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# FACIES ARCHITECTURE OF THE CAMBRIAN DEPOSITS OF THE BALTICA SHELF IN THE LUBLIN BASIN, SE POLAND

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**Abstract**: In the Cambrian, the Lublin Basin was a shallow-water area, located on the western edge of the Baltica palaeocontinent. The Cambrian sedimentary sequence, forming the lower part of the sedimentary cover of the North European Platform, is lithologically diversified and reflects dynamic variation in depositional environment. This paper presents the distribution of palaeofacies and sedimentary environments in the early Lublin Basin, including changes in their lateral extent during its evolution in the Cambrian. In order to evaluate the facies architecture of the Lublin Basin, a sedimentological analysis was carried out. On the basis of the detailed logging of drill cores, lithofacies made up of conglomerates, sandstones, mudstones and heterolithic deposits were distinguished; 16 lower-rank sublithofacies were identified. Their specific assemblages are indicative of shelf-type lithofacies associations, *i.e.* (1) tidal flat with muddy, mixed and sandy tidal plain sublithofacies including subtidal channels; (2) barrier–lagoon; (3) shoreface with lower, middle and upper shoreface subassociations; and (4) offshore with upper and lower offshore subassociations, including sandy tidal ridges. During the early Cambrian, the lateral variability and environmental succession indicate a transgressive, long-term trend and the migration of a lagoonal environment across wide tidal plains and the shoreface up to an offshore environment. The Lublin Basin reached its greatest lateral extent and maximum depth in the upper lower Cambrian. Next, an opposite trend began and during the middle Cambrian a regression cycle is recorded in successive changes in sedimentary environments that reflect a progressive shallowing. Multiple changes in adjacent environments indicate repeated and cyclical, lower-rank ingressions.

**Key words:** Lower Palaeozoic, Baltica, shelf, sedimentary environments, lithofacies.

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## INTRODUCTION

The Lublin Basin was a sedimentary area, genetically connected to the continent of Baltica (e.g., Pożaryski and Kotański, 1979; Garetsky *et al.*, 1987; Nikishin *et al.*, 1996; Pacześna and Poprawa, 2005a, b; Nawrocki and Poprawa, 2006). The Cambrian deposits of the Lublin Basin represent a continuous, shallow-marine, sedimentary succession, related to the transgression of Iapetus, which took place during the latest Proterozoic and the earliest Palaeozoic (e.g., Brasier, 1980, 1992; Vidal and Moczydłowska, 1995). During the Cambrian, the complex, shallow-marine, depositional system underwent dynamic changes. This regime, stimulated by changes in the palaeoenvironment, resulted in the development of local facies in the marginal zone. Its variability illustrates the distribution and range of individual environments, giving insight into the spatial development of the depositional system of the western edge of Baltica. This was subjected to natural processes occurring in the Early Palaeozoic, for example, characterized by a lack of vegetation on land, different lengths of the daily cycles, a low concentration of oxygen in atmosphere, high air temperature, different life forms inhabiting the seas, high sea levels, and a relatively short distance between the Earth and the Moon. These factors significantly influenced the rate of erosion and weathering, the distribution and variability of river networks, as well as the configuration and dynamics of sedimentary basins, especially in the coastal zone (Klein and Ryer, 1978; Brasier, 1992; Veizer *et al*., 2000; Foster, 2014).

The Cambrian deposits of the Lublin Basin have been the subject of numerous studies, which focused on the records of individual deep wells (e.g., Lendzion, 1975, 1989a, b; Miłaczewski, 1975; Pacześna, 2007, 2008, 2010, 2011, 2012, in a series published by the Polish Geological Institute, titled "Profiles of Deep Hole Drilling"), the stratigraphy of the Cambrian deposits (e.g., Lendzion, 1969, 1983a; Pacześna, 1985, 2014), palaeotectonic and palaeogeographic interpretations (Moczydłowska, 1988, 1995; Poprawa and Pacześna, 2002; Nawrocki and Poprawa, 2006), sedimentological and palaeoenvironmental investigations (e.g., Lendzion, 1983a, b; Sikorska, 1984; Jaworowski, 1997; Jaworowski and Sikorska, 2005, 2006; Pacześna and Poprawa, 2005a, b; Pacześna, 2006, 2010; Modliński, 2010) and hydrocarbon exploration (e.g., Pacześna *et al.,* 2005; Podhalańska *et al.*, 2016a).

The present account focuses on a study of the Cambrian sedimentary cover in the marginal zone of Baltica. The aim of the paper was the interpretation of the sedimentary environments and reconstruction of the basin architecture belonging to the shallow-marine Lublin Basin during the Cambrian, based on the designation of sedimentary environments and subenvironments and their mutual relationships and lateral ranges. The proposed model is more precise in relation to existing data (e.g., Pacześna & Poprawa, 2005a, b; Pacześna, 2006; Pacześna, 2010 and references therein) and presents a palaeofacies range that coincides with the transgressive-regressive trend of the Cambrian evolution of the Lublin Basin. This English version of the paper is preceded by a chapter published in the Polish monograph (Stadnik *et al.*, 2017).

# STUDY AREA

## Geological setting

Deposits of the Lublin Basin are found in the southern part of the Podlasie Syneclise, which is located on the western edge of the East European Platform (Fig. 1; Żelaźniewicz *et al.*, 2011), within the tectonic unit of the Lublin Slope (Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005a, b; Pacześna, 2010). The Cambrian deposits of the Lublin Basin make up the lower parts of the sedimentary succession of the East European Platform and thus form the lowest part of the Neoproterozoic–Lower Palaeozoic sedimentary cover. They occur at depths of between 160 m (the Kock 5 well)and 5,306.8 m (Łopiennik IG1) and are available in cores only.

## Palaeogeography

During the Proterozoic and Lower Palaeozoic, the Lublin Basin existed along the western edge of the Baltica palaeocontinent (e.g., Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005a, b; Nawrocki and Poprawa, 2006; Golonka, 2012) and together with the Podlasie Basin had a prolongation in the Baltic Basin (Fig. 1; Nawrocki and Poprawa, 2006). The Lublin Basin originated in the late Neoproterozoic as a structure of an active rift (e.g., Vidal and Moczy-

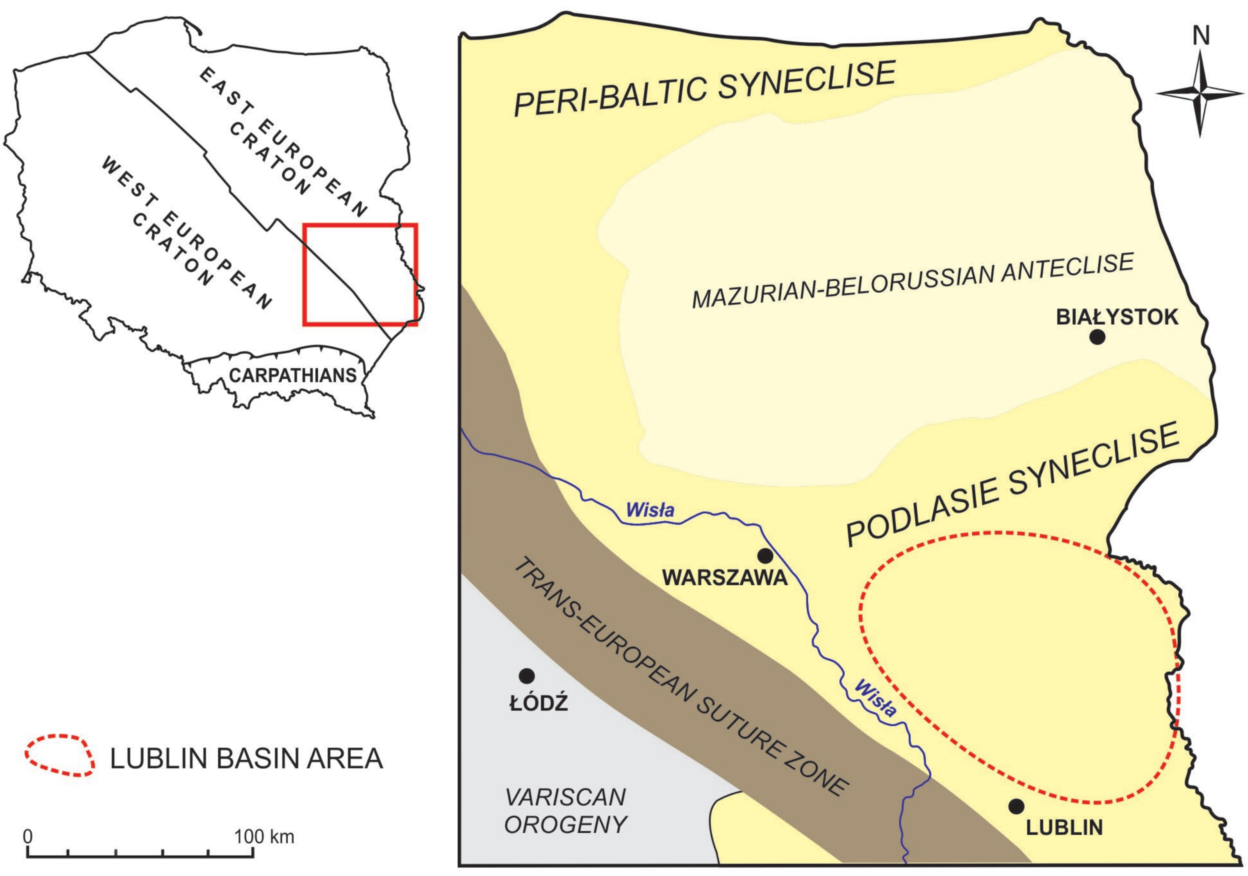


**Fig. 1.** Location of study area against the background of the main tectonic units (under Devonian cover); after Żelaźniewicz *et al.* (2011), modified.

