblage (A1 in Text-fig. 2) was found in depth interval 138.4–135.3 m. Only a few forms of no stratigraphic significance were encountered below (150.0–138.4 m) and these are not discussed here. Assemblage A1 is sparse, with many specimens unrecognisable even at generic level. Nevertheless, the general characteristics of this assemblage and some better preserved specimens (Text-fig. 4A–Q) allow for a more comprehensive analysis. The most abundant are spherical or close to spherical forms representing *Leiosphaeridia* spp. and *Lophosphaeridium* spp., accompanied by *Comasphaeridium* spp., as well as specimens (or their fragments) representing the informal group Herkomorphitae, with the surface of the central body divided into regular or irregular polygons (?*Retisphaeridium* sp., ?*Cristallinium* sp., ?*Dictyotidium* sp., ?*Cymatiosphaera* sp.). Relatively common is *Liepaina plana* Yankauskas and Volkova in Volkova *et al*., 1979 (Text-fig. 4A), the index taxon of the *Volkovia–Liepaina* Zone (Moczydłowska 1991), widely known from the upper part of Cambrian Series 2 on the East European Platform (Volkova *et al.* 1983; Moczydłowska 1991, 1999), but recognised also from the lowermost Miaolingian of that area (Volkova *et al.* 1983), Spain (Palacios 2015; Palacios *et al.* 2021), northern Norway (Palacios *et al.* 2020, 2022), and Gotland in Sweden (Hagenfeldt 1989a, b). Another characteristic taxon is *Skiagia insignis* (Fridrichsone, 1971) Downie, 1982 (Text-fig. 4B), spanning the uppermost lower to basal middle Cambrian (Volkova *et al.* 1983; Hagenfeldt 1989a, b). A different species of *Skiagia*, i.e., *S. ciliosa* (Volkova, 1969) Downie, 1982 (Text-fig. 4N), is common in the lower Cambrian, but also noted in the Miaolingian *Acadoparadoxides oelandicus* Superzone (Volkova *et al.* 1983; Hagenfeldt 1989b; Eklund 1990; Moczydłowska 1998, 1999). Stratigraphically significant are *Ammonidium* cf. *notatum* (Volkova, 1969) Jachowicz-Zdanowska, 2013 (Text-fig. 4M) and *Eklundia varia* (Volkova, 1969) Jachowicz-Zdanowska, 2013 (Text-fig. 4H) noted widely in the *Protolenus* Zone and the lower *A. oelandicus* Superzone (Vanguestaine and van Looy 1983; Volkova *et al.* 1983; Hagenfeldt 1989a, b; Moczydłowska 1998; Palacios *et al.* 2006). An important and significant element of this assemblage is *Eliasum* cf. *llaniscum* Fombella, 1977 (Text-fig. 4E), the index taxon of the lower Miaolingian (Moczydłowska 1998, 1999; Palacios and Moczydłowska 1998), although the species was reported from the uppermost lower Cambrian (Volkova *et al.* 1979; Hagenfeldt 1989a; Young *et al.* 1994). Jankauskas and Lendzion (1992, 1994) suggested that *E. llaniscum* and other representatives of the Kibartian Acritarch Horizon appear already in the Rausve Acritarch Horizon, but this view was doubted by Moczydłowska (1998, p. 68). In the Holy Cross Mountains, representatives of *Eliasum* spp. evidently first appear in the *Volkovia–Liepaina* Zone, co-occurring with trilobites indicative of the *Protolenus*–

Text-fig. 4. Acritarchs from the Kobierniki Beds, and the Lenarczyce and Brzezinki formations in the Lenarczyce PIG 1 well. Symbols refer to number of slide and location of specimen according to England Finder. A – *Liepaina plana* Yankauskas and Volkova in Volkova *et al*., 1979; 5287C-G35-4, 138.4 m. B – *Skiagia insignis* (Fridrichsone, 1971) Downie, 1982; 5285-P45-4, 136.2 m. C – *Comasphaeridium silesiense* Moczydłowska, 1998; 5284-L35, 135.3 m. D – *Adara alea* Martin in Martin and Dean, 1981; 5287C-J44, 138.4 m. E – *Eliasum* cf. *llaniscum* Fombella, 1977; 5287A-O42-4, 138.4 m. F – *Comasphaeridium longispinosum* Hagenfeldt, 1989b; 5285-C35-4, 136.2 m. G – ?*Volkovia* sp.; 5285-X45, 136.2 m. H – *Eklundia varia* (Volkova, 1969) Jachowicz-Zdanowska, 2013; 5285-U47-2, 136.2 m. I – *Pterospermella vitalis* Yankauskas in Volkova *et al*., 1979; 5287B-Z39-1, 138.4 m. J – *Multiplicisphaeridium xianum* Fombella, 1977; 5287B-J43, 138.4 m. K – *Multiplicisphaeridium* cf. *sosnowiecense* Moczydłowska, 1998; 5287-C48-4, 138.4 m. L – *Celtiberium dedalinum* Fombella, 1977; 5287B-Z39-1, 138.4 m. M – *Ammonidium* cf. *notatum* (Volkova, 1969) Jachowicz-Zdanowska, 2013; 5285-S37, 136.2 m. N – *Skiagia ciliosa* (Volkova, 1969) Downie, 1982; 5284-Y48-3, 135.3 m. O – *Leiovalia tenera* Kiryanov, 1974; 5284-M39-3, 135.3 m. P – *Tubulosphaera* cf. *craterae* Palacios, 2015; 5287C-X39-2, 138.4 m. Q – *Lophosphaeridium latviense* (Volkova, 1974) Moczydłowska, 1998; 5284-Z39-1, 135.3 m. R – *Retisphaeridium dichamerum* Staplin, Jansonius and Pocock, 1975; 5252-D39, 131.7 m. S – *Cristallinium cambriense* (Slavíková, 1968) Vanguestaine, 1978; 5282-D32-3, 132.2 m. T – *Izhoria angulata* Golub and Volkova in Volkova and Golub, 1985; 7770-H46, 39.5 m. U – *Timofeevia phosphoritica* Vanguestaine, 1978; 7770-K43, 39.5 m. V – *Timofeevia lancarae* (Cramer and Díez, 1972) Vanguestaine, 1978; 5252-G42-1, 131.7 m. W – *Timofeevia pentagonalis* (Vanguestaine, 1974) Vanguestaine, 1978; 5122-E28-3, 103.0 m. X – ?*Vulcanisphaera* sp.; 5249A-R35, 128.9 m. Y – *Vulcanisphaera africana* Deunff, 1961, emend. Kroeck *et al.*, 2020; 5249A-C33-2, 128.9 m. Z – *Vulcanisphaera simplex* Jardiné, Combaz, Magloire, Peniguel and Vachey, 1974, emend. Kroeck *et al*., 2020; 7775-O49-3, depth 50,5 m. AA – *Polygonium pungens* (Timofeev, 1959 *ex* Martin, 1968) Albani, 1989; 5122-C29, 103.0 m. BB – *Polygonium minimum* (Timofeev, 1959) Volkova, 1990; 5282-S34, 132.2 m. CC – *Polygonium uncinatum* (Downie, 1958) Richardson and Rasul, 1978; 7775-K37, 50.5 m. DD – *Solisphaeridium chinese* Moczydłowska and Stockfors, 2004; 5122-N26, 103.0 m. EE – *Solisphaeridium cylindratum* Moczydłowska, 1998; 5282-D39, 132.2 m. FF – *Trichosphaeridium hirtum* (Timofeev, 1959) Timofeev, 1976; 5122-O37, 103.0 m. GG – *Trichosphaeridium annolovaense* Timofeev, 1966; 5122-D39, 103.0 m. HH – *Calyxiella izhoriensis* Golub and Volkova in Volkova and Golub, 1985; 5249A-A28-2, 128.9 m. II – *Trunculumarium revinium* (Vanguestaine, 1973) Loeblich and Tappan, 1976; 5122-Z34-2, 103.0 m. JJ – *Scalenadiacrodium comleyense* Potter, Pedder and Feist-Burkhardt, 2012; 5122-D36, 103.0 m. KK – *Nellia sukatschevii* (Timofeev, 1959) Volkova, 1998; 7773-D45, 42.5 m. LL – *Nellia acifera* (Umnova in Umnova and Vanderflit, 1971) Volkova, 1998; 5122-T39, 103.0 m. MM – *Nellia magna* Volkova, 1990; 5121-A36, 39.7 m. NN – *Ninadiacrodium caudatum* (Vanguestaine, 1973) Raevskaya and Servais, 2009; 5249A-H27-3, 128,9 m. OO – *Ninadiacrodium dumontii* (Vanguestaine, 1973) Raevskaya and Servais, 2009; 5282A-D32-3, 132.2 m. PP – *Buedingiisphaeridium tremadocum* Rasul, 1979; 5282-H46, 132.2 m. QQ – *Acanthodiacrodium snookense* Parsons and Anderson, 2000; 5283-U-45, 134.5 m. RR – *Ruvalia triangulata* Volkova, 1999; 5121-U31, 39.7 m. SS – *Dasydiacrodium* cf. *tricorne* Timofeev, 1959 *ex* Downie and Sarjeant, 1965; 7770-T50, 39.5 m. TT – *Ooidium* sp.; 5122A-E_40, 103.0 m. UU, VV – *Ellenia armilata* (Vanderflit in Umnova and Vanderflit, 1971) Volkova, 1984; UU – 7775-O50, 50.5 m; VV – 7770-U37_2, 39.5 m. Scale bars equal 10 µm.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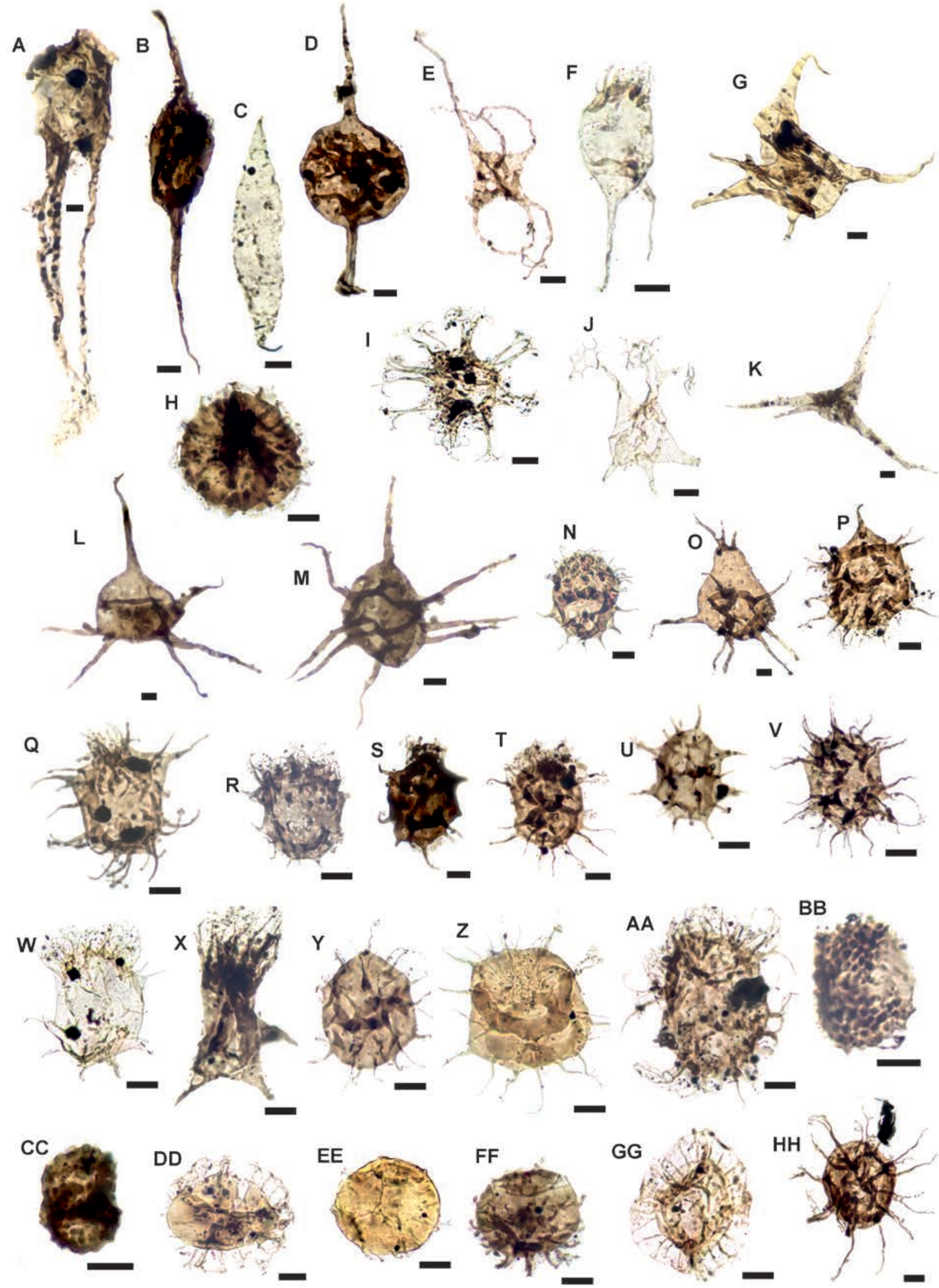
Issafeniella Zone (Żylińska and Szczepanik 2009, their pl. 7). However, in the Lenarczyce PIG 1 well, forms of *Eliasum* spp. are very rare, with only three specimens noted. Acritarchs whose range is strictly restricted to the Miaolingian are represented in assemblage A1 by *Comasphaeridium silesiense* Moczydłowska, 1998 (Text-fig. 4C). This taxon was recorded in the Cambrian strata of Upper Silesia (southern Poland), which Moczydłowska (1998) referred to the Furongian, whereas Buła and Jachowicz (1996) and Jachowicz-Zdanowska (2013) considered the strata to be Miaolingian. In Spain, *C. silesiense* was recognised as the index taxon of the *C. silesiense* Zone (Palacios *et al*. 2006), which is the equivalent of the *A. oelandicus* Superzone. Such a stratigraphic position is also suggested by *Comasphaeridium longispinosum* Hangenfeldt, 1989b (Text-fig. 4F), *Lophosphaeridium* cf. *latviense* (Volkova, 1974) Moczydłowska, 1998 (Text-fig. 4Q), and *Celtiberium dedalinum* Fombella, 1977 (Text-fig. 4L). Assemblage A1 shows large similarities to the Kibartian association from the Baltic region (Lithuania, Latvia). Interestingly, in some successions (e.g., the lower–middle Cambrian of Finnmark, Norway), *S. ciliosa* occurs only in older rocks together with acritarchs indicative for the lowermost Miaolingian (Palacios *et al*. 2022), and its occurrence within the Kibartian assemblage may be explained by redeposition.

