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FACIES ARCHITECTURE OF THE CAMBRIAN SUCCESSION AT THE WESTERN MARGIN OF BALTICA IN THE PODLASIE REGION (E POLAND)

Marek WENDORFF

AGH University of Science and Technology;
al. Mickiewicza 30; 30-069 Kraków, Poland; e-mail: wendorff@agh.edu.pl

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Abstract: Sedimentary features of the Cambrian-age succession transected in seven borehole cores sited in the Podlasie region document vertical and lateral variations of shallow-marine sedimentary facies, deposited at the rifted western margin of the Baltica Palaeocontinent. The boreholes are distributed along two lines of cross-section (E–W and NE–SW) running roughly perpendicular to the margin of the palaeocontinent. The easternmost borehole represents a proximal setting located on a relatively stable, shallow basement in the east; the remaining boreholes document conditions of deposition in the subsiding shallow-marine basin, extending towards the SW. Fourteen sedimentary facies defined on the basis of their lithological and sedimentary features are interpreted in terms of the sedimentary environments they represent. Strata deposited upon the stable craton in the east document a stratigraphically condensed succession of proximal facies, 240 m thick, whereas a sequence three times thicker is positioned distally, 170 km to the west. Facies associations in the proximal section represent the lower to upper shoreface in the lower part of the section and evolve upwards to the intermediate shoreface. Facies complexes in the remaining, intermediate and distal areas form a symmetrical megasequence, composed of a positive (i.e., fining-upwards – FU) transgressive sequence, overlain by a negative (coarsening-upwards – CU) regressive sequence. The vertical arrangement of the sedimentary subenvironments during the transgression indicates a tidally influenced shoreline followed by oscillations between the swash zone, the upper, intermediate and lower shoreface, and the offshore. The symmetry of the megasequences and the rhythmic pattern of the component facies complexes indicate that the intensity of supply in the terrigenous material and the efficiency of its reworking and redistribution within the basin were similar during the transgression and the regression. The facies types and variations within the basal part of the succession reflect syndepositional movements of tectonic blocks parallel to the rifted basin margin. Differences in total thickness and facies associations between the two lines of cross-section approximately perpendicular to the basin margin indicate that sedimentation was also influenced by a synsedimentary hinge fault, extending in a WSW–ENE direction.

Keywords: Cambrian, Baltica, sedimentary facies, shelf, transgression, regression.

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INTRODUCTION

The Podlasie Zone is a NE part of the Lublin Basin (Fig. 1), active at the western margin of the Baltica Palaeocontinent from the Late Proterozoic to the Early Palaeozoic (Poprawa and Paczešna, 2002; Paczešna and Poprawa, 2005b; Golonka *et al*., 2017, 2019). The infilling sedimentary succession is located within the Polish sector of the East European Platform (Żelaźniewicz *et al*., 2011). The sedimentary rocks of the basin range in age from Neoproterozoic to Cambrian, are unmetamorphosed and rest unconformably upon the Mesoproterozoic crystalline basement (Ryka, 1984). Initially, continental sediments were deposited in the active rift during the Neoproterozoic. The marine transgression that followed in the latest part of the Ediacaran resulted from post-rift thermal subsidence (Botor *et al*., 2017, 2019) of the passive margin of Baltica and created a shallow-marine basin (Poprawa and Paczešna, 2002; Paczešna and Poprawa, 2005a; Paczešna, 2006).

Continuity of sedimentation from the Ediacaran to the Cambrian is a characteristic feature of the marine successions of the Podlasie-Lublin depository. The hiatus that follows ranges from the upper part of the middle Cambrian to the top of the late Cambrian and reflects pre-Ordovician

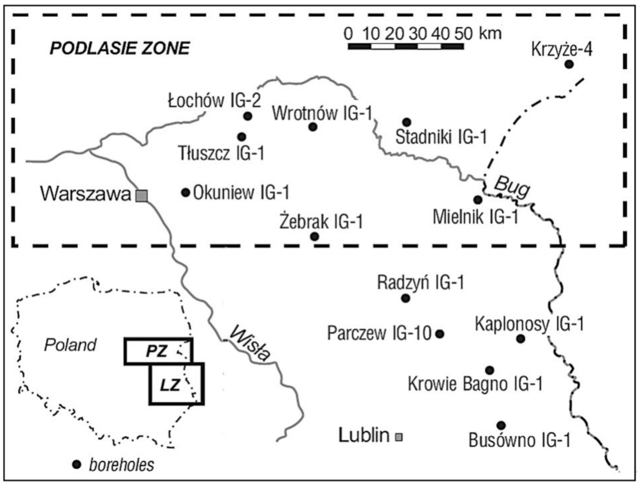

Fig. 1. Location map of the Podlasie Zone (PZ) of the Cambrian Basin discussed in this paper and the adjacent Lublin Zone (LZ), showing the position of boreholes transecting the Cambrian strata (after Pacześna and Poprawa, 2005a; Wendorff, 2017). Both the PZ and LZ are parts of the Lublin Basin.