dłowska, 1995; Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005a; Pacześna *et al*., 2005). Its development was the consequence of thermal subsidence that took place at the passive edge of Baltica (Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005a; Pacześna *et al*., 2005a, b; Nawrocki and Poprawa, 2006; Pacześna, 2006). First, during Neoproterozoic sedimentation, a sequence of continental deposits was laid down. They overlie the synrift volcanites, Ediacaran in age. Next, in the latest Neoproterozoic, this area was covered by Iapetus waters and marine complexes were deposited. Shallow-marine sedimentation was dominant during the early Cambrian–middle Ordovician, with a break in the late Cambrian, when an erosional gap was recorded (e.g., Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005a, b; Pacześna *et al.*, 2005; Nawrocki and Poprawa, 2006; Pacześna, 2006).

### Lithostratigraphy

In the Lublin Basin, unmetamorphosed, continental and shallow-marine clastic deposits belonging to the Neoproterozoic–Cambrian succession lie unconformably on the lower Mesoproterozoic basement of crystalline rocks (e.g., Ryka, 1984; Bogdanova *et al.*, 1997; Malinowski *et al.*, 2005; Pacześna and Poprawa, 2005a; Krzemińska *et al.,* 2007; Pacześna, 2010). The sedimentary cover is made up of clastic rocks, in which volcanic rocks of the Upper Neoproterozoic occur locally (Areń, 1982; Pacześna and Poprawa, 2005a, b). A continuous sedimentary sequence occurs in the Precambrian (Ediacaran)–middle Cambrian interval. Ordovician and locally Silurian or Carboniferous deposits lie directly on the middle Cambrian deposits (Lendzion *et al*., 1979; Lendzion, 1983a, b). The angular unconformity and hiatus, associated with the lack of a geological record of the uppermost part of the middle Cambrian and the upper Cambrian is the result of advanced erosional processes during the pre-Ordovician ascension (Jaworowski, 1997; Pacześna, 2006, 2014; Podhalańska *et al*., 2016b). The chronostratigraphy of the Cambrian succession is based on trace fossil assemblages, acritarchs and trilobites. Several formations were distinguished in the deposits investigated: the Włodawa Formation, the Mazovia Formation, the Radzyń-Kaplonosy formations and the Kostrzyn Formation (Fig. 2; Pacześna and Poprawa, 2005a, b; Pacześna 2006b, 2014).

The Ediacaran–Cambrian Włodawa Formation, the first sequence of Cambrian sediments, is represented by mudstones, sandstones and mud-dominated, heterolithic deposits as well as medium- and coarse-grained, cross-stratified sandstones with glauconite. The thickness of the Włodawa Formation in the Lublin Basin is estimated at 101 m (Poprawa and Pacześna, 2002). The Włodawa Formation passes into the lower Cambrian Mazovia Formation, characterized by the presence of sand- and mud-dominated, heterolithic deposits, with reduced amounts of mudstone, occurring with fine- and medium-grained sandstones. The sandstones contain a variable amount of glauconite, which is found mainly in the bottom part of the formation. Some of the sandstones are porous. The total thickness of this complex ranges from 45 to 129 m (Poprawa and Pacześna, 2002). The upper part of the lower Cambrian is represented by the Kaplonosy and Radzyń formations, with a total thickness of 327–432 m (Poprawa and Pacześna, 2002). In lithologic logs, the Kaplonosy and Radzyń formations were considered to be unseparated. They consist of very fine-, fine- and medium-grained sandstones, which in the upper part are replaced by packages of heterolithic deposits and mudstones. Within these formations, intensive bioturbation structures are observed. The Kaplonosy and Radzyń formations pass upwards into the middle Cambrian Kostrzyn Formation, consisting of fine-grained and very fine-grained, low-angle, cross-laminated sandstones. Locally, they are accompanied by packages of heterolithic deposits and mudstones. The upper boundary of this formation is erosional. The thickness of the Kostrzyn Formation reaches 29–298 m (Poprawa and Pacześna, 2002).

## MATERIALS AND RESEARCH METHODS

The sedimentological analysis was based on detailed logging of cores from deep boreholes, drilled by the Geological Institute and the Polish Oil and Gas Company (PGNiG). The cores were selected with reference to the maximum recovery of the Cambrian lithological section. For this study, material from 6 deep wells, located in a strip between the Bug and the Wisła rivers from Zamość in the south to Biała Podlaska in the north (Fig. 3) was used, i.e., the Łopiennik IG1, Radzyń IG1, Parczew IG10, Busówno IG1, Kaplonosy IG1, and Białopole IG1 wells. The cores are stored at the Central Core Warehouse of the Polish Geological Survey (CAG PIG), at Hołowno and Iwiczna.

Sedimentological logging included the description of lithology, sedimentary structures, colour of the dry rock (according to the Munsell Rock Color Book, 2013); the measurement of grain size according to the Wentworth scale (Wentworth, 1922); the degree of sorting; the thickness of the lithofacies intervals according to the Ingram's scale (e.g., Tucker, 2003), and the degree of bioturbation. For recognition of the Lublin Basin palaeoenvironment, individual lithofacies and facies associations were presented on graphic logs; representation of them on the core logs at scales of 1: 100 and 1: 200 was helpful for determination of their ranges and lateral extent.

## RESULTS

### Lithofacies

In the Cambrian deposits of the Lublin Basin, several main lithofacies were distinguished (Tab. 1a, b) on the basis of the modified classifications of Miall (1977, 1978), Zieliński and Pisarska-Jamroży (2012) and Zieliński (2014). The main criterion was lithology. Thus, deposits were subdivided into conglomerates (G), sandstones (S), mudstones (T) and heterolithic deposits (H), which consist of mixed sandstones, mudstones and siltstones (Figs 4A–F, 5A–F, 6A–E). The secondary criterion was the sedimentary structures occurring in all the lithological variants. In the strongly bioturbated intervals, in which the original, primary structures were no longer discernible, only the lithology and the degree of bioturbation were taken into account (Tab. 1).