The taxon whose presence hinders the stratigraphic interpretation of the assemblage is *Adara alea* Martin in Martin and Dean, 1981 (Text-fig. 4D), reported so far exclusively from the upper Miaolingian *P. paradoxissimus* Superzone (e.g., Martin and Dean 1981, 1988; Moczydłowska 1998; Palacios *et al*. 2006; Jachowicz-Zdanowska 2013). In the extensively studied and apparently continuous successions of the Kisteldalen Formation in northern Norway (Palacios *et al.* 2022) and the Ossa Morena successions in Spain (Palacios *et al.* 2021), representatives of *Adara* spp. appear much higher stratigraphically compared to the remaining forms described from the Lenarczyce PIG 1 well. Therefore, the co-occurrence of these forms in one sample cannot be unequivocally explained. The possibility that the sample was contaminated during the maceration should be ruled out, as no other samples were processed with it. Acritarch redeposition in response to the transgression following the Hawke Bay regressive event can be rejected since in the sections from the Holy Cross Mountains and adjacent areas (Szczepanik 2001; Żylińska and Szczepanik 2009), as well as numerous successions recording the upper part of the *A. oelandicus* Superzone (e.g., Szczepanik 2000) or *P. paradoxissimus* Superzone, the acritarch asssemblages are dominated by *Cristallinium cambriense* (Slavíková, 1968) Vanguestaine, 1978 and *Cymatiosphaera cramerii* Slavíková, 1968, which are absent in samples from the Lenarczyce PIG 1 well. Moreover, representatives of *Eliasum* spp., typical for the Miaolingian of the Holy Cross Mountains, are very rare in this well. Due to the same reasons, and the generally large thicknesses of Cambrian strata in the Holy Cross Mountains, the presence of condensed intervals, in which mixing of acritarchs characterised by different stratigraphic ranges elsewhere could have taken place, seems highly improbable in the case of the analysed succession. Therefore, the most plausible interpretation imposes the presence

Text-fig. 5. Acritarchs from the Lenarczyce and Brzezinki formations in the Lenarczyce PIG 1 well. Symbols refer to number of slide and location of specimen according to England Finder. A – *Arbusculidium perlongum* Di Milia, Ribecai and Tongiorgi, 1989; 7775-P46, 50.5 m. B – *Leiofusa stoumonensis* Vanguestaine, 1973; 5252-R32, 131.7 m. C – *Poikilofusa squama* (Deunff, 1961) Martin, 1973; 5282A-E35, 132.2 m. D – *Lusatia* sp.; 5282A-F41, 132.2 m. E – *Dasydiacrodium veryhachioides* Di Milia, Ribecai and Tongiorgi, 1989; 5249-V26, 128.9 m. F – ?*Buchinia* sp.; 7770-K38, 39.5 m. G – *Estiastra* cf. *magna* Eisenack, 1959; 5122-T39, 103.0 m. H – *Athabascella* sp.; 7775-E36, 50.5 m. I – *Vogtlandia notabilis* Volkova, 1990; 7775-H44, 50.5 m. J – *Vogtlandia petropolitana* (German and Timofeev, 1974) Volkova, 1990; 5122A-G37, 103.0 m. K – *Estiastra* sp. 1; 5249-Z37, 128.9 m. L – *Gigadiacrodium martinae* (Pittau, 1985) Szczepanik, Servais and Żylińska, 2017; 5282A-D35-2, 132.2 m. M – *Gigadiacrodium vidalii* Szczepanik, Servais and Żylińska, 2017; 5249-V33, 128.9 m. N – *Dasydiacrodium* sp. 1; 5122-C35, 103.0 m. O – *Dasydiacrodium* sp. 2; 5250-D44-2, 129.3 m. P – *Dasydiacrodium* cf. *obsonum* Martin, 1988; 5122-A42-4, 103.0 m. Q – *Ladogella rotundiformis* Golub and Volkova in Volkova and Golub, 1985; 5252-R40, 131.7 m. R – *Ladogella rommelaerei* (Martin in Martin and Dean, 1981) Di Milia, Ribecai and Tongiorgi, 1989; 5252-T30, 131.7 m. S – *Ladogella volkovae* Di Milia, Ribecai and Tongiorgi, 1989; 5282A-O39, 132.2 m. T – *Ladogella*? cf. *intermedia* Parsons and Anderson, 2000; 5249A-D48-3, 128.9 m. U – *Actinotodissus achrasii* (Martin, 1973) Yin, 1986; 5283-F29_4, 134.5 m. V – *Acanthodiacrodium* cf. *petrovii* Timofeev, 1959; 5249A-T41_3, 128.9 m. W – *Arbusculidium* cf. *A. polypus* Di Milia, Ribecai and Tongiorgi, 1989; 5122-X37, 103.0 m. X – *Arbusculidium polypus* Di Milia, Ribecai and Tongiorgi, 1989; 7775-E35_2, 50.5 m. Y – *Actinotodissus* cf. *crinitus* (Rasul, 1979) Moczydłowska and Stockfors, 2004; 5122A-V35, 103.0 m. Z – *Actinotodissus formosus* (Górka, 1967) Moczydłowska and Stockfors, 2004; 5122-H36_3, 103.0 m. AA – *Schizodiacrodium brevicrinitium* Golub and Volkova in Volkova and Golub, 1985; 7775-D37, 50.5 m. BB, CC – *Acanthodiacrodium* cf. *angustum* (Downie, 1958) Combaz, 1967; BB – 7770-H50_1, 39.5 m; CC – 7770-K37_3, 39.5 m. DD – *Cymatiogalea velifera* (Downie, 1958) Martin, 1968; 7770-S43_3, 39.5 m. EE – *Cymatiogalea cristata* (Downie, 1958) Rasul, 1974; 5122-C26, 103.0 m. FF – *Cymatiogalea bellicosa* Deunff, 1961; 7773-P42, 42.5 m. GG – *Cymatiogalea* cf. *membranispina* Deunff, 1961; 7770-J41, 39.5 m. HH – *Baltisphaeridium capillatum* (Naumova, 1950) Umnova, 1975; 7773-C29, 42.5 m. Scale bars equal 10 μm.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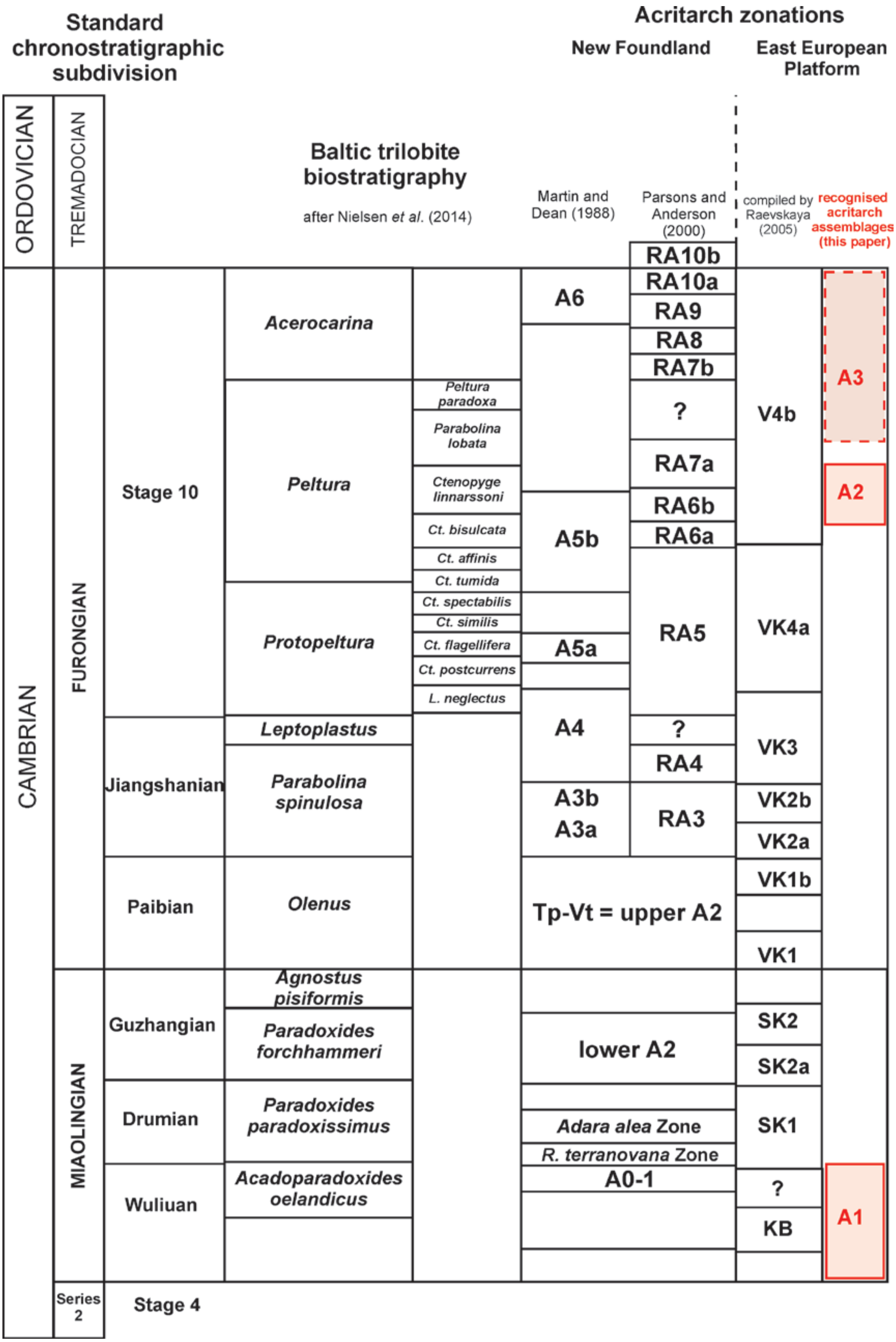
of a uniform assemblage that may be transitional between the Kibartian and the *Eliasum–Cristallinum* assemblages. It could have existed during the interval corresponding to the Hawke Bay regression, and its lack in the successions from Baltoscandia or the East European Platform may have resulted from regression, as already suggested by studies of trilobites from the Holy Cross Mountains (Żylińska and Masiak 2007). Worth mentioning is the presence of *Adara alea* in the Cambrian Series 2 of China (Yin *et al.* 2020), where it was supposed to co-occur with *Skiagia* spp. and serve as the index taxon of the local *Adara alea–Skiagia ornata* Zone. However, the poor preservation of the acritarchs from the Balang Formation in China, recognised and illustrated in Yin *et al.* (2020), hinders such strong conclusions and further studies are required to solve the problem. Taking into account all the presented issues, it should be considered that deposits from depth interval 138.4–135.3 m (and probably the lowermost part below this interval) represent the oldest Miaolingian (Wuliuan) or span the Cambrian Stage 4-Wuliuan boundary, and should thus rather not be correlated with the *Eliasum–Cristallinium* Zone**.**

Above the depth of 134.5 m, the acritarch assemblage changes rapidly, both in terms of specimen abundance, state of preservation, and taxonomic composition (Text-figs 4 and 5). The assemblage is very numerous, perfectly preserved and with abundances varying from 300 to 1000 specimens per slide. Two microfloral assemblages were identified in depth interval 134.5–39.5 m, i.e., an older one (A2) in depth interval 134.5–103.0 m, and a younger one (A3) in depth interval 55.5–39.5 m (Text-figs 2, 6). The interval between 103.0 and 55.5 m was not sampled for microphytoplankton analysis.

Assemblage A2 contains numerous forms of the informal group Diacromorphitae with a symmetrical shape of poles (*Acanthodiacrodium* spp., *Actinotodissus* spp.), Acanthomorphidae (mainly *Polygonium* spp. and *Solisphaeridium* spp.), and specimens with a characteristic large opening, belonging to the informal 'galeate acritarchs'. This is a typical microfloral assemblage of middle Furongian and lowermost upper Furongian acritarchs, known from Cambrian successions of this age in localities adjacent to the Holy Cross Mountains (Szczepanik 2009, 2014, 2015a, b; Jachowicz-Zdanowska 2011; Szczepanik *et al.* 2017; Szczepanik and Żylińska 2017). Very similar acritarch associations were recognised in Baltica (East European Platform and Baltoscandia; Welsch 1986; Bagnoli *et al.* 1988; Di Milia *et al.* 1989; Tongiorgi and Ribecai 1990; Volkova 1990; Paalits 1992), West Avalonia (Martin and Dean 1981, 1988; Parsons and Anderson 2000), East Avalonia (Vanguestaine 1974, 1978; Ribecai and Vanguestaine 1993; Young *et al.* 1994; Moczydłowska and Crimes 1995; Bruck and Vanguestaine 2004; Vanguestaine and Bruck 2008; Potter *et al.* 2012), and different parts of Gondwana (Di Milia 1991; Vecoli 1996; Vecoli and Playford 1997; Ribecai *et al.* 2005; Albani *et al.* 2006; Araoz and Vergel 2006; Ghavidel-Syooki 2006, 2019; Vergel *et al.* 2007; Vecoli *et al.* 2008; Spina *et al.* 2017). A very characteristic feature of this assemblage is the presence of numerous very large acritarchs representing *Gigadiacrodium* spp. (Text-fig. 5L, M; see also Szczepanik *et al.* 2017), large forms of *Polygonium* spp. (Text-fig. 4AA–CC), *Solisphaeridium* spp. (Text-fig. 4DD, EE), and *Veryhachium* spp. Similar acritarchs were found in the Łysogóry Region near Mąchocice (Chabowe Doły Mill and Ravine; Szczepanik *et al.* 2017; Szczepanik and Żylińska 2017). According to biostratigraphic interpretations based on trilobites (Żylińska 2001, 2002), taxa from the lower part of the succession (Chabowe Doły Mill) indicate the *Ctenopyge tumida* Zone (as currently understood by Nielsen *et al.* 2014), while the upper part (Chabowe Doły Ravine) represents the *Ctenopyge linnarssoni* Zone. Both zones occur in the upper Furongian *Peltura* Superzone (*sensu* Nielsen *et al.* 2014; Text-fig. 6).