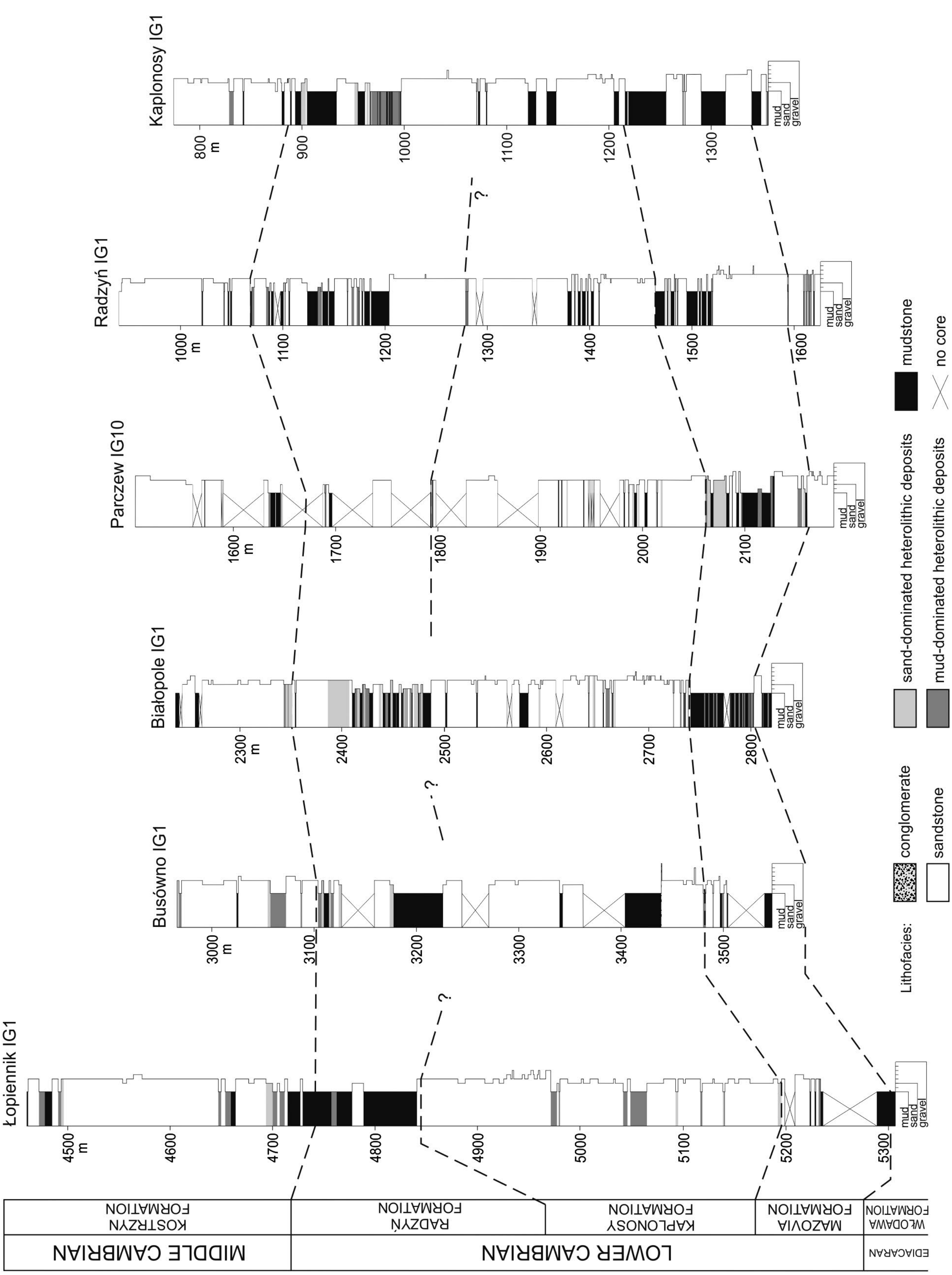


**Fig. 2.** Correlation of lithostratigraphic logs of the Cambrian deposits in the Lublin Basin.

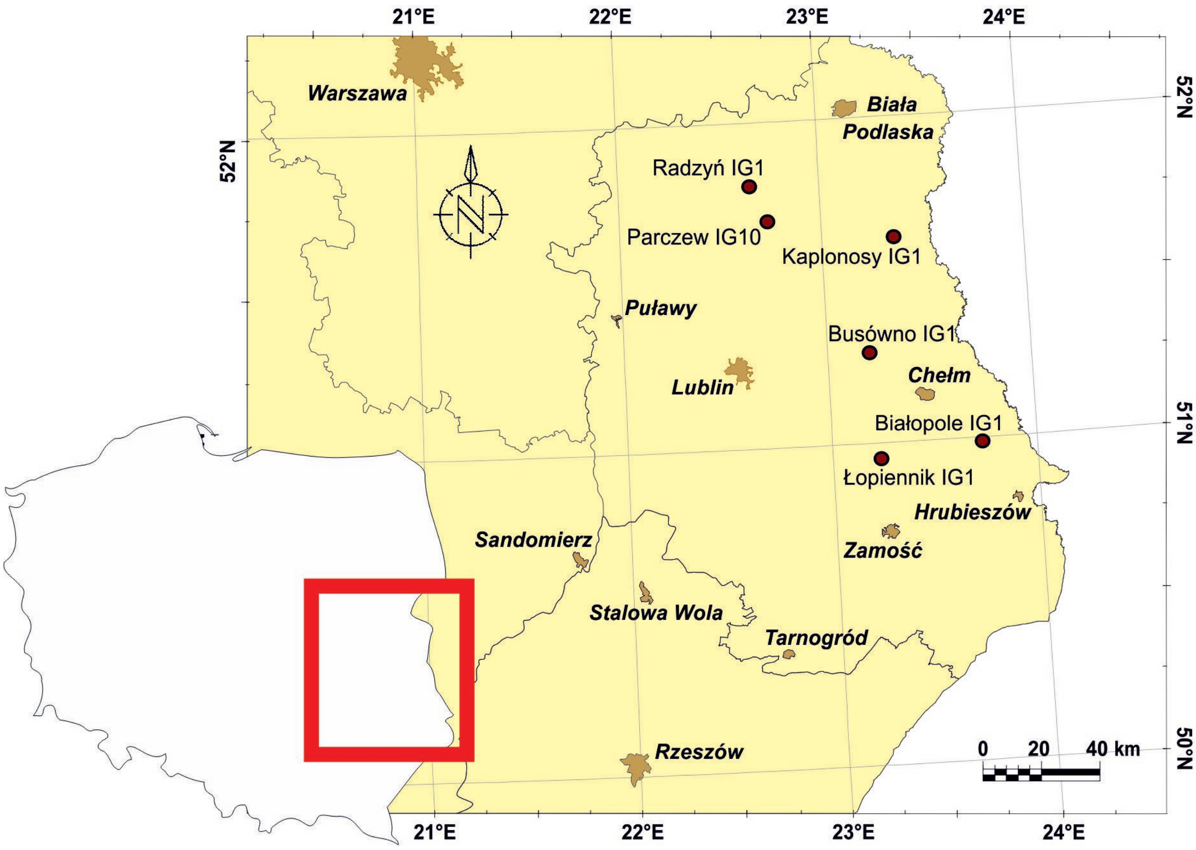


**Fig. 3.** Location of analysed boreholes penetrating the top of the Cambrian in the Lublin part of the slope of the East European Craton; after Stadnik *et al.* (2017), modified

## Lithofacies associations and sedimentary environments

The lithofacies associations are assemblages of facies, which are specific for individual sedimentary environments. The most distinctive sedimentological features were used to define lithofacies associations, following the concepts of Reineck and Singh (1975), Moslow (1983), Davis (1985), Einsele (1992), Walker and Plint (1992), Johnson and Baldwin (1996), Prothero and Schwab (1996), Clifton (2005), Niedoroda (2005), Bird (2008), Knaust and Bromley (2012).

**Facies association I. Tidal flat facies:** In this association, the heterolithic deposits predominate (HT – mud-dominated heterolithic deposits, HS – sand-dominated heterolithic deposits, HSdb – sand-dominated, bioturbated heterolithic deposits, HTdb – mud-dominated, bioturbated heterolithic deposits) and in varying proportions, lithofacies of sandstones (mainly Sl – low-angle, cross-laminated, Sf – flaser-bedded, Sh – parallel-laminated, Sx – large-scale, cross-laminated) and mudstones (Th – parallel, flat-laminated, Tw – wavy- and lenticular-bedded, Tm – massive) occur. Depending on the predominance of the psammite or aleurite fractions, three subassociations have been identified. They represent deposits of muddy, mixed and sandy tidal flat, corresponding to the outer, middle and inner tidal flat (see Einsele, 1992). Very fine-grained lithofacies (HT, Tw, Th, Tm, often with a high degree of bioturbation) predominated in the mud flat deposits. Mixed tidal flat deposits are dominated by sand- and mud-dominated heterolithic deposits and less common lithofacies of sandstones and mudstones. However, sandy tidal flat deposits are represented mainly by lithofacies of sandstones and sand-dominated, heterolithic deposits.

Diagnostic indicators in sandy tidal flat include herringbone cross-bedding in the sandstones, with opposite directions of laminas and lenticular and wavy lamination in the heterolithic deposits. In cross-bedded packages of the heterolithic complexes, reactivation surfaces and silt diapirs occur as well as flaser bedding. These are unique to tidal deposits. Bioturbation structures are abundant, but mainly in upper parts of the sequence, in the heterolithic deposits and mudstones.

In the sandy flat sequence, the subassociation of tidal channels was recognized with numerous muddy clasts concentrated at the usually erosive, lower surface.

Subtidal channel facies here were identified as a separate subassociation. The characteristic features of these deposits included the presence of sandstones of different grain sizes (both fine-, medium- and coarse-grained), co-occurring in the lithofacies Sl, Sx, Sl, Sr and interbedded with lithofacies HT, HS, and Tm, rarely with lithofacies Tw and Th. Mud casts are a common component. Their transition into the typical sequence of a tidal flat was observed in some sections. Usually, these channels formed near the subassociation of barriers.

The repeated succession of the sandstone packages, representing the sandy (outer) tidal flat, passes into heterolithic

**Table 1.**

Facies types in the Cambrian deposits of the Lublin Basin; after Stadnik *et al.* (2017), modified

| Lithology | Lithofacies | Structure | Grain size * | Description | Upper contact | Lower contact | Thickness of facies * |
|---|---|---|---|---|---|---|---|
| CONGLOMERATE | G – extrabasinal | massive | p (max. φ 5 cm, vc) | The framework grains are dominated by very well-rounded grains, bladed and oblate, rarely prolate in shape, with a small amount of quartz (up to φ 0.5 cm) with a low degree of roundness (Fig. 4A). The framework grains are variable; mainly loosely packed (dispersed framework), densely packed (compacted framework) in places. Upper surface is erosional. | HT | HT | VTn (max. 3 cm) |
| CONGLOMERATE | GS - intraformational | massive | p (max. φ 5 cm, vc) | In the sandy matrix, oblate grains of mudstone occur (up to 1 cm), with varying degrees of roundness and lithological type corresponding to the mudstone lithofacies in the logs analyzed (Fig. 4B). Total amount of the clasts is above 50% and is variable in relation to matrix. The framework grains are dispersed. | Sl (Sh HT) | Sl (Sx HT HSdb) | Tn, M, Tc, VTc (max. 60 cm) |
| | | | p (max. φ 4 cm, vc) | A variation of this lithofacies is a conglomerate that contains clasts of sandstone, generally poorly rounded, showing similarities in lithological features to the surrounding rock in the logs analyzed (Fig. 4C). The framework grains are mainly dispersed. The grain size is up to 1.5 cm. Grains of pyrite occur in the clay cement. | Sl | no data | VTn (max. to 8 cm) |
| SANDSTONE | Sh | **parallel lamination** (flat and wavy) | f, vf (m, c, vc) | Sedimentary structures defined by dispersed mud material, variation in colour, coarser grains (c, m), admixtures of glauconite or the presence of continuous and discontinuous mud laminae up to 1 mm thick (max. 3 mm; Fig. 4D). Mineral composition consists of grains of quartz, in places feldspar, glauconite and muscovite. | Sl Sx HS HSdb | Sl HS HSdb Sf (Sx HT) | YTn, Tn, M (Tc) (max. 170 cm) |
| SANDSTONE | Sx | **large-scale cross-lamination** (>20º) | f, vf (m, c) | Sedimentary structures are represented by different types of cross-bedding, legible or gently. They are defined by mud laminae or dispersed mud material, glauconite or mud clasts parallel to the lamination (Fig. 4E). The framework grains consist of quartz, in places pyrite and glauconite. | Sl Sf Sh (Sr) | Sl Sf Sh (Sr) | Tn, M (Tc, VTc) max. 130 cm) |
| SANDSTONE | Sl | **low-angle cross-lamination** (<20º) | f, vf (m, c) | Sedimentary structures are defined by mud laminae up to 1–2 mm or dispersed mud material, glauconite, even mud clasts occurring parallel to the lamination (Fig. 4F). There are different types of bedding, mainly flat and wavy. The framework grains are dominated by quartz, rarely by feldspar, muscovite, glauconite and pyrite. Lithofacies Sl is one of the most common in the Cambrian deposits of the Lublin Basin. | Sf Sx Sh (HS HSdb Sr) | Sf Sx Sh (HS HSdb Sr) | VTn, Tn, M, Tc, VTc (max. 740 cm) |
| SANDSTONE | Sr | **small-scale low-angle cross-lamination** | f, vf | Small-scale ripple cross-lamination (wavy and current ripples, less frequently climbing ripples) defined by concentrations of silt or clay (Fig. 5A). Quartz-rich psammitic fraction predominates. | Sl Sf Sx HS | Sl Sf Sx HS | M (Tc) (max. 100 cm) |
| SANDSTONE | Sf | **flaser bedding** | f, vf | Cross-lamination defined by streaks of silt and clay material (Fig. 5B). | Sl, Sx Sh HS HSdb (HTdb Sr) | Sl, Sx Sh HS HSdb (HTdb Sr) | VTn, Tn, M, Tc, VTc (max. 740 cm) |
| SANDSTONE | Sdb – bioturbated | **chaotic** (secondary) | f, vf (m, c) | The primary structure is indiscernible, deformed by bioturbation (Fig. 5C). The deposits of this lithofacies usually are porous. | Sl HSdb (Sh) | Sl HSdb (Sh) | Tc (M, VTc, Tn) (max. 390 cm) |

**Table 1.**

Facies types in the Cambrian deposits of the Lublin Basin; after Stadnik *et al.* 2017), modified. Continuation from the former page.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **HETEROLITHIC DEPOSITS** | **HS – sand-dominated** | **wavy and flaser bedding** | vf, f, p, s (m) | Interbedded thin layers of sandstone and mudstone, with a quantitative predominance of the sandstone parts (Fig. 5D). The thickness of the layers varies from a few millimetres to a few centimetres, with sandstones mainly concentrated in layers 2–5 cm thick. Sandstones with flaser bedding, in places low-angle cross-laminations (ripple laminations), parallel and wavy, flat laminations as well as reactivation surfaces. In mudstones, parallel (flat or wavy) laminations and lenses of silt or psammite. In places, small (up to a few centimetres) silt diapirs occur. Lower surfaces are sharp, occasionally not sharp, related to the gradation between the psammitic and aleuritic fractions. In the layers, especially the mudstone parts, bioturbation occurs to varying degrees. | Sl<br>Sh<br>Sf<br>HSdb<br>HT<br>Tw | Sl<br>Sh<br>Sf<br>HSdb<br>HT<br>Th<br>HTdb | Tc, M (Tn, VTc) (max. 460 cm) |
| | **HT – mud-dominated** | **wavy and lenticular bedding** | p, s, vf, f (m) | Interbedded thin layers of siltstone and sandstone with a quantitative predominance of mudstone parts. Mudstones occur in layers a few centimetres thick (usually 2–5 cm), while the sandstones are in layers up to 2 cm thick (fig.5E). In the mudstones, parallel- (flat or wavy) or lenticular-bedded silt or psammite layers occur. In the sandstones, flaser bedding, wavy and cross-laminations predominate. In places, small silt diapirs occur. Lower surfaces are usually sharp, related to the gradation between the psammitic and aleuritic fractions. Bioturbation structures are common, especially in the mudstone parts. | HS<br>Tw<br>Sl<br>Sh | HS<br>Sl<br>Tm<br>Sh | Tc, M (Tn, Vtc) (max. 410 cm) |
| | **HSdb – bioturbated** | **chaotic** (secondary) | vf, f, p, s (m) | Structureless mixture of psammitic and aleuritic and/or pelitic fractions, with the predominance of the psammitic fraction, strongly bioturbated (Fig. 5F). The primary structure is indiscernible, deformed by bioturbation. It corresponds to the sand-dominated heterolithic deposits, or sandstones, laminated with mud. | Sl<br>Sh<br>HS<br>HTdb | Sl<br>Sh<br>HS<br>HTdb | Tc (VTc, M, Tn, VTn) . (max. 370 cm) |
| | **HTdb – bioturbated** | **chaotic** (secondary) | p, s, vf, f (m) | Structureless mixture of aleuritic, pelitic and psammitic fractions, with the predominance of the aleuritic and pelitic fractions (Fig. 6A). The primary structure is indiscernible, deformed by bioturbation. It corresponds to the mud-dominated heterolithic deposits or mudstones, laminated with psammite. | HSdb<br>HS<br>Tw<br>Sl<br>Sh | HSdb<br>HS<br>Tw<br>Sl<br>Sh | Tc (VTc, M, Tn, VTn) (max. 450 cm) |
| **MUDSTONE** | **Tm** | **massive** | p, s | Mudstone with occasional, single, discontinuous, very thin laminas or lenses of siltstone or very fine-grained to fine-grained sandstone (Fig. 6B). In some places, muscovite and pyrite (single crystals or concentrations) occur. Frequent bioturbation occurs. | Tw<br>HT | Tw<br>HT<br>Tdb | M, Tc, VTh (max. 370 cm) |
| | **Tw** | **wavy and lenticular bedding** | p, s (vf, f) | Mudstones with flat lenses, ripple-like, consist of silt, very fine- to fine-grained sandstone, rarely medium-grained (Fig. 6C). Muscovite is frequent. In the psammite intervals, glauconite occurs. Bioturbation is common. | Tm<br>Th,<br>HT<br>Sl, HS<br>Tdb<br>HTdb | Tm<br>Th, HT<br>Sl, HS<br>Tdb<br>HTdb | M, Tc (VTc, Tn, VTn) (max. 910cm) |
| | **Th** | **parallel, flat lamination** | p, s (vf, f) | Mudstones, laminated with silt or very fine-grained psammite (rarely fine- and medium-grained) (Fig. 6D). Muscovite is frequent. In the psammite laminas, glauconite occurs. Bioturbation is common. | Tw<br>HS<br>Sl | Tw<br>HT<br>Sl | Tc (M, VTc, Tn, VTn (max. 410 cm) |
| | **Tdb** | **chaotic** (secondary) | p, s (vf) | The primary structure is indiscernible, deformed by bioturbation (Fig. 6E). Originally, the sublithofacies corresponded to mudstones, lenticular bedded or wavy and parallel-, flat-laminated, with silt and very fine- to fine-grained psammite. | Tw<br>HTdb | Tw<br>HTdb | Tc, VTc (max. 200 cm) |

* fraction size after Wentworth (1922): p – pebbles, vc – very coarse-grained psammite, c – coarse-grained psammite, m – middle-grained psammite, f – fine-grained psammite, vf – very fine-grained psammite, s – silt, c – clay.

** thickness of facies after Campbell's terminology for thickness of beds and laminae (Campbell, 1967): up to 3 – very thin (VTn), 3–10 cm – thin (Tn), 10–30 cm – middle (M), 30–100 cm – coarse (Tc), above 100 cm – very coarse (VTc).