The Furongian acritarch assemblage recognised in the Lenarczyce succession is a combination of both assemblages from the Łysogóry Region. It contains an extremely rich assemblage with characteristic gigantic acritarchs, typical for Chabowe Doły Mill, but on the other hand contains taxa found only in the stratigraphically younger Chabowe Doły Ravine locality. The most characteristic acritarchs are large specimens of *Gigadiacrodium* spp. (Text-fig. 5L, M), *Solisphaeridium* spp. (Text-fig. 4DD, EE), *Polygonium* spp. (Text-fig. 4AA–CC), *Poikilofusa squama* (Deunff, 1961) Martin, 1973 (Text-fig. 5C), *Leiofusa stoumonensis* Vanguestaine, 1973 (Text-fig. 5B), and *Lusatia* sp. (Text-fig. 5D). Diacromorphitae are also represented in large numbers, with particularly abundant acritarchs of *Actinotodissus* spp. (Text-fig. 5U, Y, Z), with a large number of *Actinotodissus achrasii* (Martin, 1973) Yin, 1986 (Text-fig. 5U), and *Ladogella* spp. (Text-fig. 5Q–T), of which *L. rotundiformis* Golub and Volkova in Volkova and Golub, 1985 (Text-fig. 5Q) is the most numerous. Another relatively common taxon is *Vulcanisphaera africana* Deunff, 1961, emend. Kroeck *et al.*, 2020 (Text-fig. 4Y). There are also forms belonging to species that have their developmental optimum in the mid-



Text-fig. 6. Furongian acritarch assemblages from the Lenarczyce PIG 1 well against the Cambrian bio- and chronostratigraphic zonation.

dle Furongian (Volkova 1990; Parsons and Anderson 2000), but whose stratigraphic ranges also span the upper Furongian. These include *Trunculumarium revinium* (Vanguestaine, 1973) Loeblich and Tappan, 1976 (Text-fig. 4II), *Calyxiella izhoriensis* Golub and Volkova in Volkova and Golub, 1985 (Text-fig. 4HH), *Ninadiacrodium caudatum* (Vanguestaine, 1973) Raevskaya and Servais, 2009 (Text-fig. 4NN), *N. dumontii* (Vanguestaine, 1973) Raevskaya and Servais, 2009 (Text-fig. 4OO), and *Lusatia* sp. (Text-fig. 5D). *Timofeevia* spp. occurs sporadically, being represented by *T. phosphoritica* Vanguestaine, 1978 (Text-fig. 4U), *T. lancarae* (Cramer and Díez, 1972) Vanguestaine, 1978 (Text-fig. 4V), and *T. pentagonalis* (Vanguestaine, 1974) Vanguestaine, 1978 (Text-fig. 4W). Herkomorphitae acritarchs representing *Retisphaeridium* spp. and *Cristallinium* spp. (Text-fig. 4R, S) are relatively more numerous in the Lenarczyce PIG 1 succession than in the age-equivalent assemblages from Łysogóry.

The assemblage from the sample at 103.0 m is slightly different. Its taxonomic composition is generally similar to those from depth interval of 138.4–124.5 m, although representatives of *Retisphaeridium* sp., *Cristallinium* sp., and *Timofeevia* sp. are much less abundant. Instead, there are more 'galeate' forms and numerous acritarchs representing *Ladogella* spp. Forms of *Arbusculidium* spp. appear also in this interval, including the stratigraphically important *A.* cf. *polypus* Di Milia, Ribecai and Tongiorgi, 1989 (Text-fig. 5W). Representatives of *Trichosphaeridium* spp. (Text-fig. 4FF, GG), *Vogtlandia* spp. (Text-fig. 5I, J), and *Nellia* spp. (Text-fig. 4LL, MM) have here their first occurrence in the succession. The presence of a distinctive form of *Acanthodiacrodium snookense* Parsons and Anderson, 2000 (Text-fig. 4QQ), characteristic of assemblage RA6 in the acritarch zonation of Newfoundland (Parsons and Anderson 2000; Text-fig. 6), where it is present in the *Ctenopyge bisulcata* and *C. linnarssoni* trilobite zones (middle part of *Peltura* Superzone), suggests a corresponding age, which is also suggested by the presence of *Ladogiella rotundiformis* Golub and Volkova in Volkova and Golub, 1985 (Text-fig. 5Q) and *L.* cf. *intermedia* Parsons and Anderson, 2000 (Text-fig. 5T). The occurrence of *Arbusculidium* cf. *A. polypus* (Text-fig. 5W) and *Cymatiogalea* cf. *membranispina* Deunff, 1961 (Text-fig. 5GG) in the upper part of the succession (at 103.0 m) allows the reference of the strata to assemblage RA7 of the Newfoundland scheme (Parsons and Anderson 2000), correlated in that scheme with the middle part of the upper Furongian *Peltura* Superzone.

Similar conclusions can be drawn by comparing the palynomorph assemblage described from Lenarczyce with acritarchs from the East European Platform. In the biostratigraphic scheme of Volkova (1990), the assemblage can be correlated with zone VK4, with acritarchs from the depth of 103.0 m corresponding to the upper part of this zone, i.e., VK4B, which can also be correlated to the upper part of the *Peltura* Superzone.

A very rich microfloral assemblage was observed in depth interval 55.5–50.5 m; it is mostly composed of the same species described from the lower part of the succession, but occurring in different proportions (lower part of A3). Acritarchs of *Ladogella* spp. and various 'galeate' forms are very abundant here, while forms of *Polygonium* sp. and *Solisphaeridium* sp. are much less numerous. The typical *Arbusculidium polypus* (Text-fig. 5X) and the very characteristic *A. perlongum* Di Milia, Ribecai and Tongiorgi, 1989 (Text-fig. 5A) appear for the first time, as do forms of *Ellenia armilata* (Vanderflit in Umnova and Vanderflit, 1971) Volkova, 1984 (Text-fig. 4UU, VV) and *Schizodiacrodium brevicrinitium* Golub and Volkova in Volkova and Golub, 1985 (Text-fig. 5AA). The acritarch assemblage recognised in samples from depths of 55.5 and 50.5 m is very similar in its taxonomic composition to the microfloristic association (DGH 1b) from the Furongian of Öland (Di Milia *et al.* 1989), referred by those authors to Zone A5b of Martin and Dean (1988). A detailed comparative analysis of this assemblage with the Newfoundland assemblage (Parsons and Anderson 2000, p. 18) suggests that it may represent the uppermost part of the *Ctenopyge linnarssoni* Zone (*Peltura* Superzone). It is noteworthy that in this part of the succession, at the depth of 50.5 m, the presence of *Vulcanisphaera simplex* Jardiné, Combaz, Magloire, Peniguel and Vachey, 1974, emend. Kroeck *et al.*, 2020 (Text-fig. 4Z) was observed for the first time. In other successions, this taxon generally occurs only in the uppermost Furongian (*Acerocarina* Superzone; Kroeck *et al.* 2020).

The youngest microphytoplankton assemblage (uppermost part of A3, Text-fig. 6) was identified in depth interval 42.5–39.5 m, i.e., in the uppermost part of the Cambrian succession. Three samples examined from depths 42.5 m, 39.7 m, and 39.5 m display a very rich microfloristic assemblage. The morphologically most diverse 'galeates' are most abundant, with the dominating genus *Cymatiogalea* (mainly *C.* cf. *membranispina* Deunff, 1961; Text-fig. 5GG). Among Diacromorphitae (forms with a diacriodal symmetry), those with differentiated poles (*Ladogella*, *Arbusculidium* and *Dasydiacrodium*) are by far more numerous. Symmetrical forms (*Actinotodissus* and *Acanthodiacrodium*) are relatively less numerous. The presence of *Baltisphaeridium* [*B. capillatum* (Naumova, 1950) Umnova, 1975; Text-fig. 5HH] is also observed for the first time here, and acritarchs representing *Schizodiacrodium* spp. are much more abundant, being recorded for the first time (sample from 50.5 m). Such taxonomic composition and especially the presence of *Acanthodiacrodium* cf. *angustum* (Downie, 1958) Combaz, 1967 (Text-fig. 5BB, CC), *Athabascella* sp. (Text-fig. 5H), and *Ruvalia triangulata* Volkova, 1999 (Text-fig. 4RR) suggest that the rocks from depth interval 42.5–39.5 m may already represent the uppermost part of the Cambrian (*Acerocarina* Superzone). The presence of *Athabascella* sp. and *Ruvalia* spp. may even indicate a Tremadocian age. However, the high proportion of typical upper Cambrian acritarchs suggests that most likely this sample derives from the uppermost part of the *Peltura* and *Acerocarina* superzones**.**

Acritrach specimens similar to assemblage A3 were documented in the Furongian to Tremadocian transition in Baltica-related localities, i.e., Moscow Syneclize (Volkova 1990, 1999), vicinity of St. Petersburg (Volkova 1995; Volkova and Golub 1995), Estonia (Volkova 1989, 1990, 1993, 1995; Paalits 1995), and the Russian Arctic (Moczydłowska and Stockfors 2004; Moczydłowska *et al*. 2004; Raevskaya and Golubkova 2006). Furthermore, the same microfloral community has been identified in Avalonia (Newfoundland; Martin and Dean 1981, 1988; Parsons and Anderson 2000), and various parts of Gondwana (Araoz and Vergel 2006; Ghavidel-Syooki 2019).

Trilobite and brachiopod fauna

The macrofauna in the Cambrian interval of the Lenarczyce PIG 1 well is rare and poorly preserved, with only one specimen of an olenid trilobite recognised at depth 42.5 m (Text-fig. 2) and about twenty specimens of lingulid brachiopods noted in depth interval 41.5–69.8 m.

The only trilobite (Text-fig. 7A) is a small, incomplete olenid cranidium (inferred sagittal length of 3.5 mm), assigned to the genus *Peltura* Milne-Edwards, 1840. This diagnosis is based on the following features: small palpebral lobes situated far forwards and close to glabella, one pair of almost effaced lateral glabellar furrows that are not connected across the glabella, a sagittally long occipital ring, and the transverse posterior width of the fixed cheeks less than half of the transverse width of the occipital ring. With respect to these features, the closest pelturine species are *P. scarabaeoides* (Wahlenberg, 1818), *P. westergaardi* Henningsmoen, 1957, *P. costata* (Brøgger, 1882) and *P. transiens* (Brøgger, 1882). Due to the poor state of preservation it is impossible to assign the specimen to any of these taxa with full confidence and the specimen is retained in open nomenclature.

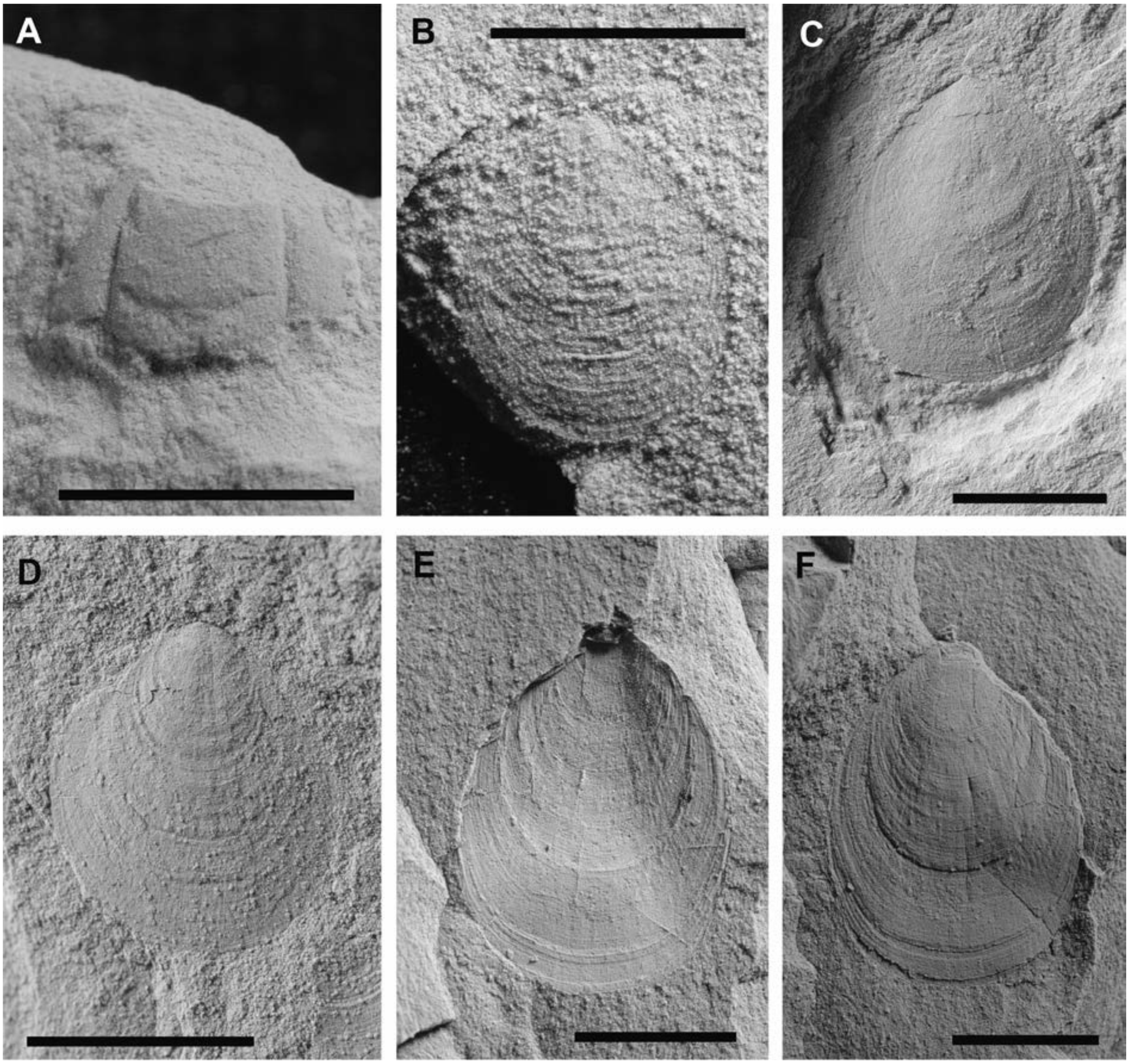
In Scandinavia, *P. scarabaeoides* and *P. westergaardi* characterise the middle of the *Peltura* Superzone (*Peltura scarabaeoides* and *Parabolina lobata* zones), whereas *P. costata* and *P. transiens* occur in the lowermost part of the *Acerocarina* Superzone (*Acerocarina granulata–Peltura costata* Zone) (see Nielsen *et al.* 2014, 2020 for fossil ranges). In the Holy Cross Mountains, olenid trilobites were described from the Furongian in exposures and wells in the Łysogóry Region (Orłowski 1968; Tomczykowa 1968; Żylińska 2001, 2002). *Peltura scarabaeoides* was noted rarely in Chabowe Doły Młyn and commonly in Chabowe Doły Ravine (ChD in Text-fig. 1C), in strata corresponding to the lower part of the *Peltura* Superzone (*Peltura acutidens–Ctenopyge tumida* Zone and *Peltura scarabaeoides* Zone) and *P.* cf. *westergaardi* was observed in the Wilków 1 well (Text-fig. 1C), in strata correlated with the upper part of the *Peltura* Superzone (*Parabolina lobata* Zone). Poorly preserved pelturine specimens from the Jeleniów 3, Brzezinki 1 (Bk in Text-fig. 1C) and Bukowiany 1a wells were assigned to *Peltura* sp. A, B and C by Tomczykowa (1968), and subsequently to *Peltura* cf. *transiens* and *P.* cf. *costata* by Żylińska (2001). These pelturines co-occur with diverse olenids, including *Leptoplastides* spp., *Parabolina* (*Parabolina*) *heres* Brøgger, 1882 and *Parabolina* (*Neoparabolina*) *frequens* (Barrande, 1868), which characterise the *Acerocare* Zone *sensu lato* of Żylińska (2001, 2002), corresponding to the presently recognised *Acerocarina* Superzone. A detailed subdivision of this interval into zones is not possible at this moment; the zones distinguished by Tomczykowa (1968) were abandoned due to redescription of the fauna (Żylińska 2001, 2002).