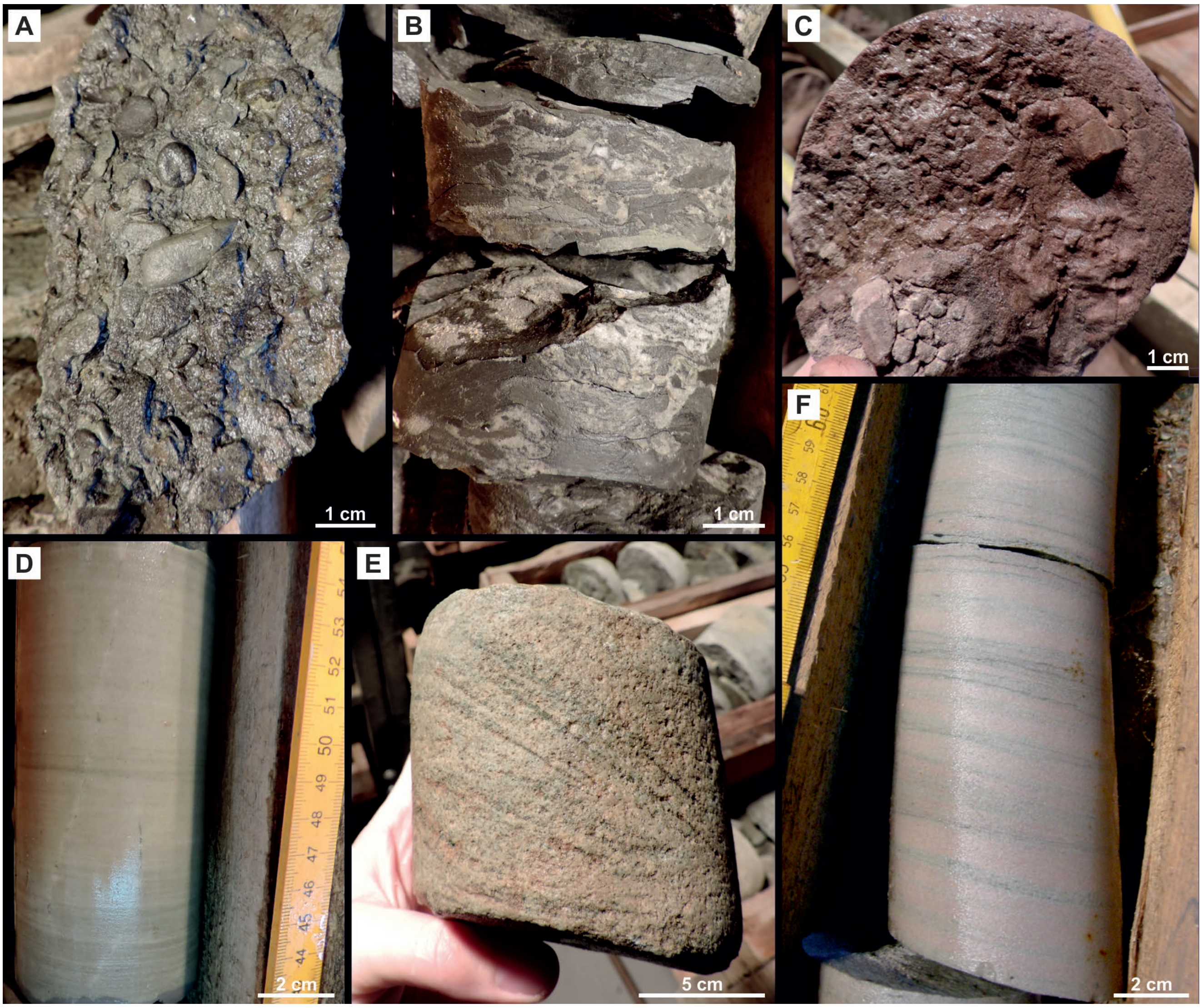


**Fig. 4.** Cambrian deposits of the Lublin Basin – sublithofacies of conglomerate and sandstone. **A.** Extrabasinal clast conglomerate (Kaplonosy IG1 well, interval 986.0–990.5 m). **B.** Intraformational conglomerate (Busówno IG1 well, interval 3437.0–3443.8 m). **C.** Intraformational conglomerate with sand grains (Kaplonosy IG1 well, 1148.9–1151.9 m). **D.** Parallel-laminated sandstone, flat or wavy (Łopiennik IG1 well, 4872.2–4881.2 m). **E.** Large-scale cross-laminated sandstone (Kaplonosy IG1 well, interval 1346.5–1350.4 m). **F.** Low-angle cross-laminated sandstone (Białopole IG1 well, interval 2600.2–2618.2 m); after Stadnik *et al.* (2017), modified.

deposits with disturbed internal structure (mixed flat), and finally into the deposits of a muddy tidal flat. Within them, similar, lower-rank cycles occur.

Deposits of the tidal-flat association overlie sediments representing the association of the offshore, the upper shoreface or barrier/lagoon zone. In the uppermost part, they represent shoreface and barrier deposits.

The facies association of the tidal flat occurs mainly in the lower Cambrian deposits, in the Mazovia and Kaplonosy formations. The longest continuous log of this association, with a thickness of over 100 m, was recorded in the Łopiennik IG1 core.

**Facies association II. Barrier/lagoon facies:** Barrier facies are thick complexes of sandstones, highly porous, passing into the facies of the shoreface, lagoon, or tidal flat. They were recognized in the logs of almost all cores, in all formations.

The main lithological components of the lagoonal association are dark-coloured mudstones, which are almost the sole component of this complex. Locally, thin (up to 5 cm) lenticular and parallel lamination occurs, as well as low-angle cross-lamination and hummocky cross-stratification. The deposits are bioturbated to different degrees, quite intensely in some intervals.

A lagoonal environment was recognized in a few cores, in the lower part of the Włodawa Formation in the Busówno IG1, Parczew IG10 and Łopiennik IG1 boreholes.

**Facies association III. Shoreface facies:** The coastal zone is subdivided into the lower shoreface (inner), the middle shoreface and the upper shoreface (surf zone).

In the lower shoreface, mainly fine-grained and very fine-grained sandstones occur, usually parallel-laminated and interbedded with mudstones. Hummocky cross-stratification (HCS) was observed frequently in the sandstones. The sedi-

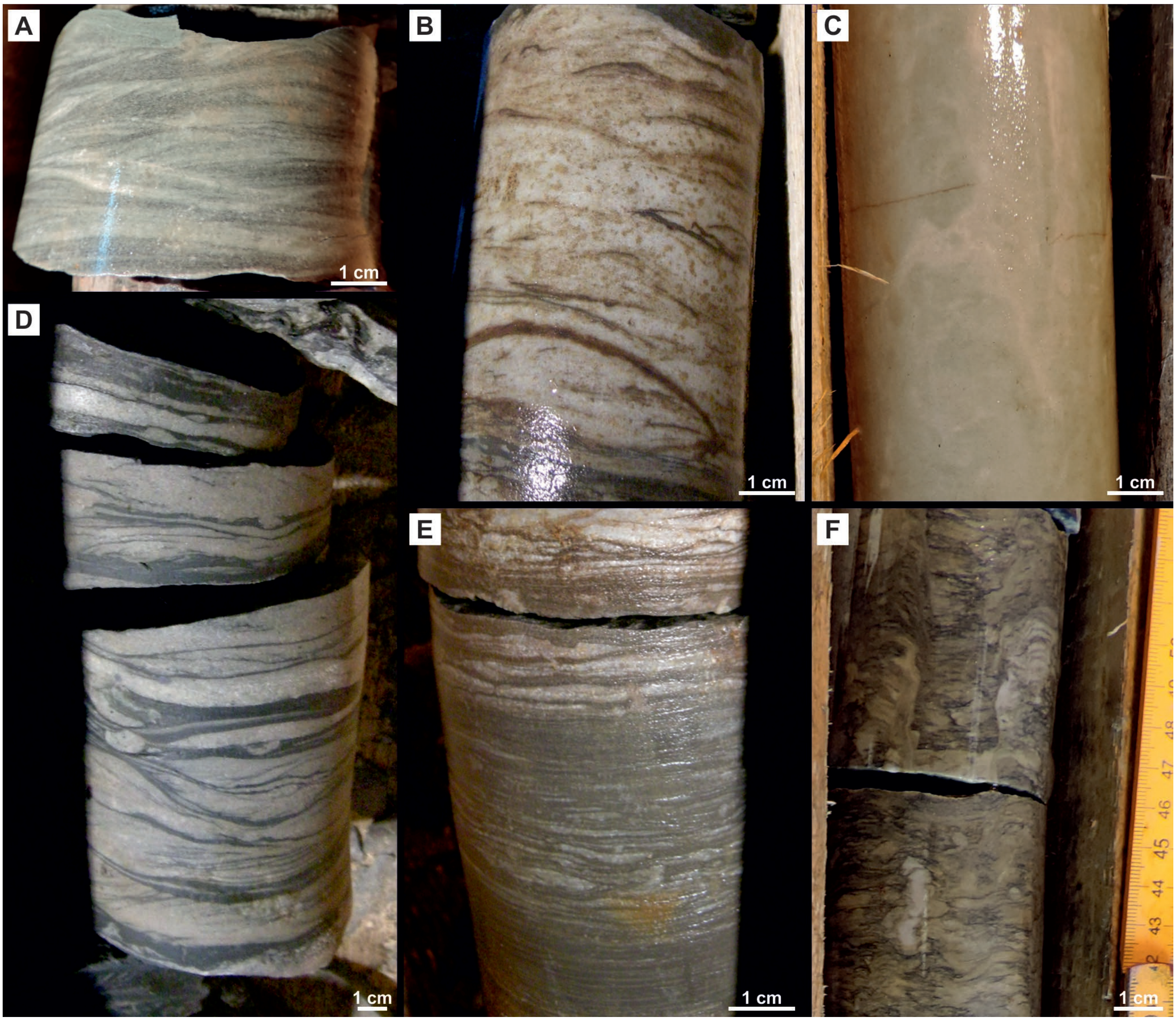

**Fig. 5.** Cambrian deposits of the Lublin Basin – sublithofacies of sandstone and heterolithic deposits. **A.** Small-scale, low-angle cross-laminated sandstone (Busówno IG1 well, interval 3477.8–3491.8 m). **B.** Flaser-bedded sandstone (Białopole IG1 well, interval 2349.3–2358.5 m). **C.** Bioturbated sandstone (Łopiennik IG1 well, interval 4863.2–4872.2 m). **D.** Wavy- and flaser-bedded sand-dominated heterolithic deposits (Parczew IG10 well, interval 2076.5–2091.5 m). **E.** Wavy- and flaser-bedded mud-dominated heterolithic deposits (Białopole IG1 well, interval 2325.8–2334.8 m). **F.** Bioturbated, sand-dominated heterolithic deposits (Łopiennik IG1 well, interval 4881.2–4889.6 m); after Stadnik *et al.* (2017), modified.

mentary structures usually are strongly disturbed by bioturbation. The subassociation is mainly represented by Sh, Sr (formed from asymmetric ripple marks reported by Einsele, 1992), and Th, but also by HS, HSdb, HT, HTdb lithofacies.