Brachiopod specimens were collected from the uppermost part of the Lenarczyce Formation and from the Brzezinki Formation. The specimens are variably preserved; in many cases only fragmentary valves occur. The material is typically composed of external impressions of mostly ventral and probably also dorsal valves representing the lingulid order Obolidae (Text-fig. 7B–F). The specimens have elongate subtriangular shells (length:width ratio of about 1.35) or rounded subtriangular shells (length:width ratio of about 1.1–1.2), with an ornamentation of fine concentric growth lines; the maximum valve width occurs about its mid-length or slightly posteriorly.

Facies	Description	Bioturbation and fossils	Mechanism of deposition
Pebbly conglomerates (Gp)	Both clast- and matrix-supported pebbly conglomerates (Text-fig. 8a-c) with sharp basal contacts revealing various bed thickness, ranging from 5 cm up to 1 m. Pebbles are approximately ellipsoidal and oval, subrounded to rounded, moderately to poorly sorted with sizes ranging from 0.5 to 2 cm (max. 5 cm) along longer axis. Large ellipsoidal and elongated pebbles are parallel or inclined to the bedding surface, and in places display a noticeable imbrication. In addition, some thin beds show normal grading. Rarely, the conglomerate beds grade upward into coarse-grained massive sandstones with dispersed pebbles, up to 1 cm in diameter. Pebbles are made up of quartz arenitic sandstones and siltstones (including sandstones and siltstones with a phosphatic matrix) and rare mudstones. The matrix is typically fine to medium-grained sandstones.	BI (0)	Deposition from bedload of mass (debris) flows or pebbly hyperpycnal flows (see Mulder and Alexander, 2001; Zavala *et al*. 2011). Imbrication of individual larger clasts in matrix-supported conglomerates is interpreted as a result of their free rotation at the base of a turbulent flow (see Postma *et al*. 1988; Zavala 2020).
Pebbly and massive sandstones (Sp, Sm)	Grey, greenish and dark grey, medium-grained (in places fine-grained), structureless sandstones (Sm) with scattered pebbles (Sp) (Text-fig. 8d-g) and sometimes with diffuse lamination. Their basal contacts are usually sharp. Thickness ranges from 10 to 20 cm, subordinately even 30 cm. Pebbles and clasts are moderate to well rounded (usually ellipsoidal), up to a few centimetres in diameter (usually 0.5 to 1.0 cm, up to 5 cm in the case of large outsized clasts). Pebbles are made up of mudstones and sandstones (including phosphate sandstones), and are usually randomly suspended (sometimes as outsized pebbles) in the sandy massive background (Text-fig. 8d–f). In some cases tiny pebbles are concentrated in discontinuous and parallel aligned laminae and thin beds (Text-fig. 8g) or form thin interbeds with subtle normal grading. Thin mud laminae and flasers have been reported in some massive beds as well (Text-fig. 8f). Subordinate components include pyrite aggregates, up to 0.5 mm in diameter.	BI (0); scarce mottling bioturbation in case of massive beds – BI (1)	Deposition from inertia-dominated concentrated flows or alternating bedload-fallout deposition from sediment-laden turbulent flows (see Mulder and Alexander, 2001; Zavala *et al.* 2011). The outsized clasts floating in the sandy background suggest deposition from a cohesionless debris flow or a high-density turbidity current (see Postma *et al*. 1988). Clay drapes/laminae point to deposition from suspension following a considerable drop in flow velocity.
Parallel to low-angle laminated sandstones (Sl)	Light to dark grey or greenish grey, fine- to medium-grained sandstones showing plain parallel lamination with individual laminae ranging from 1 mm up to 6 mm in thickness (Text-figs 8h-j; 9a, b), subordinately even 8 mm. They usually form 20 cm to 1 m thick beds with sharp and erosive basal contacts. Thin mud laminae and drapes occur in places (Text-fig. 9b). Some thicker laminae consist of crushed tiny phosphatic shells of brachiopods and tiny siltstone and mudstone pebbles, up to 3 mm in diameter, placed parallel to the lamination. Thicker laminae show a grain-size variation manifested by fining- or coarsening-upward pattern (Text-fig. 8h, i). Internal erosional surfaces occur in places as well (Text-fig. 8j).	BI (0)	Deposition from: 1) dilute unidirectional flows under the upper flow regime; or 2) high-concentration gravity underflows with variable flow intensity indicated by some thicker laminae.
Cross-bedded sandstones (Sc)	Subordinate facies made up of medium-grained, moderately to well-sorted sandstones that form a few to several centimetres thick beds showing low- to high-angle cross-bedding (Text-fig. 9c). In places, the bedding is accentuated by small mudstone and sandstone pebbles.	BI (0)	Deposition from a traction carpet under the lower flow regime by migrating bedforms.
Sandstones with hummocky cross-stratification (Shc)	Grey, fine- and medium-grained sandstones showing low-angle laminated sets separated by subtle low-angle truncations (Text-fig. 9d, e). Locally, laminae are draped by discrete sub-millimetre dark mudstone laminae.	BI (0)	Deposition from oscillating storm waves or combined oscillating-unidirectional flows (see Dott and Bourgeois 1982; Arnott and Southard 1990).
Mudstone/Siltstone/Sandstone heteroliths (Ht)	Alternating centimetre-thick beds and laminae of mudstones, siltstones and fine-grained sandstones forming heterolithic intervals (Text-fig. 9f-h) ranging from dozen centimetres up to 1.0-1.5 m in thickness. They can be either sandstone- or mudstone-dominated. Some siltstone and mudstone beds show a significant admixture of mica-forming thin laminae. Grey to dark clayey mudstones are massive or discretely laminated. The siltstone and sandstone laminae and interbeds are either structureless or display millimetre-scale lamination, sometimes normal grading. Locally, they exhibit current-ripple and oscillation-ripple lamination and lenses overlain by mud drapes (Text-fig. 9f–h). Some irregularities at the bases of the sandstone/siltstone beds are casts of biogenic grazing structures and resting traces.	BI (1–2), trace fossils: *Treptichnus pedum*, *T. rectangularis*, *Planolites* isp., rare *Cruziana* isp., *Rusophycus* isp. and *Palaeophycus* isp.	Deposition from a traction carpet of decelerating unidirectional flows and suspended load. Couplets of mudstones and siltstones with abundant mica flakes exhibit features of deposition from a lofting plume (see Zavala *et al*. 2011).

Facies	Description	Bioturbation and fossils	Mechanism of deposition
Mudstones (Mc, Ms)	Grey to dark grey clayey and silty mudstones (Mc and Ms, respectively), largely structureless; locally, however, subordinate silt laminae disturb apparently massive intervals. Faint bioturbational mottling has been noted within some laminae or thin intervals. In places, sand-sized quartz grains and tiny mudstone or siltstone clasts are scattered in the muddy background. A common constituent of this facies is pyrite which forms tiny discontinues laminae and micro- to macroscale aggregates.	BI (0–1) Lingulid brachiopods and trilobite specimen of *Peltura* sp. (Text-fig. 7).	Suspension fallout or flows of muddy suspensions

Table 3. Facies of the upper Furongian succession in the Lenarczyce PIG 1 well.



Text-fig. 7. Specimens of trilobite (A) and brachiopod (B-F) fauna from the Furongian of the Lenarczyce PIG 1 well. A – cranidium of the olenid *Peltura* sp., MWGUW ZI/66/134, 42.5 m. B-F – valves of undetermined lingulid brachiopods; B – ventral? valve, MWGUW ZI/66/135, 69.5 m; C – ventral? valve, MWGUW ZI/66/136, 62.0 m; D – dorsal? valve, MWGUW ZI/66/137, 69.8 m; E, F – MWGUW ZI/66/138, part and counterpart of dorsal? valve, 44.0 m. Specimens coated with ammonium chloride before photographing. Scale bars equal 5 mm.

Valve proportions and their general outline may vary considerably during ontogeny in both fossil and extant lingulates (e.g., Popov and Holmer 1994; Sutton *et al.* 2000b), therefore they can be used for defining lingulid species only together with the characters of the internal morphology and the pseudointerareas, otherwise, they are considered as poor taxonomic characters. Therefore, due to poor preservation and very low abundance, the material does not allow for a precise and confident specific assignment.

Previous studies on lingulid brachiopods from the Cambrian of the Holy Cross Mountains (Biernat and Tomczykowa 1968) indicated the presence of *Lingulella* cf. *davisii* (M'Coy, 1851), *Lingulella lepis* Salter, 1866, and *Obolus* sp. in Furongian strata recovered from several wells located to the north of the Main (Łysogóry) Range (Tomczykowa 1968; see also Żylińska 2001, 2002). Lingulids (*Lingula* sp., *Lingulella* sp.) were also mentioned (but not illustrated) from the Furongian of the Daromin IG 1 well (Tomczykowa and Tomczyk 2000). Brachiopod specimens from the existing cores are in obvious need of revision; this topic, however, is beyond the scope of this paper. One of the issues that shows the complexity of this taxonomic study is for example the fact that *L. lepis* is now partly synonymised with *Broeggeria salteri* (Holl, 1865) (see Sutton *et al.* 1999, 2000a) and partly with *Lingulella antiquissima* (Jeremejew, 1856) (see Popov and Holmer 1994 and Stutton *et al.* 1999); according to Popov and Holmer (1994, p. 47), *L. lepis* should be considered as a *nomen dubium*.

CAMBRIAN FACIES ASSOCIATIONS

Miaolingian facies associations

The Miaolingian (middle Cambrian) sedimentary record in the Lenarczyce PIG 1 well consists of mudstones with intercalations of siltstones and fine-grained sandstones (Text-fig. 2). Mudstones are grey and mostly massive, with locally preserved flat lamination, while siltstones and sandstones occur as light grey thin beds (less than 2 cm thick) and laminae. In some intervals, mudstones, siltstones and sandstones exhibit millimetre- to centimetre-scale heterolithic stratification with wavy and flaser bedding, and ripple lamination (Ht in Table 3). The contact between the mudstones and the coarser facies is always sharp. Notably, the mudstones display synsedimentary microfaults. The mudstones contain acritarch assemblages, and thus the entire Miaolingian succession is referred to shallow marine (shelfal) settings.

Miaolingian strata crop out in Lenarczyce village at 500 m to the south of the location of the studied well. They consist of greenish grey (at weathered state) mudstones of facies M largely devoid of coarser interbeds, dated by acritarchs as the lower part of the Miaolingian, though the assemblage in this outcrop is slightly younger than that identified in the studied well (Żylińska and Szczepanik 2009.

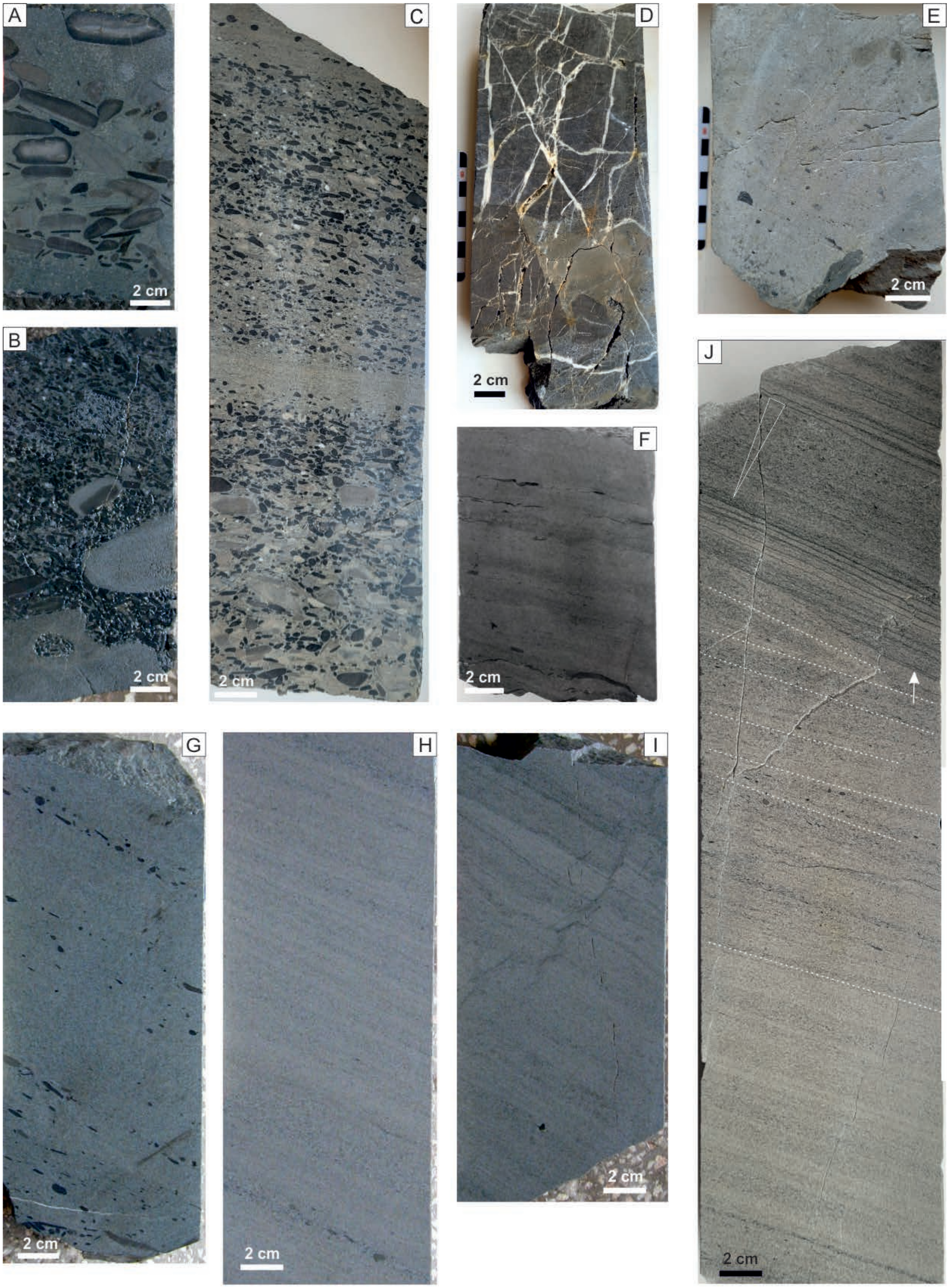
Furongian facies associations

Seven sedimentary facies have been distinguished in the upper Furongian succession of the well (Table 3, Text-figs 8, 9). They have been grouped into four facies associations (FA1–4; Text-fig. 10) representing various environments of the siliciclastic shelf. Their relationship with the marine environment is supported by the presence of brachiopod and trilobite fauna, and acritarch microphytoplankton.

Lenarczyce Formation

Facies Association 1 (FA1) mostly consists of grey and dark grey silty and clayey mudstones (Ms, Mc in Table 3) accompanied by massive, pebbly and subordinate laminated sandstones (Sp, Sm, Sl in Table 3), occurring in the lowermost part of the Lenarczyce Formation, in depth interval 124.6–133.5 m (Text-fig. 10). Sandstone beds are sharp-based and 10 to 50 cm thick. Mudstones are predominantly massive, devoid of bioturbation and in places containing dispersed large quartz grains, as well as tiny mudstone and siltstone clasts. Sandstones from depth interval

Text-fig. 8. Facies of the Lenarczyce Formation. A, B – matrix-supported conglomerate with inverse grading (A) and pebble-supported conglomerate (B) consisting of small phosphate pebbles (black), scattered large quartz grains and outsized sandstone pebbles, 99.6–101.5 m. C – fine-grained conglomerate showing normal and reverse grading separated by massive sandstone, 73.1–73.5 m. D–G – pebbly and massive sandstones (Sp, Sm); pebbly sandstone (Sp) bed with large sandy mudstone clasts (D) from 132.5–132.8 m; coarse-grained massive sandstone bed (Sm) with dispersed mudstone clasts (E) from 124.5–124.6 m; sandstone bed from 109.1–109.3 m with suspended mudstone clasts and flasers (F); pebbly fine-grained sandstone bed (Sp) with small phosphate pebbles and mudstone clasts lying more or less parallel to the bedding plane (G), 79.0–79.2 m, dip ~40º. H–J – parallel/low-angle laminated sandstones (Sl); H – variable thickness of laminae and grain-size alternation manifested by coarse granules, 110.5–111.0 m, dip ~40º; I – laminated sandstones with mudstone drapes, variable thickness of laminae, note syn-sedimentary tectonic fault, 121.6–121.8 m; J – laminated sandstones (Sl) with variable thickness of laminae enhanced by coarse granules grading upwards into sandstones with low-angle lamination and mud drapes interpreted as hummocky cross-stratification (Shc), separated by inversely graded sandstones, note internal erosional scour (arrow), 73.6–74.2 m; dip ~30º. For facies symbols see Table 2.

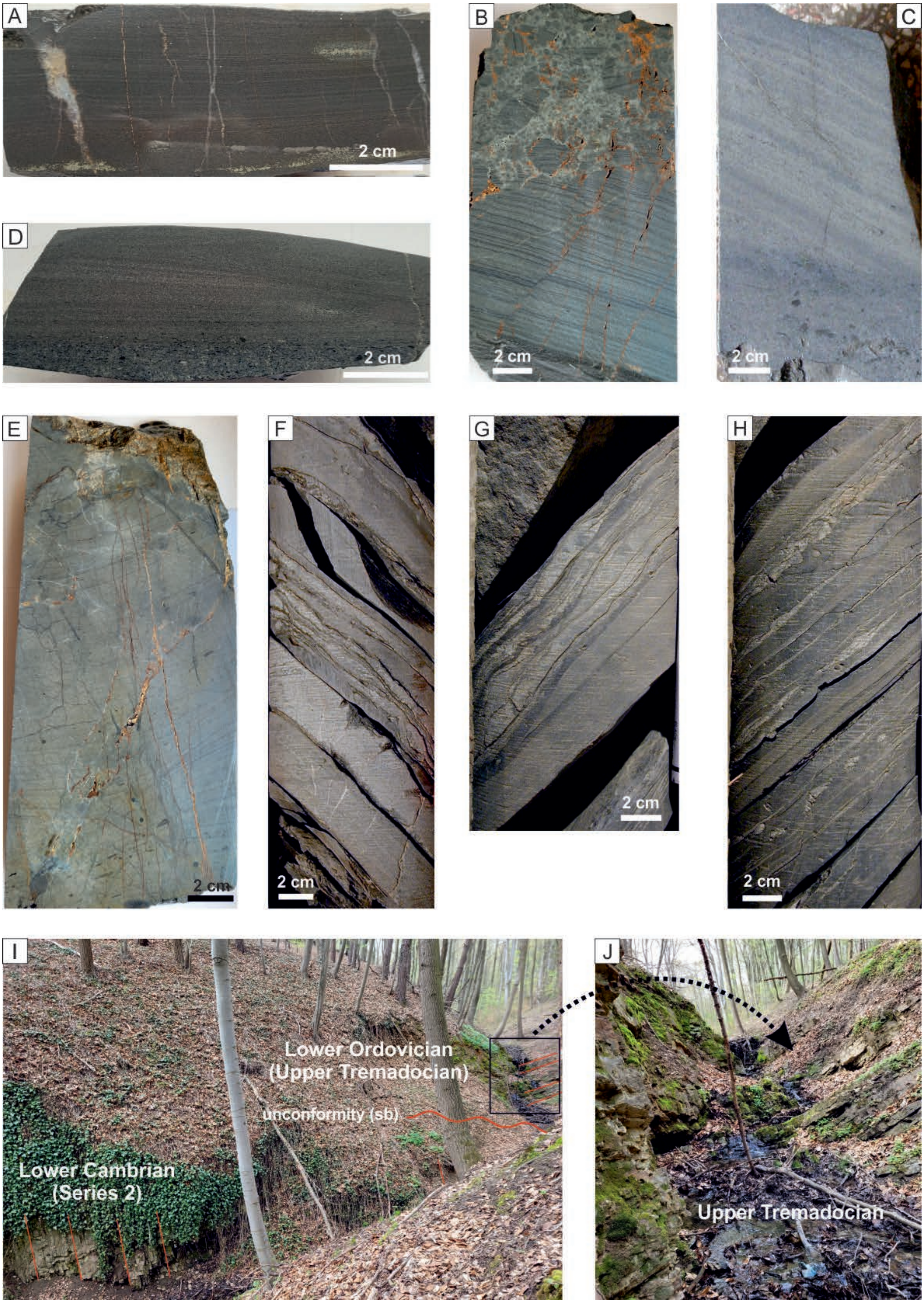

A
2 cm
B
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
J
2 cm
G
2 cm
H
2 cm
I
2 cm

132.5–133.5 m contain mudstone and siltstone clasts resembling the Miaolingian deposits from the core. They are poorly rounded and less than 0.5 cm up to 5 cm in diameter (Text-fig. 8D). In places, carbonate cement occurs in these clast-bearing sandstones. In turn, a massive sandstone bed at the depth of 127.8 m with well-rounded pebbles at the base (up to 2 cm along the longer axis) is a prominent horizon within the predominantly mudstone facies (Text-fig. 10). Tiny siltstone/mudstone clasts are also present in two sandstone beds with diffuse lamination; they are commonly parallel aligned.

Facies Association 2 (FA2) forms distinctive intervals within the Lenarczyce Formation (depth intervals: 72.7–83.3, 87.7–91.5, and 103.5–124.6 m), with sharp contacts with the facies associations below and above (Text-fig. 10). It is largely composed of parallel to low-angle laminated and massive sandstone beds (Sl and Sm in Table 3; Text-figs 8E–J, 9A, B) showing sharp boundaries and thicknesses ranging from 20 up to 100 cm. In places, internally diffuse and discontinuous scour surfaces are present in the laminated sandstones. Some beds consist of alternating massive and plane-parallel sandstone. The sandstones are fine- to medium-grained, locally even coarse-grained, and generally unburrowed, although some beds display discrete bioturbational mottling in their uppermost part. Subordinate facies in this association are cross-bedded sandstones, up to 20 cm thick (Sc; Text-figs 9C, 10). Locally, the sandstones are intercalated by up to several-centimetre-thick mudstones or sandstone-dominated heteroliths. The laminae within some laminated sandstones show variable thicknesses, and a grain-size variation manifested by coarse granules and tiny rip-up clasts (Text-fig. 8H–J). In places, subtle mud drapes were reported between the individual laminae (Text-fig. 8I). Some sandstone beds reveal a variable content of small, rounded to sub-rounded sandstone pebbles, ranging from 0.2 up to 1 cm in diameter, that are either scattered in a sandy background, or aligned parallel to the lamination (Text-fig. 8G). Massive sandstones (Sm in Table 3) from depth interval 73.7–83.3 m are interbedded with rare pebble conglomerate beds (facies Gp) ranging from 5 to 10 cm in thickness (Text-fig. 10; Table 3). These conglomerate interbeds are crudely stratified and show mostly normal grading, although a few examples of inverse grading were also noted (Text-fig. 8C). Outsized pebbles (up to 3 cm in diameter) 'float' within the massive sandstones in between the conglomerate beds. In places, thin (0.5–2 cm thick) concentrations of tiny brachiopod phosphate shells are present. Moreover, small-scale synsedimentary faults have been reported in some sandstone beds, mostly in depth interval 110.2–124.5 m (Text-fig. 8I).

Facies Association 3 (FA3) occurs in depth intervals 68.2–72.7, 83.3–87.7, and 91.5–103.5 m of the Lenarczyce Formation, and overlies FA2 (Text-fig. 10). The bulk of this facies association consists of alternating millimetre- to centimetre-scale mudstone, siltstone, and sandstone laminae and beds forming mudstone- or sandstone-dominated heteroliths (Ht in Table 3; Text-fig. 9F–H). They are intercalated by sharp-based sandstone and conglomerate bed varying in thickness from several to 20 cm, occasionally even 0.5 to 1.0 m (Text-fig. 10). Siltstones and sandstones in the heterolithic intervals are largely massive, and parallel to low-angle laminated. In a few cases, normal grading was also noted. Fine mica flakes are abundant on some mudstone and siltstone bedding planes. In places, the heterolithic intervals are weakly to moderately burrowed, and show slight soft sediment deformation (Text-fig. 9H). The bioturbation intensity, however, is never pervasive and not sufficient to entirely obliterate the original stratification. The trace fossil assemblage includes *Treptichnus pedum* (Seilacher, 1955), *T. rectangularis* (Orłowski and Żylińska, 1996), *Planolites* isp., rare *Cruziana* isp., and only one specimen of *Rusophycus* isp. Locally, thin siltstone and sandstone beds within the heterolithic intervals show combined-flow ripple lamination. Some intervals are dominated by massive mudstones or silty mudstones, which in places exhibit faint lamination (Ms and Mc in Table 3). Thicker sandstone layers are sharp-based,

Text-fig. 9. Sandstones and heteroliths of the Lenarczyce and Brzezinki formations. A – laminated fine-grained sandstone bed (Sl); Brzezinki Formation, 48.8 m. B – laminated sandstone (Sl) with mudstone drapes truncated by an erosional surface covered by a conglomerate lag, note syn-sedimentary tectonic fault, topmost part of the Lenarczyce Formation, 68.2-68.5 m, dip ~25º. C – cross-bedded medium grained sandstones (Sc) overlying massive pebbly sandstones; Lenarczyce Formation, 112.4-112.5 m. D – fine-grained sandstone bed with hummocky cross stratification (Shc) overlying normally graded coarse-grained sandstones containing dispersed small siltstone pebbles, Lenarczyce Formation, 71.5 m. E – fine-grained sandstone bed with hummocky cross stratification (Shc) and scattered tiny mudstone clasts from 45.6-45.8 m, Brzezinki Formation. F, G – sandstone/mudstone heteroliths (Sht) showing beds with parallel lamination and combined-flow ripple lamination; Lenarczyce Formation, from 91.6-91.8 m (F) and 98.8-98.9 m (G). H – heterolithic composite bedset (Sht) with parallel/undulatory laminated and oscillation-rippled siltstones, starved ripples, minute bioturbations, and small-scale load structures, Lenarczyce Formation, 97.5-97.7 m. I, J – angular unconformity between Cambrian (Series 2) and upper Tremadocian strata in Kędziorka (Chojny Ravine) in the southern HCM; sb – sequence boundary; red lines mark the bedding. →


A
2 cm
B
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
G
2 cm
H
2 cm
I
Lower Ordovician
(Upper Tremadocian)
unconformity (sb)
Lower Cambrian
(Series 2)
J
Upper Tremadocian

massive or parallel to low-angle laminated (Sm and Spl in Table 3), whereas the pebbly conglomerate beds (Gp in Table 3) in places show weak normal grading, and are replaced upwards by massive or laminated fine-grained sandstones. Subordinately (especially in depth interval 68.2–73.7 m), siltstone and fine-grained sandstone beds show small-scale hummocky cross-stratification (Shc in Table 3) above the normally graded interval (Text-fig. 9D), as well as distinctive double mud drapes in low-angle lamination disturbed by small-scale synsedimentary microfaults (Text-fig. 9B). A distinctive unit occurring at depth interval 99.6–101.5 m shows a transition from conglomerate facies Gp to sandstone facies Sm and Sl (Text-fig. 10). The conglomeratic package exhibits a bipartite composition consisting of a lower bed (20 cm) with rounded sandstone pebbles, up to 4 cm in diameter, showing vague inverse grading (Text-fig. 8A), and an upper bed (70 cm) dominated by ellipsoidal and rounded quartz-phosphatic pebbles, up to 1 cm in diameter, accompanied by outsized, up to 3 cm in diameter, rounded sandstone pebbles (Text-fig. 8B). Tiny siltstone and mudstone pebbles are present in the overlying facies Sm and Sl, scattered in the massive background or aligned parallel to lamination.