In the middle shoreface, very well sorted, fine- to medium-grained sandstone lithofacies are found. They are represented by the Sl and Sr sublithofacies, occasionally Sx and Sf. It is a subenvironment, in which the degree of bioturbation and the amount of HCS have been reduced.

The upper shoreface, which was rarely preserved in lithological record, is represented by the Sf, Sl and Sh lithofacies. In the swash zone, the Sr lithofacies with symmetrical ripples is observed. The size fraction of granular material in the sandstones is larger than in the middle shoreface. Medium and/or thick psammite is concentrated in laminations or in beds several centimetres thick. Accumulations of heavy minerals that form laminations are typical for these deposits.

Deposits of the shoreface environment occur mainly within the Kaplonosy-Radzyń and Kostrzyn formations. Within the shoreface deposits, subenvironmental changes were observed.

**Facies association IV. Offshore facies:** In the offshore facies association, upper and lower offshore subassociations were recognized. The boundaries between these subassociations were taken after Pemberton *et al.* (2012). The sublithofacies of Th, Tw and mud-dominated heterolithic deposits (HT), frequently bioturbated (Tdb, HTdb), predominate in the lower offshore. In the mud-dominated, heterolithic deposits, layers of sandstones with parallel lamination and sandy lenses with symmetrical ripples of wave origin, were

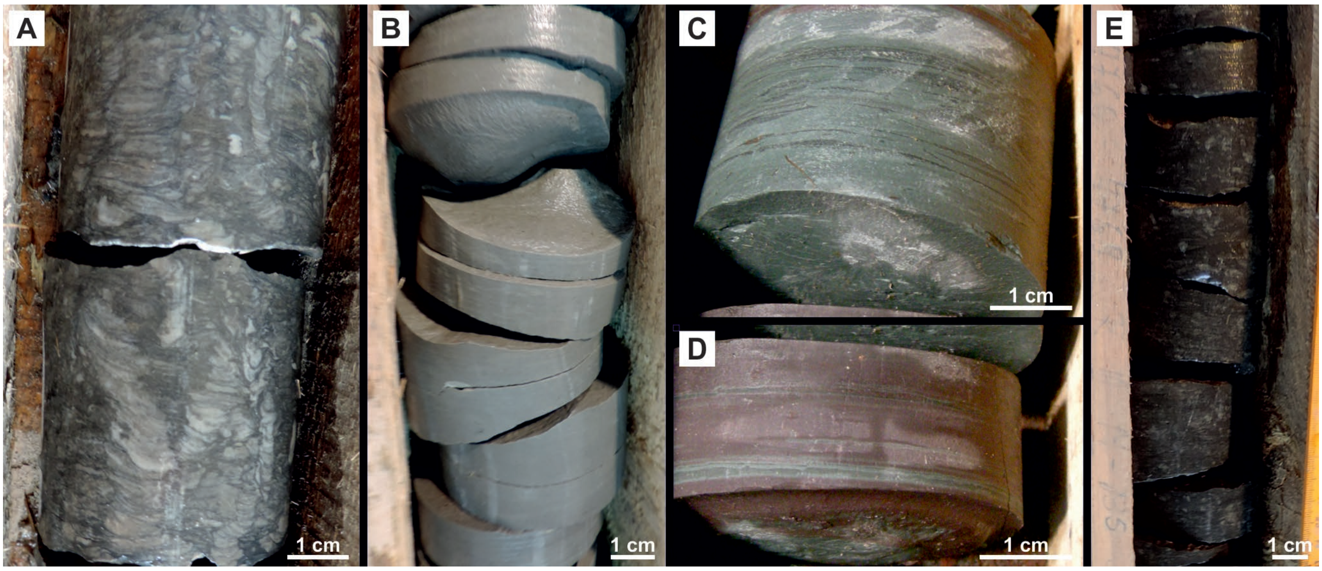


**Fig. 6.** Cambrian deposits of the Lublin basin – sublithofacies of heterolithic deposits and mudstone. **A.** Bioturbated, mud-dominated heterolithic deposits (Łopiennik IG1 well, interval 5064.0–5068.7 m). **B.** Massive mudstone (Łopiennik IG1 well, interval 4872.2–4881.2 m). **C.** Wavy- and lenticular-bedded mudstone (Białopole IG1 well, interval 2716.5–2720.6 m). **D.** Parallel-laminated mudstone (Białopole IG1 well, interval 2716.5–2720.6 m). **E.** Bioturbated mudstone (Łopiennik IG1 well, interval 4760.0–4769.0 m); after Stadnik *et al.* (2017), modified.

recognized. In the upper offshore and occasionally in the lower offshore deposits, classic sequences of storm deposits occur. Their lower surface is commonly erosive. They usually begin with normal graded sandstones containing clasts (mainly mud clasts), which pass upward into fine- and very fine-grained sandstones, initially parallel-laminated (Sh), and in their upper part with classical hummocky cross stratification (Sl), and ripples of wave origin at the top. This sequence was commonly observed in the offshore deposits, although the complete sequence is not always preserved.

In the deposits of the Lublin Basin, transitions between the lower and upper offshore occur, indicating multiple oscillations of sea level. In these sequences, transitions to the lower shoreface also were observed.

In the offshore deposits, there are sequences representing sandy tidal ridges. They consist of fine-grained psammite, with an admixed fraction of medium- and coarse-grained sand. They include cross-lamination, usually of the low-angle type.

The offshore deposits are observed in almost all cores, mainly in the Radzyń Formation and in the Kostrzyn Formation. The greatest thickness is observed in the Łopiennik IG1 core, where a complex approximately 145 m thick occurs.

## DISCUSSION

### Mechanism of sedimentation

In the Lublin Basin, after the relatively long period of marine sedimentation on the Baltica shelf, the Ediacarian transgression began. The sedimentary complexes of this time span vary considerably in terms of lithology (Fig. 2) and sedimentological analysis suggests that they belonged to the entire spectrum of shallow-marine associations from tidal flats to offshore sequences. These associations correspond to particular sedimentary environments. One of the main factors responsible for such a variety of environments is the dynamic variable energy of the environment depending on undulation and the range of sources of allogenic material.

In general, tidal flats are characterized by variable dynamics of the environment, within a relatively short distance of the coastal zone. Depositional sequences represent the result of high sensitivity of sea-level changes and environmental energy (Prothero and Schwab, 1996). A sequence that displays a transition from sand to mud denotes a gradual decrease in energy. In the lithological record, it is characterized by a fining-upward sequence (Prothero and Schwab, 1996). Accordingly, the sandy tidal flat passing into mixed flat, and muddy tidal flat formed in low-energy conditions (Johnson and Baldwin, 1996). Such sequences are common in the Cambrian tidal-flat deposits of the Lublin Basin. The lower-rank, similar cycles show the record of individual tidal layers, i.e. deposits that are the product of individual, daily tides.

The occurrence of herringbone cross-bedding in sandstones, with opposite inclinations of the laminae, associated with bipolar palaeoflow directions (Johnson and Baldwin, 1996), and in the heterolithic deposits, lenticular and wavy lamination, reveal an episodic increase in environmental energy. The presence of reactivation surfaces and silt diapirs in the cross-bedded, heterolithic tidal-flat deposits is the result of the rhythmic oscillation of tidal currents and the flaser bedding reflects fluctuations in flow velocities (Nio and Yang, 1991). A dynamically variable image of the tidal flat is presented by the tidal channels preserved in the sandy flat sequence.