Brzezinki Formation

Facies Association 4 (FA4) is composed of dark grey clayey to silty mudstones (Mc and Ms in Table 3) forming the Brzezinki Formation occurring in depth interval 39.4–68.2 m (Text-fig. 10). The base of this facies association is delineated by an erosional surface overlain by an up to 10 cm thick conglomerate lag containing sandstone clasts set up in a silty mudstone matrix (Text-fig. 9B). The clasts are of the same lithology as the underlying sandstone bed. The mudstones are largely massive; some of them, however, exhibit discrete silt laminae and lenses, as well as bioturbational mottling or cryptic bioturbation confined to single laminae. Overall, bioturbation intensity is low (BI below 1) and the ichnofabric records the activity of surface-grazing benthic meiofauna. This apparently monotonous succession is interrupted by subordinate siltstones to fine-grained sandstones ranging from a few to 30 cm in thickness. Their bases are usually sharp and erosional, and show sole marks, mostly flutes. These beds are massive or horizontally laminated (Sm and Sl in Table 3; Text-fig. 9A) but a thicker fine-grained sandstone layer in depth interval 45.6–45.8 m reveals hummocky cross-stratification with rare, tiny siltstone pebbles (Text-fig. 9E). The top of FA4 and the Brzezinki Formation is an erosional unconformity overlain by upper Tremadocian glauconitic conglomerate (Text-fig. 10).

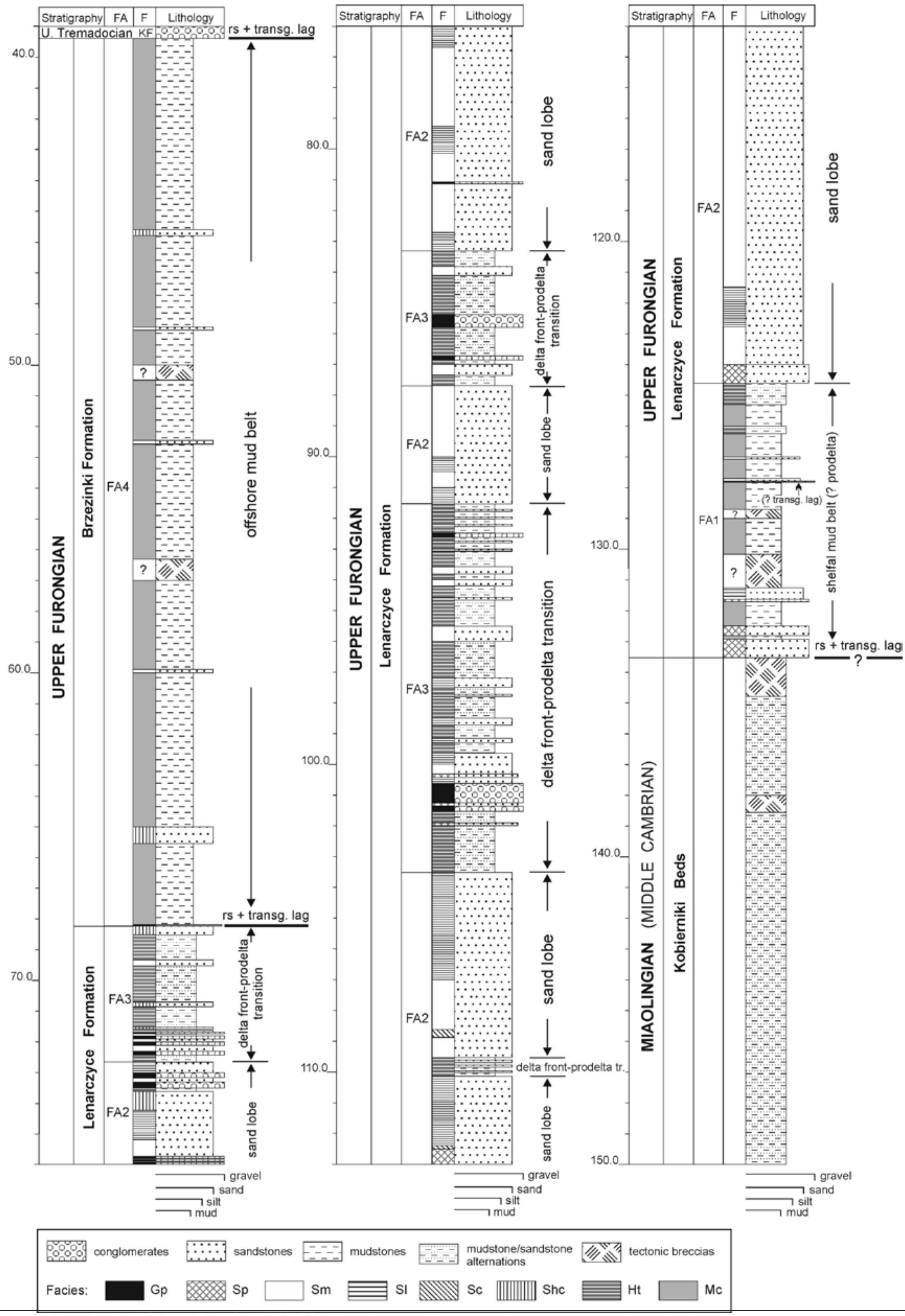
DISCUSSION

Tectonic evolution

The Cambrian succession the the Lenarczyce PIG 1 well reveals two key features that can be used to reconstruct the tectonic evolution of the southern Holy Cross Mountains during the late Furongian. The first one refers to the two different styles of tectonic deformation (Szczepanik *et al*. 2004a; Salwa *et al*. 2006) and the second one to the erosive top boundary of the upper Furongian Brzezinki Formation and the related stratigraphic gap encompassing only the early Tremadocian. The stratigraphic gap between the Cambrian and Ordovician in other localities of the southern Holy Cross Mountains (e.g., Zalesie, Kędziorka, Mokradle, Zbrza, Brzeziny; Text-fig. 9I, J) is much wider. Besides the early Tremadocian, it includes the Furongian and most of the Miaolingian, and is associated with an angular unconformity (Czarnocki 1939; Tomczyk 1964; Tomczyk and Turnau-Morawska 1964; Deczkowski and Tomczyk 1969; Kowalczewski 2000).

There is a general agreement that the Cambrian rocks in the southern Holy Cross Mountains were folded during the Holy Cross and Sandomirian tectonic phases in the mid-Cambrian and early Tremadocian, respectively (Samsonowicz 1934; Czarnocki 1939; Tomczyk 1964; Znosko and Chlebowski 1976; Kowalczewski 1990, 2000). The lower Cambrian succession in the immediate southern vicinity of the Lenarczyce PIG 1 well reveals intensive tectonic deformation including tight folds both inclined and overturned/recumbent, and thrusts in between (see Kowalczewski 1990). Interestingly, in the Osiek 141 well, located 30 km to the south-west from Lenarczyce, an angular unconformity was noted between lower Cambrian mudstones and putative middle Cambrian sandstones (Kowalczewski 1990). However, the middle Cambrian age of those sandstones was based only on their lithological similarity to the Miaolingian Słowiec Sandstone Formation. Therefore, the age of the unconformity in the Osiek 141 well and its possible correlation with the unconformity in Lenarczyce is speculative, although the structural pattern between these sites seems similar (Kowalczewski *et al*. 2006).

Gągała (2005) recognised two pre-late Tremadocian successive tectonic episodes in the southern



Text-fig. 10. Detailed sedimentological log of Cambrian strata in the Lenarczyce PIG 1 well showing the distribution of facies and facies associations in the upper Furongian. Abbreviations: F – facies; FA – facies associations; KF – Kędziorka Formation; rs – ravinement surface. For facies symbols see Table 3.

Holy Cross Mountains. The first one is recorded as westerly advancing thrusts and related gravity-induced rock sliding activated probably in the early Cambrian (or at the early–middle Cambrian boundary). The second one corresponds to northerly-verging thrusts – succeeded by folds changing the inclinations of previous structures – produced by the N-S compression prior to the late Tremadocian, and interpreted by Gągała (2005) as the deformation style 'typical of thrust-and-fold belts'. The thrusting and folding recorded in the Kobierniki Beds and the lowermost part of the Lenarczyce Formation (depth interval 128.0–133.5 m) took place when the bedding planes were horizontal or inclined at a low angle, which can be inferred from the fact that there is a constant angular relationship between the faults and the bedding planes (Salwa *et al*. 2006). Thus, the tectonic deformation in this interval of the Lenarczyce PIG 1 well seems to be related to the growing of the thrust-and-fold recognised by Gągała (2005), which finally might have resulted in the uplift of the southern Holy Cross Mountains as postulated by Tomczyk (1964). In turn, the Lenarczyce Formation above the depth 128.0 m, as well as the succeeding Brzezinki Formation and the Ordovician strata exhibit a conspicuously different tectonic style devoid of thrusts and folding (Salwa *et al*. 2006).

Integrated white mica and detrital zircon geochronology indicate that the maximum age of the deformation event affecting the lower Cambrian succession in the Kielce Region probably took place at c. 510 Ma, that is approximately at the lower–middle Cambrian transition (Callegari *et al.* 2025). Based on tectonic data from the Lenarczyce PIG 1 well (Szczepanik *et al.* 2004a; Salwa *et al.* 2006), it can be assumed that the tectonic deformation of the Cambrian succession in the southern Holy Cross Mountains postulated by Gągała (2005) and Callegari *et al.* (2025), ended before the late Furongian, which is roughly consistent with the previous concepts suggesting their termination in the early late Cambrian (see Czarnocki 1950; Tomczyk 1964; Kowalczewski 2000). Thus, it appears that the final tectonic deformation of the lower and middle Cambrian rocks in the southern Holy Cross Mountains took place during the Holy Cross tectonic phase, prior to the late Furongian.

Furongian depositional system and regional tectonic implications

The stratigraphic, tectonic and facies data clearly indicate that the upper Furongian succession in the Lenarczyce PIG 1 well represents a new sedimentary cycle initiated in a time interval corresponding to the early *Peltura* Superchron or possibly slightly earlier, during the transition from the older *Protopeltura* Superchron. This sedimentary cycle developed mostly after the tectonic phase responsible for the deformation of Miaolingian strata. Sandstones with mudstone clasts from the basal part of FA1 (lowermost Lenarczyce Formation) appear to represent transgressive deposits, but the initial flooding is hard to decipher, since the corresponding depth interval of 127.8–133.5 m is brecciated (Text-fig. 10). Nevertheless, the composition and weak rounding of clasts in the basal sandstones of FA1 (depth 133.5 m) show that they derived from the underlying Miaolingian mudstones and siltstones of the Koberniki Beds, and likely represented transgressive ravinement deposits. Grey and dark grey mudstones predominating above reflect the expansion of a mud-dominated shelfal setting. Mud is dispersed across the shelf by hypopycnal or hyperpycnal plumes generated by river floods, or redistributed by storm waves and tidal action (Allison *et al.* 2000; Traykovski *et al.* 2000; Bhattacharya and MacEachern 2009; Schieber 2016). In the case of FA1, the fine-grained material was deposited from hemipelagic suspension, although periodic mud flows transported tiny clasts as can be inferred from the sedimentological features of the mudstone facies (M in Table 3). However, the characteristics of the sandstone facies in FA1 (i.e., their massive character with floating clasts, diffuse lamination and parallel aligned clasts) indicate that cohesionless debris flows or high-density turbidity currents operated as well. The sedimentary conditions were unfavourable for faunal activity as evidenced by the lack of bioturbation, which might have resulted from increased sediment delivery and periodic oxygen deficiency. In previous reports, two erosional surfaces have been placed at the depths 127.8 m and 135.5 m, each marking the base of a new sedimentary cycle (Szczepanik *et al*. 2004a; Salwa *et al*. 2006). In the present paper, the latter one is the base of the upper Furongian succession, while the former erosional surface refers to the lower contact of the sandstone bed with a pebble lag (Text-fig. 10). Given a conspicuous contrast in the tectonic style close to depth 128.0 m (Szczepanik *et al.* 2004a; Salwa *et al.* 2006), this sandstone bed may represent a post-tectonic transgressive pulse in a muddy belt. An alternative interpretation is its deposition from a sandy mass flow interrupting the settlement of the 'background' muddy sediment, as in the case of similar sandstone beds below and above.

The overlying part of the Lenarczyce Formation exhibits a conspicuous recurrence of sandstone-dominated FA2 followed by heterolithic intervals of FA3 (Text-fig. 10). FA2 sandstones reflect basinward progradation of the sandy sediment deposited mostly by dilute unidirectional flows in the upper flow regime (Sl in Table 3) or suspended load from turbulent gravity flows (Sm in Table 3). Grain-size variation between the laminae in the parallel-laminated sandstones and internal scour surfaces indicate changes in flow velocity (waxing and waning pulses), which is a common feature of a single flooding event characteristic for hyperpycnal flows (see Plink-Björklund and Steel; Steel *et al.* 2018; Zavala 2020). The sedimentary conditions were unfavourable for filter- and suspension-feeding organisms as can be inferred from the general lack of trace fossils in FA2, mostly due to high sediment influx and turbidity variation, both suggesting direct linkage to a fluvial delivery system. The occurrence of low-angle lamination related with hummocky cross stratification at depth interval 73.6–74.2 m (Text-figs 8J and 10) indicate that the oscillatory storm-wave action operated occasionally during the progradation of FA2, generally below the fairweather wave base. Subordinate sub-millimetre mud drapes in the laminated beds suggest suspension settling during flow attenuation, which alternatively may be associated with weak tides. The conglomerate interbeds in FA2 (Gp in Table 3) are likely the products of reworked river mouth gravels (gravely mouth bars) resedimented seaward as series of gravely mass flows (Nemec and Steel 1984; Myrow *et al.* 2002; Larsen *et al.* 2024). The sandstone intervals between them contain 'floating' outsized pebbles, suggesting deposition from cohesionless debris flows or a high-density turbidity current (see Postma *et al.* 1988).

The main sedimentary facies of FA2 (i.e., parallel-laminated and massive sandstones) are commonly reported from sand bodies deposited by hyperpycnal flows in shelfal, slope and deep basinal settings (Mutti *et al.* 1996, 2000, 2003; Mulder *et al.* 2003; Plink-Björklund and Steel 2004; Olariu *et al.* 2010; Zavala *et al.* 2011; Steel *et al.* 2018). The sandstone units with vague and distinct plane-parallel lamination have been noted in packets of closely stacked sand beds developed at the toe of an advancing mouth-bar prograding over the edge of a collapse scar topography (slope failure; Nemec *et al.* 1988). The cited authors interpreted these units as aggradational sand lobes related to mouth-bar failure, formed by surging erosive turbidity currents (referred to as amalgamated 'top cut-out' turbidites T*a* and T*ab*), generated by fluctuations in river discharge or channel shift. The studied Furongian succession is devoid of unquestionably identifiable collapse-related features, therefore slope (mouth-bar) failure cannot be applied in this case. Van den Berg *et al.* (2002) stated that the deposition of faintly laminated and massive sands was by underflows related to breaching that is retrogressive failure of a subaqueous slope, but this scenario seems unlikely in the case of the medium-grained sandstones of the Lenarczyce Formation since breaching occurs in well-sorted fine clear sands. Given the facies characteristics of FA2, it seems likely that this succession represents sand bars formed in the delta front-prodelta transition (Text-fig. 11) comparable to the detached distal mouth bars (with quasi-planar lamination) described by Ahmed *et al.* (2014), formed by hyperpycnal fluvial effluents at the delta foreslope.

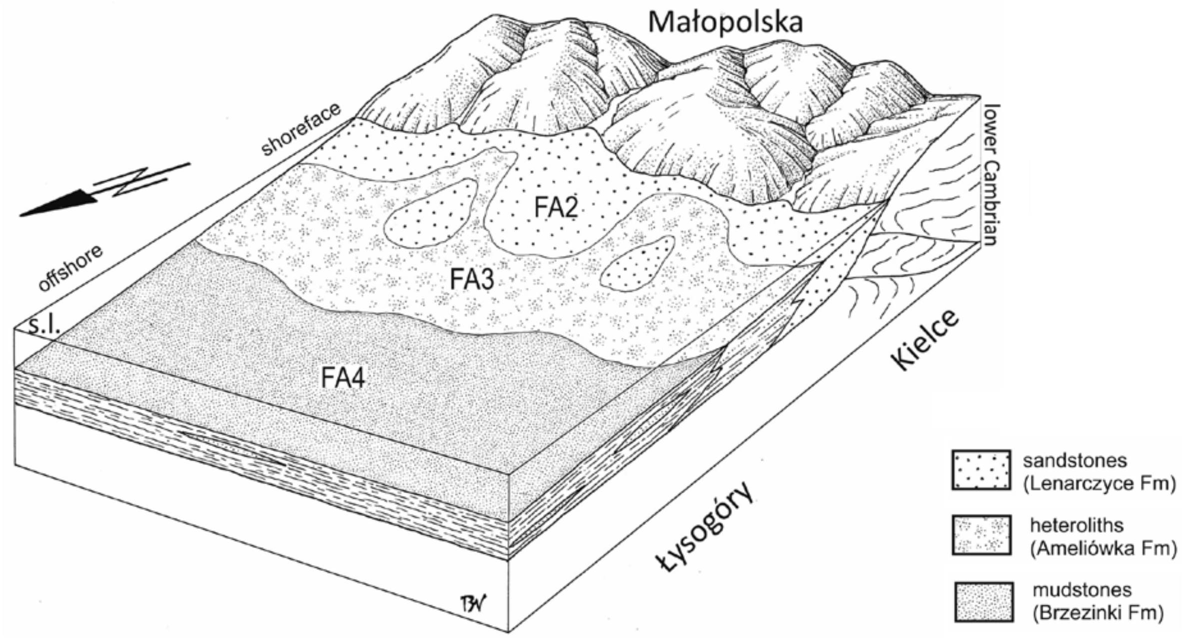
The heterolithic deposits of FA3 reflect a retrogradational phase and a related shift to deeper-water settings. The mud settlement (*via* hemipelagic suspension in fairweather conditions) was interrupted by high-energy events delivering a coarser-grained sediment marked by isolated outsized beds. Some mudstone-sandstone and mudstone-siltstone alternations in FA3 may be possibly rhythmites accumulated from the lofting plume of hyperpycnal flows redistributing mica flakes (compare Zavala *et al.* 2011; Zavala 2020). The low to moderate diversity and overall small size of trace fossils (showing paucity in burrowing intensity) in the mudstone-sandstone couplets and their predominantly deposit-feeding and grazing behaviours imply harsh environmental conditions, which might have been trigerred by repeated pulses of increased sedimentation rate and/or low salinity caused by fresh-water river plumes. This ichnologic signature coupled with the abundance of pyrite in the sedimentary record may indicate a periodically reduced oxygen level in the bottom deposit or even at the sediment-water interface. The sedimentological character of FA3 corresponds to the transition from a distal delta front to a prodeltaic shelf (Text-fig. 11). The sediment distribution and depositional processes were driven by effluent-generated underflows (dilute gravity mass flows), storm currents and oscillatory wave action alternating with periods of mud settling. The millimetre- to centimetre-thick massive, normally graded and laminated siltstones, and fine-grained sandstone beds are attributed to episodic deposition from decelerating unidirectional currents. In turn, the presence of combined-flow ripples that are comparable to wave-modified turbidites (Myrow *et al.* 2002, 2008) and the small-scale hummocky cross-stratification indicate that storm wave reworking was an important agent affecting the depositional conditions (see Bhattacharya and

MacEachern 2009). It is widely accepted that storm waves provide additional turbulence needed to maintain sediment-gravity flows in shelf settings and participate in the redistribution of muddy sediment (Traykowsky *et al.* 2000; Wright *et al.* 2001; Mutti *et al.* 2003; Mackquaker *et al.* 2010). The conglomeratic interbeds of facies Gp (some with outsized pebbles) in FA3 are the products of mass flows (derived from the coastal zone) discharging phosphatic siltstone pebbles from an extrabasinal source. Occasionally, the gravelly to sandy mass flows emplaced more than 1.0 m thick units as that in depth interval 99.6–101.5 m consisting of conglomerates with outsized pebbles grading upwards into laminated to massive coarse-grained sandstones (Text-fig. 10). Nemec and Steel (1984) interpreted similar facies as river-borne coarse-grained sediments supplied from the delta front by high-energy floods or storm events (see also Larsen *et al.* 2024). Thicker sandstone beds (up to 20 cm), structureless in their base and parallel to low-angle laminated higher up, can be related to a storm-generated scour infill (Myrow 1992; Lin and Bhattacharya 2021). Myrow *et al.* (2008) and Lamb *et al.* (2008) indicate that sandstone event beds can also be delivered to the prodeltaic shelf from nearshore slumps of the delta front in response to high pore-fluid pressures triggered by cyclic wave loading.

The facies features and their vertical stacking in the Lenarczyce Formation are compatible with the flood-dominated delta front-proximal prodelta sedimentary system. Limited data do not allow us to reconstruct the spatial facies architecture of the upper Furongian succession in the southern Holy Cross Mountains. Nevertheless, the rapid vertical facies changes in the Lenarczyce Formation and synsedimentary microfaults in some sandstone beds suggest that sediment supply and accommodation space during deposition of this succession might have been controlled by tectonic mobility postdating the Miaolingian-Furongian 'Holy Cross' tectonic phase. Tectonically active basins are commonly supplied by flood-dominated fluvio-deltaic systems with storm modifications, characterised by relatively small drainage areas crossed by 'dirty' rivers (see Porębski 1981; Nemec and Steel 1988; Mulder and Syvitski 1995; Mutti *et al.* 1996, 2003). These typically mountainous settings are effective in producing hyperpycnal deposits with a high sediment concentration capable of plunging in the continental shelf in contrast to large-scale rivers with sediment trapped in the extensive floodplain-deltaic system (Mulder and Syvitski 1995; Mutti *et al.* 1996, 2003; Steel *et al.* 2018). In this context, the FA2 sandstones reflect the seaward progradation of sand lobes attributed to catastrophic fluvial effluents supplying coarse-grained sediment from the tectonically active hinterland (uplifted fold-and-trust belt in the south/south-east).

Significantly, the abrupt facies recurrence in a flood-dominated delta system can also be affected by seasonal climate changes driving fluctuations in river discharge (Mulder and Syvitski 1995; Myrow *et al.* 2008; Zhang *et al.* 2016). The Furongian climate is hypothesised to have been in a hyperwarming state (Landing 2012), and modulated by astronomically-driven changes (Sørensen *et al.* 2020). Climate change is responsible for weathering intensity and production of clastic sediments in the hinterland, and their subsequent redistribution to the marine basin *via* rivers after major storm-induced floods. It seems likely that the flood-related discharges recorded in the Lenarczyce Formation may reflect climatic (seasonal wet periods) and tectonic (hinterland uplift) interaction driving sediment supply and accommodation space. These processes are particularly important controls in deltas developed in tectonically active basins with a short distance between the depositional sink and sediment source (see Porębski 1981; Nemec and Steel 1988; Mulder and Syvitski 1995; Myrow *et al.* 2008).

A conspicuous facies change at the boundary of the Lenarczyce and Brzezinki formations (i.e., between the FA3 heteroliths and the FA4 mudstones) is interpreted as a rapid shift to an offshore mud belt in response to the landward shoreline migration (Text-fig. 11). A thin conglomeratic lag at the base of the Brzezinki Formation (base of FA4; Text-figs 9B, 10) corresponds to the transgressive ravinement deposit and related reworking of the sandstone substrate. There must have been a relatively long period of non-deposition prior to reworking, which facilitated partial lithification of the underlying sandstone bed of the topmost Lenarczyce Formation. The newly generated accommodation space was filled by increased input of fine-grained clastics deposited largely from the 'background' muddy suspension and mud flows periodically interrupted by high-energy storm events recorded by fine-grained sandstone beds showing hummocky cross-stratification, faint parallel lamination, or a structureless appearance. The largely unburrowed nature of the mudstone facies indicates unfavourable conditions for bioturbational activity associated with oxygen deficiency at the sediment-water interface and episodic increased delivery of fine-grained sediment. However, the bottom sediment was occasionally colonised by diminutive benthic organisms responsible for the meioturbational mottling of the surficial deposit, as well as lingulid brachiopods.



Text-fig. 11. Schematic block-diagram displaying the depositional model of the upper Furongian sedimentary facies of the Lenarczyce PIG 1 well and their putative distribution in the Holy Cross Mountains. Drawing by Bogusław Waksmundzki.

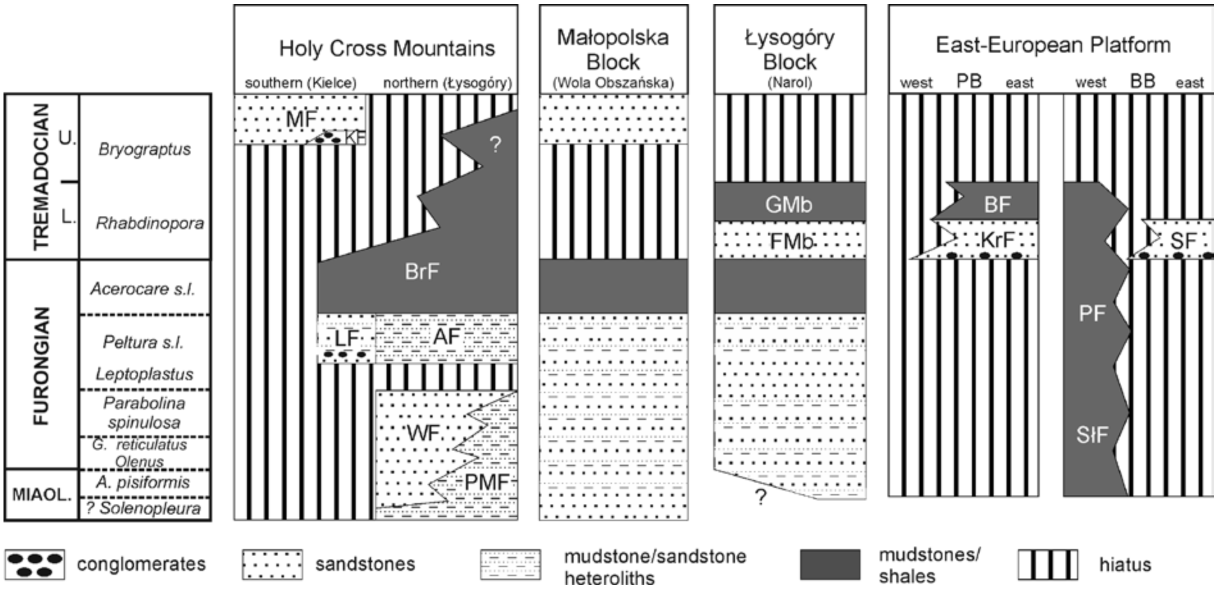
The Brzezinki mudstones (FA4) are topped by an erosional unconformity (Text-fig. 10) reflecting a transgressive ravinement and corresponding to a sequence boundary produced by the late Tremadocian marine flooding (Trela 2022). This flooding event left a thin conglomeratic veneer preserved as the upper Tremadocian Kędziorka Formation. Interestingly, the primary presence of lower Tremadocian muddy deposits was postulated in the southern Holy Cross Mountains (at least in their northern margin – Miedzygórz Quarry) e.g., by Znosko and Chlebowski (1976) on the basis of graptolite fossils found in the mudstone clasts of the uppermost Tremadocian/Floian conglomerates. At first, their opinion was confirmed by the presence of acritarch specimens in the dark mudstones of the Ublinek 1 well, attributed to the Tremadocian (Michniak and Olkowicz-Paprocka 1976). However, taxa listed from that well and recognised in the nearby Ublinek 1bis well have turned out to be indicative for the late Furongian (Szczepanik 1996). Thus, it seems plausible that the late Tremadocian transgression contributed to the removal of post-Furongian or even the upper Furongian from most of the southern Holy Cross Mountains, augmenting southwards the stratigraphic gap between the Cambrian and Ordovician. Alternatively, the late Tremadocian transgression could have encroached directly onto the lower Cambrian rocks exposed along the southern margin of the Holy Cross Mountains and folded prior to the late Furongian. Thus, the Cambrian–Ordovician boundary in the southern Holy Cross Mountains seems to be a complex unconformity resulting from both pre-late Furongian folding and thrusting, and post-Furongian changes of relative sea-level. In our opinion, the Sandomirian tectonic phase should be rather regarded as a post-Furongian block faulting activity differentiating the basin topography rather than an early Tremadocian folding of Cambrian strata (see Samsonowicz 1934; Tomczyk 1964; Mizerski 2004) or a post-late Tremadocian folding postulated by Znosko and Chlebowski (1976).