The environment of barrier and lagoon includes the zone between the shoreface and tidal flat. It consists of barrier, partly exposed lagoon, and inlets that provide water ex-

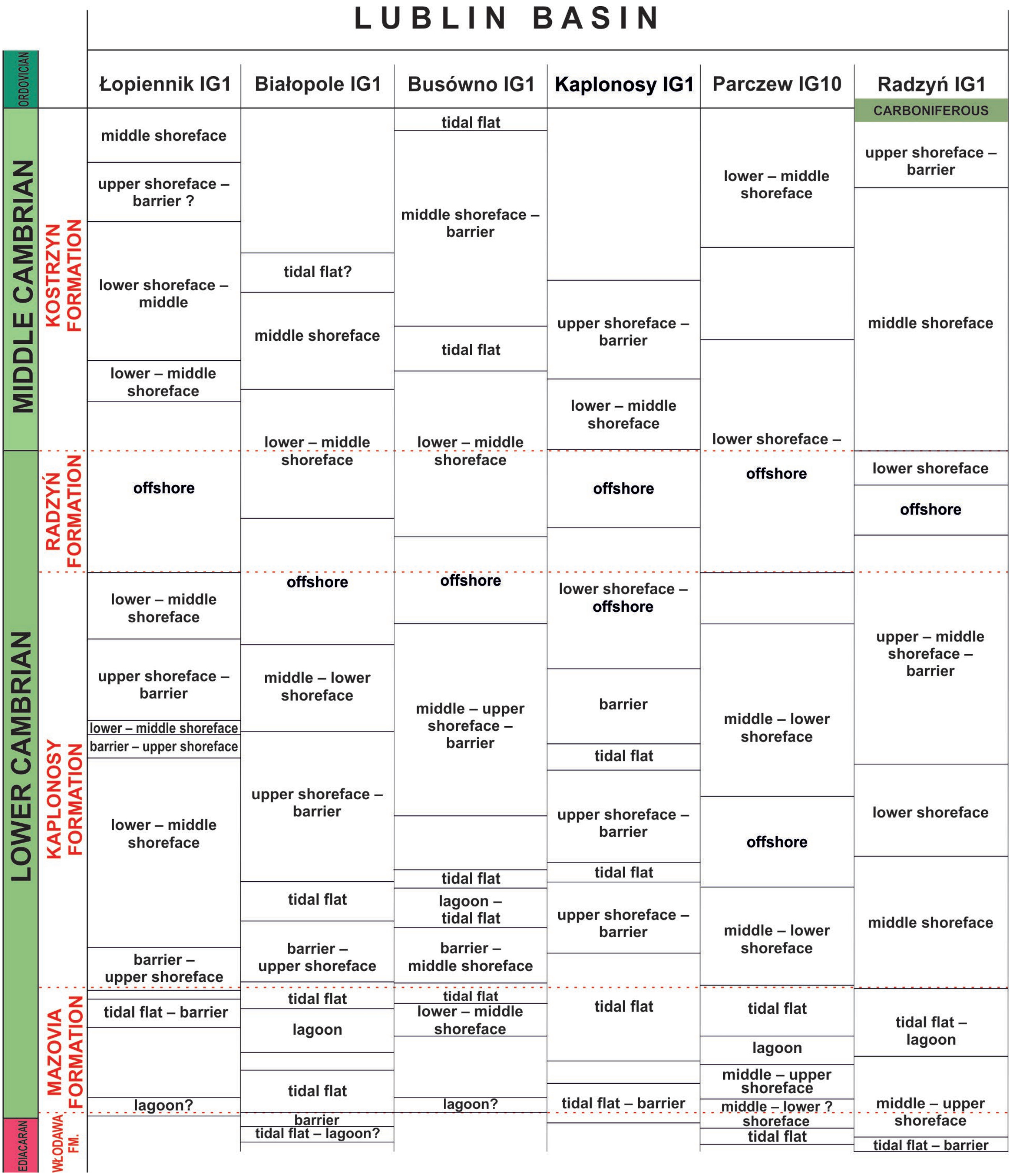


**Fig. 7.** Depositional environments of the Lublin Basin against the background of lithostratigraphic scheme; the range of environments corresponds to their thicknesses in individual logs; after Stadnik *et al.* (2017), modified.

change (Galloway and Hobday, 1983), as well as various sand bodies (see Jaworowski, 1997). For a passive continental margin, transgressive barriers are typical, forming relatively low, narrow and elongated strips, separating the shoreface from the lagoon (Hiscott, 1982; Galloway and Hobday, 1983). They often migrate, being exposed or periodically submerged, with their stability dependant on the supply of clastic material and the amplitude of tides (Prothero and Schwab, 1996). Barriers/sand bodies are composed mainly of lithofacies of porous and well-sorted sandstones, up to several metres thick. Characteristic features include coarsening-upward trends and meshing with the lagoonal facies, inlets within the tidal flat and dune sands (Prothero and Schwab, 1996), what is preserved in sections studied.

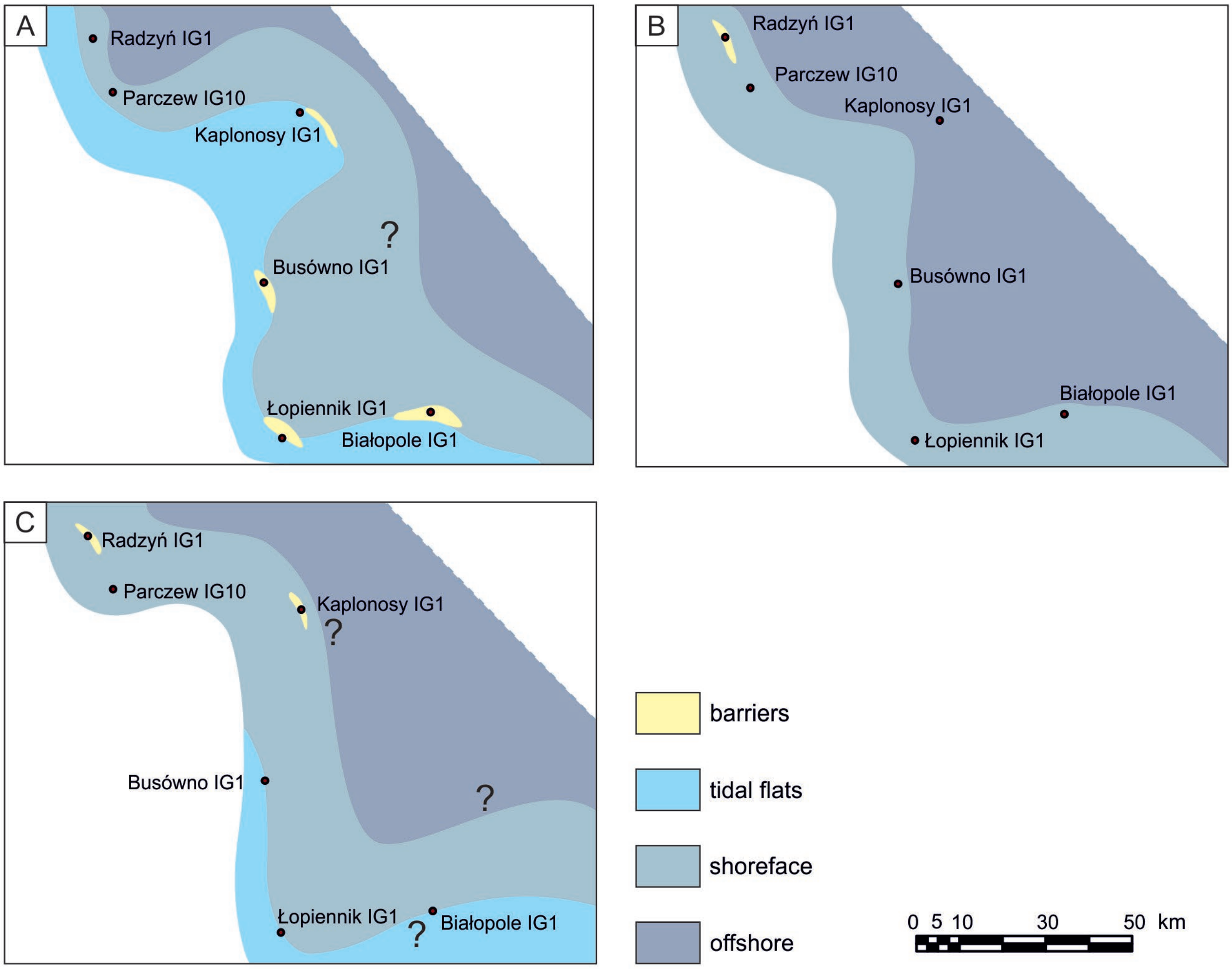


**Fig. 8.** Distribution of facies and palaeoenvironments in the Cambrian formations of the Lublin Basin on the edge of the Eastern European Platform. **A.** Mazovia/Kaplonosy formations (lower part of the early Cambrian). **B.** Radzyń Formation (upper part of the early Cambrian). **C.** Kostrzyn Formation (middle Cambrian); after Stadnik *et al.* (2017), modified.

Thin intervals of lenticular and parallel lamination, as well as low-angle cross-lamination and hummocky cross-stratification within the lagoonal environment indicate the occasional transport in the traction of the finest, non-cohesive fractions and the influence of storm waves. The different degree of bioturbation in lagoonal deposits suggests deposition in a hypoxic basin, cut off from the open sea (Prothero and Schwab, 1996).

During the Cambrian, the Lublin Basin was dominated by sedimentation in a shoreface environment. It was common especially during the middle Cambrian, but also in the early Cambrian. Coastal deposits were created with the action of diversified wave energy. Depending on the environmental energy, the coastal zone is subdivided into the lower shoreface with relatively low wave energy (near the fair-weather wave base), the middle shoreface located in the wave breaking zone, with significant environmental energy, and the high-energy upper shoreface (surf zone). The differential dynamics of these subenvironments, determined by the waves and the currents induced by them, significantly affect the types of lithofacies that form in these zones.