Regional correlation of Furongian strata and their palaeogeographic context

The Furongian siliciclastic succession in the Lenarczyce PIG 1 well should be considered a key section with stratigraphic, facies and tectonic data providing a new insight into the late Cambrian evolution of the Holy Cross Mountains, precisely the Małopolska and Łysogóry blocks. A lithological and facies comparison of the Cambrian succession between the southern and northern Holy Cross Mountains can be made only for the upper Miaolingian to Furongian strata, because rocks of only this stratigraphic interval occur in both regions. In contrast to the southern Kielce Region, Furongian rocks in the northern (Łysogóry) part of the Holy Cross Mountains are much better represented in outcrops and wells (Orłowski 1968, 1975; Tomczykowa 1968; Żylińska 2002; Szczepanik *et al.* 2004b, 2017; Jaworowski and Sikorska 2006; Żylińska *et al.* 2006), but their contact with older Cambrian strata is unknown. The oldest Furongian strata confirmed by trilobites are represented by sandstones of the Wiśniówka Formation (Text-fig. 3) and occur in the Wiśniówka Duża and Wąworków quarries (Text-fig. 1C; Orłowski 1968; Żylińska 2001, 2002; Żylińska *et al*. 2006). The exposed strata represent the lowermost part of the *Parabolina* Superzone (*Parabolina brevispina* Zone) or a wider interval encompassing also the uppermost part of the *Olenus* Superzone (*Olenus scanicus* Zone) (Żylińska 2001, 2002; Żylińska *et al.* 2006). Succeeding trilobite data come from a much younger interval indicating at most the middle Furongian (Żylińska 2001, 2002). Kowalczewski *et al.* (2006) suggested a stratigraphic gap at the lower–middle Furongian boundary and lack of rocks corresponding to the upper part of the *Parabolina* Superzone and the *Leptoplastus* Superzone (see also Żylińska and Szczepanik 2002). The presence of a similar stratigraphic gap was assumed by Lendzion (1983) and Bednarczyk (1984) in the Baltic Syneclise (Baltic Basin) of the East European Platform in contrast to Jaworowski and Sikorska (2006), who postulated a sedimentary continuity in this stratigraphic interval. The Furongian succession in the Wiśniówka Duża Quarry reveals a complex tectonic structure consisting of thrust and strike-slip faults, and synkinematic folds that originated from E-W and NW-SE compression (Żylińska *et al*. 2006), interpreted either as a marginal thrust-and-fold belt (Dadlez *et al*. 1994) or a platform structure with homoclinal NE-dipping beds (Orłowski and Mizerski 1995).

Higher up, the Furongian succession in Łysogóry is composed of clayey mudstones with thin siltstone intercalations and subordinate sandstone beds referred to the Ameliówka Formation (new; Table 1, Text-figs 3, 12) of unknown thickness, but not less than 60 m (Tomczykowa 1968; Tomczykowa and Tomczyk 2000; Kowalczewski *et al.* 2006). They grade upwards into the dark clayey mudstones of the Brzezinki Formation reaching 150 m in thickness (emended herein; Table 1, Text-figs 3 and 12), which span the upper Furongian to lower Tremadocian. The Ameliówka Formation is exposed in small outcrops along the Lubrzanka Gorge (Lisie Jamy, Chabowe Doły Mill and Ravine; Orłowski 1968; Tomczykowa 1968; Żylińska 2002; Szczepanik *et al*. 2017) and occur also in the Zabłocie IG 1 well located to the north-west of the Wiśniówka area (Szczepanik *et al.* 2004b). Olenid trilobites and agnostoid arthropods recovered from the Chabowe Doły exposures and supported by acritarchs allow us to indicate that the succession spans the upper but not uppermost Furongian, i.e., the lower part of the *Peltura* Superzone (*Peltura minor* to *Peltura scarabaeoides* zones after Żylińska 2002; see also Szczepanik *et al.* 2017). The trilobite record from Lisie Jamy and Zabłocie IG 1 is not diagnostic enough to give a precise age assignment; the recognised acritarch assemblages indicate the boundary interval between the *Leptoplastus* and *Protopeltura* superzones (Żylińska 2002; Szczepanik *et al.* 2004b). The Furongian part of the Brzezinki Formation is attributed to the *Peltura* and *Acerocarina* superzones (*Peltura scarabaeoides* Zone and *Acerocare* Zone *sensu lato* of Żylińska 2002). Its lowest part is most probably recorded in the Wilków 1 well (only a few specimens); it represents the upper part of the *Peltura* Superzone (*Parabolina lobata* Zone; see Tomczykowa 1968; Żylińska 2002). Higher up the succession contains a diverse olenid assemblage, including: *Parabolina* (*Parabolina*) *heres*, *Parabolina* (*Neoparabolina*) *frequens*, *Parabolina* (*Parabolina*?) *jemtlandica* Westergård, 1922, *Peltura* cf. *transiens*, *Peltura* cf. *costata*, *Leptoplastides latus* (Tomczykowa, 1968), *Leptoplastides ulrichi* (Kayser, 1897), *Leptoplastides coniunctus* (Tomczykowa, 1968), and several other taxa (Tomczykowa 1968; Tomczykowa and Tomczyk 2000; Żylińska 2001, 2002). The assemblage has a low representation of olenids typical for the Alum Shale Formation of Scandinavia (Żylińska 2001, 2002) and a high representation of olenids characteristic of open shelfal settings (e.g., Nikolaisen and Henningsmoen 1985; Tortello and Clarkson 2008). Although Tomczykowa (1968) defined four local zones in the upper Furongian of Łysogóry, those were later abandoned, following a redescription of the trilobite fauna, and replaced by the *Acerocare* Zone *sensu lato* (Żylińska 2001, 2002). In view of the updated biozonation of Nielsen *et al.* (2014, 2020), the trilobitic interval of the Brzezinki Formation most likely corresponds to the lower part of the *Acerocarina* Superzone, and thus there is no palaeontological record for the uppermost Furongian in the wells analysed by Tomczykowa (1968) and Żylińska (2001, 2002). In the Jeleniów 2 well, lower Tremadocian graptolite specimens of *Dictyonema* (*Rhabdinopora*?) sp. and *Bryograptus* sp. were noted in the Brzezinki Formation (Tomczyk and Turnau-Morawska 1967; Tomczykowa 1968).

The Furongian siliciclastic succession was also documented in the southern Lublin region, located



Text-fig. 12. Regional correlation of Furongian deposits in Poland. Abbreviations: AF – Ameliówka Member (this paper), BB – Baltic Basin, BF – Białowieża Formation, BrF – Brzezinki Formation (this paper), FMb – Frampol Member, GMb- Goraj Member, KF – Kędziorka Formation, KrF – Krzyże Formation, LF – Lenarczyce Formation (this paper), MF – Międzygórz Formation, PF – Piaśnica Formation, PB – Podlasie Basin, PMF – Pepper Mts. Formation, SF – Sępopol Formation, SłF – Słowińska Formation, WF – Wiśniówka Formation.

to the south-east of the Holy Cross Mountains (Kowalska *et al.* 2000; Jaworowski and Sikorska 2006; Jachowicz-Zdanowska 2011; Szczepanik 2015b). The stratigraphic equivalent of the Lenarczyce Formation was recognised in the Wola Obszańska 10 well (eastern Małopolska Block; Text-figs 1B and 12) as middle- and coarse-grained arenitic sandstones with thin conglomerate intercalations (Kowalska *et al.* 2000). Unfortunately, they are devoid of any biostratigraphic data, which prevents their correlation with the Lenarczyce PIG 1 well. The Furongian succession of the Wola Obszańska 10 well lacks any significant tectonic deformation in contrast to the underlying, steeply dipping lower to middle Cambrian rocks (Kowalska *et al.* 2000). In the eastward located Narol IG 1 and Narol PIG 2 wells (eastern extension of the Łysogóry Block; Text-fig. 1B), the Furongian comprises sandstone-mudstone heteroliths and sandstone intervals (Jaworowski and Sikorska 2006; Pacześna 2015) dated by trilobites, brachiopods and acritarchs (Jendryka-Fuglewicz 2015; Szczepanik 2015b). Thick sandstone beds in the Furongian part of the Narol IG 1 and Narol PIG 2 cores are interpreted as shelfal tidal ridges and/or sand waves, whereas the heterolithic interval – as storm-dominated deposits (Jaworowski and Sikorska 2006).

Considering the distribution of upper Furongian sedimentary facies in the Holy Cross Mountains it can be assumed that during this time span, the Kielce and Łysogóry regions were parts of the same basin that developed to the north and north-west (according to present-day coordinates) of the area with tectonic features of a thrust-and-fold belt (see Gągała 2005). It is hard to establish the original width of this basin, since the Palaeozoic succession in both regions of the Holy Cross Mountains was tectonically shortened by 20% and 30%, respectively, during Variscan deformations (Lamarche *et al.* 2003; Krzywiec *et al.* 2017). The Lenarczyce Formation (new) represents the onshore part of the late Furongian basin with a shallow-water flood-dominated delta front system documenting the cyclic forth and back migration of sand bars/lobes (Text-fig. 11). In turn, the Ameliówka Formation (new) in Łysogóry may be referred to its prodeltaic zone (Text-fig. 11) affected by weak storm currents or diluted sediment gravity flows (see Jaworowski and Sikorska 2006).

A conspicuous facies change in the upper Furongian sedimentary record of the analysed well assigned to the mudstone-dominated Brzezinki Formation can be traced in the northern Holy Cross Mountains (Łysogóry; Text-figs 3 and 12) and further to the south-east in the Lublin area (Kowalska *et al.* 2000; Jaworowski and Sikorska 2006; Jachowicz-Zdanowska 2011; Pacześna 2015). Moreover, upper Furongian mudrock facies occur in the western part of the Baltic Basin (e.g., Szymański 2008; Majchrzyk *et al.* 2022; Text-fig. 12). Mudstones in these localities represent a basinward setting, not deeper than a distal shelf, and they are the eastward extension of the Scandinavian Alum Shales deposited under intermittent oxygen-depleted conditions (e.g., Schovsbo 2001; Gill *et al.* 2011; Dahl *et al.* 2019). In the Łysogóry Region (including the Narol area), as well as the Baltic Basin, their accumulation lasted till at least the early Tremadocian (Tomczykowa 1968; Jaworowski and Sikorska 2006; Kowalczewski *et al.* 2006; Trela 2006, 2022; Szymański 2008; Pacześna 2015; Majchrzyk *et al.* 2022), but in some localities they might have persisted up to the late Tremadocian (Tomczykowa 1968; Trela 2006, 2022). Thus, the unconformity at the Cambrian–Ordovician boundary in the southern Holy Cross Mountains passes basinward (Łysogóry) to the correlative conformity preserved in the Furongian to Tremadocian mudstones of the Brzezinki Formation. In the Narol area, Furongian mudstones are truncated by lower Tremadocian nearshore sandstones with basal transgressive conglomerates documented also in the Baltic and Podlasie basins (e.g., Szymański 2008; Trela 2022; Text-fig. 12).

CONCLUSIONS

The Cambrian siliciclastic succession of the Lenarczyce PIG 1 well provides stratigraphic, sedimentary and tectonic data on the late Furongian evolution of the Małopolska Block and the TESZ in south-eastern Poland. Based on the identified acritarch microphytoplankton, we have recognised two stratigraphic complexes differing in the style of tectonic deformation, i.e., intensely folded and thrusted Miaolingian mudstones overlain by a less deformed upper Furongian succession comprising sandstones, mudstones and conglomerate interbeds. The tectonic deformation of the Miaolingian rocks may be associated with the growing of a thrust-and-fold structure recognised in the southern Holy Cross Mountains (Gągała 2005), which terminated at the beginning of the late Furongian as can be inferred from the stratigraphic and tectonic data of the Lenarczyce PIG 1 well. They are related to the previously postulated 'Holy Cross' tectonic phase confirmed by the data presented in this paper.

The upper Furongian succession in the Lenarczyce PIG 1 well represents a new sedimentary cycle initiated in a time interval corresponding to the early *Peltura* Superzone (or its transition from the older *Protopeltura* Superzone). The sandstone-dominated Lenarczyce Formation (new) is the sedimentary record of a shallow-water flood-dominated delta front system. The sandstone intervals in this formation are interpreted as prograding sand lobes/bars onto the shallow shelf in response to increased fluvial discharge supplying coarse-grained sediment from the tectonically active hinterland. Their recurrence may also reflect seasonal climate change driving fluctuations in river discharge. The overlying dark mudstones of the Brzezinki Formation indicate a rapid shift to an offshore mud belt in response to a relative sea-level rise corresponding to the transgressive system tract delineated by a basal conglomerate lag. They are truncated by an erosional unconformity corresponding to the transgressive ravinement surface produced by late Tremadocian marine flooding.

Stratigraphic and tectonic data from the Lenarczyce PIG 1 well indicate that the unconformity at the Cambrian–Ordovician boundary in the southern Holy Cross Mountains (showing a southward-widening stratigraphic gap) is of a complex nature resulting from pre-late Furongian folding and thrusting, and post-Furongian changes of relative sea-level and/or accommodation space. In turn, the post-Furongian tectonic activity seems to be related to block faulting that differentiated the basin topography rather than to the so far postulated early Tremadocian Sandomirian folding.

The analysed data allow to infer that both the northern and southern regions of the Holy Cross Mountains were a single entity from the Furongian or even earlier, from the Miaolingian. So far, there is no evidence as to whether the two regions were separate in the Cambrian time. With regard to the Małopolska and Łysogóry blocks, the stratigraphic and facies data from the Lenarczyce PIG 1 well provide crucial arguments for their close proximity at that time.

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