One of the diagnostic features of the lower shoreface is sandstones with HCS, which forms between the fair-weather wave base and the storm wave base (Walker and Plint, 1992), or during the strong waves of intense storms, when unidirectional current velocities are around 5–10 cm/sec (Plint, 2010). A high degree of bioturbation is frequent in this environment (Prothero and Schwab, 1996; Pemberton *et al.*, 2012). The amount decreases towards the outer shoreface. The outer shoreface zone is subject to intensive erosion processes on various scales, which are most intensified in the upper shoreface. Advanced erosional processes in the swash zone usually lead to their destruction (Prothero and Schwab, 1996), which is reflected in the remnant of lithological record in the material studied. Multiple grading changes within subenvironments indicated as transitions from the lower to middle and rarely upper shoreface are associated with cyclic ingressions.

The offshore is an area (Pemberton *et al.*, 2012), which consists of the upper and lower zones. The upper offshore is the area below the fair-weather wave base (Pemberton *et al.*, 2012). It includes the part of the seabed that can be reached by storm waves. The deeper part, up to the storm wave base is known as the lower offshore. Here, storm waves appear less frequently, usually during very strong episodic storms. The characteristic lithofacies of this environment are related to relatively slow sedimentation, interrupted by storm periods. The presence of heterolithic deposits indicates a reduction in environmental energy and the thick mudstones reflect slow deposition from suspension (Reineck and Singh, 1977). Parallel lamination in the mud-dominated heterolithic deposits is the result of the supply of storm material that interrupted the slow, pelagic deposition (Walker and Plint, 1992) and the small lenses are the result of low-energy currents (Johnson and Baldwin, 1996).

In the deposits of the Lublin Basin, transitions between the lower and upper offshore occur, indicating multiple oscillations. In these sequences, transitions to the lower shoreface also appeared. Intertonguing of the lower shoreface and upper offshore deposits is common in shallow-sea environments, hence in some models of shallow-marine environments a transitional zone also is distinguished and placed between the typical lower shoreface and upper offshore deposits (Reading and Collinson, 1996).

### Facies model of the Lublin Basin

The oldest Cambrian deposits in the Lublin Basin represent part of the Włodawa Formation, the sedimentation of which began in the Ediacaran and continued into the earliest Cambrian (Fig. 7). These deposits with the lower part of the Mazovia Formation correspond to the synrift phase of basin development. They originated mainly within the environments of lagoons, barriers/barrier islands, tidal flats and shoreface (Parczew IG10, Radzyń IG1). The lagoonal environment is represented by fine-grained lithofacies, with dominant black mudstones, subordinate sandstones, as well as characteristic ichnofaunal assemblages (Lendzion, 1989a; Bromley, 1996). Barrier sequences are represented mainly by sandstones, usually porous and cross-bedded, with variable amounts of mud admixtures. The thickness of deposits originating during this period varies, increasing from the northwest toward the southeast in the Lublin Basin (Poprawa and Pacześna, 2002). This is consistent with the rift system developed along the western edge of Baltica (Pacześna, 2006). The greatest thickness of sediments is noted in the central part of the basin, where at the end of rift activity the Parczew-Radzyń depocenter developed and was connected with the presence of a syndepositional fault (Pacześna, 2006). The authors noticed the environment of shoreface with the predominance of medium-grained, cross-bedded sandstones with glauconite.

In fact, the transition of the basin to the post-rift phase (Poprawa and Pacześna, 2002; Pacześna, 2006b) did not introduce dynamic changes within environment and the transgression still progressed slowly and gradually. At this time (the final phase of the Mazovia Fm.), the unification of the sedimentation within the area analyzed was under the influence of a very wide range of tidal flats. A significant impact of tidal-flat deposition affected the upper part of this formation. The tidal-flat deposits pass upwards into deposits of the barrier/sand bodies zone. These deposits first appear in the southwestern and western parts of the basin (directions are compatible with the current position in the structure of the East European Platform). In the highest part of the formation, unification of sedimentation within extensive tidal flats is observed (Fig. 8A).

Multiple fluctuations in sea level (Haq and Schutter, 2008) have been noted within the Mazovia Formations as well as within the lower part of the Kaplonosy Formation. Subenvironments of the tidal flat, which are sensitive to sea-level changes (Prothero and Schwab, 1996), show cyclic migrations from the muddy to the sandy tidal flat. They are replaced by sandy, barrier-like complexes (Busówno IG1; Fig. 7) or upper-/middle-shoreface sequences (Busówno IG1, Białopole IG1, Łopiennik IG1, Kaplonosy IG1; Fig. 7), and in the northern part of the basin by the lower-shoreface sequences (Parczew IG10). The general rate of the transgression was rather slow, in the opinion of the present authors slower in relation to the assumption made by Poprawa and Pacześna (2002), who suggested deposition in the upper offshore environment at that time. The deepest environment the present authors found in the Parczew IG10 core and classified as lower shoreface occurring in the lower part of the Mazovia Formation (the interval is so short that is below the resolution adopted for Figure 7). For an open shallow-shelf environment in the Włodawa Formation (Pacześna, 2008) the present authors also have no evidence.

In the next stage, shoreface sedimentation occupied the Lublin Basin region. The complexes typical for that environment, together with sequences corresponding to the environment of barriers or other sandy forms, occur in the middle and upper part of the Kaplonosy Formation. The final sedimentation phase of the Kaplonosy Formation and the beginning of sedimentation of the Radzyń Formation (the upper part of the lower Cambrian) was followed by a deepening of the basin (Fig. 7). The accommodation capacity of the basin increased towards the southwest as a result of regional subsidence (Poprawa and Pacześna, 2002). In this interval, deposits representing the transition zone between the lower shoreface and the upper offshore were created (Kaplonosy IG1, Parczew IG10) as well as the upper and lower offshore (Łopiennik IG1, Białopole IG1, Radzyń IG1, Busówno IG1; Fig. 8B). The maximum depth and lateral range of the Iapetus Ocean on the Baltica shelf in Lubin Basin is recorded.

The greatest thickness of the offshore deposits of the Radzyń Formation was about 114 m in the Łopiennik IG1 borehole; in other sections the thickness varies between 56 and 25 m. In all cores, migrations of the environments connected with episodic shallowing and the transitions to the upper offshore and even the lower shoreface were noted (Fig. 7).

From the middle Cambrian, the rate of subsidence decreased, leading to changes in the accommodation capacity of the basin (Poprawa and Pacześna, 2002). The middle Cambrian deposits, which are represented by the Kostrzyn Formation, indicate a regressive trend in all sections analyzed (Fig. 7) and the shallower environments were observed. The Lublin Basin was dominated by deposits of the shoreface environment and locally by barrier-like deposits, and other sand bodies (Łopiennik IG1, Kaplonosy IG1, Radzyń IG1) or tidal-flat deposits (Łopiennik IG1, Białopole IG1, Busówno IG1) (Fig. 8C). The regressive cycle in comparison with the directly preceding transgressive cycle marks a much more dynamic and shorter time interval. The middle Cambrian deposits contact directly with the Ordovican and Carboniferous (see the Radzyń IG1 core). The stratigraphic gap is connected with advanced erosion, which took place in a land environment located along the Baltica coastal zone.

The general model of facies evolution in the Cambrian of the Lublin Basin establishes a transgressive-regressive cycle as the superordinate. The identification of sedimentary environments and their migration fit this trend. However, in the opinion of the present authors, the course of transgressive processes took place at a different rate than that suggested in earlier studies (Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005; Pacześna, 2007, 2008). Within the general trangressive-regressive trend, the multiple trangressions and regressions of second- and third-order are recorded. Their ranges are much smaller and usually include migration within neighbouring environments or subenvironments.

## CONCLUSIONS

In the Cambrian deposits of the Lublin Basin, four lithofacies were distinguished and characterized in detail. Within them, 16 sublithofacies were recognized as characteristic associations for such sedimentary subenvironments as tidal flats, barriers and lagoons, shoreface and offshore. A range of variations within them was assigned to relevant subassociations.

Analysis of the distribution and variability of individual environments in the Cambrian interval indicates the dynamic development of the coastal zone within the Lublin Basin. In the lower Cambrian, there was a transgressive trend from lagoonal deposits to lower offshore deposits, and in the middle Cambrian a regressive trend ended with land emergence. For the Cambrian interval of the Włodawa Formation and the lower part of the Mazovia Formation, a brackish depositional environment (lagoons, barriers and tidal channels) was inferred. The upper part of the Mazovia Formation passes into muddy to sandy tidal flat environments

The overlying deposits, belonging to the Kaplonosy Formation, represent diverse, shoreface environments, which in the Radzyń Formation pass into the environment of the upper and lower offshore. These deposits indicate the maximum depths and the maximum extenr of the Lublin Basin during the Cambrian.

In the Kostrzyn Formation, deposited in the middle Cambrian, a change in the sedimentation regime and the presence of shallow environments of the shoreface and locally tidal flats was observed. Within the general trangressive-regressive trend, the multiple trangressions and regressions of second- and third-orders are recorded.

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