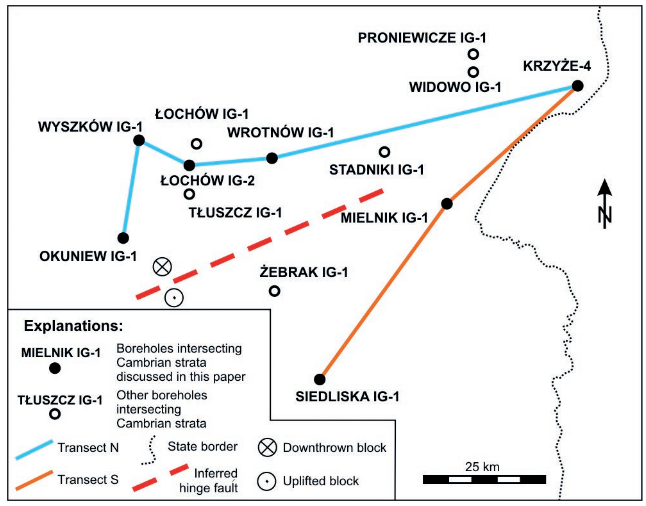

Fig. 2. Schematic location map, showing positions of the boreholes discussed and two transects, along which they are distributed. Modified from Wendorff (2017).

emergence and erosion (Pacześna and Poprawa, 2005a; Pacześna, 2014; Podhalańska *et al*., 2016a). The older part of the succession has been dated radiometrically and biostratigraphic subdivision of the younger part is based upon the Cambrian acritarch and trilobite zones (Lendzion, 1983; Moczydłowska, 1991). The stratigraphic position of the lower and upper Cambrian strata is determined by biostratigraphic criteria in some boreholes, but in some others is based on lithostratigraphic correlation. For example, in the successions transected in the Łochów IG-1 and IG-2 boreholes and the Tłuszcz IG-2 borehole (Fig. 1), the boundary between the lower and middle Cambrian strata was defined by the appearance of the trilobite association that represents the correlation level *Acadoparadoxides oleandicus* in the ferroan, brownish sandstones (Lendzion, 1983). On the other hand, correlation of the lithologic sections, for example, from Wrotnów IG-1 and Wyszków IG-1 was based on lithostratigraphic criteria, namely the development of lithological associations identical to those dated biostratigraphically in other boreholes (Podhalańska, 2008 and references therein).

The aim of this paper is to examine the sedimentary features of the successions represented in seven almost completely preserved borehole cores, in order to broaden perceptions of the depositional processes and their tectonic controls in part of the Baltica margin during the Cambrian transgression. The boreholes examined are located in the Podlasie region (Figs 1, 2). The paper, here presented in English, is a significantly modified version of the book chapter by Wendorff (2017), up to now available only in the Polish language.

MATERIALS AND METHODS

The successions transected in seven borehole cores (Krzyże-4, Łochów IG-2, Mielnik IG-1, Okuniew IG-1, Siedliska IG-1, Wrotnów IG-1, Wyszków IG-1; Fig. 2) were measured in detail and documented in sedimentological graphic logs. On the basis of careful analysis, they were subsequently generalised and reduced to the scale presented in this paper.

Core recovery in six out of the seven wells ranges from 75% to 100% and the thickness of the transected intervals ranges from 275 m to 518 m (Tab. 1). The succession transected by the Łochów IG-2 borehole is taken here as representative for the part of the basin, in which two other nearby boreholes also were drilled, namely Łochów IG-1 and Tłuszcz IG-1. Very limited recovery values in the range of 70–80 m in total in other five wells (Bodzanów IG-1 – 80.00 m; Polik IG-1 – 78.00 m, Żebrak IG-1 – 72.90 m, Widowo IG-1 – 9.28 m and Proniewicze IG-1 – 11.90 m) excluded them from further analysis, but the good state of preservation of some of their fragments provided insights that were useful in illustrating or interpreting some specific features of the Cambrian succession.

The background literature data concerning the Podlasie and Lublin basins were published in a series of volumes edited by the Polish Geological Institute – National Research Institute (PIG–NRI); the most important are related to the following boreholes: Okuniew IG-1 (Areń, 1975), Wrotnów IG-1 (Podhalańska, 2008) and Wyszków IG-1 (Podhalańska, 2007). Other relevant data sources are devoted to palaeotectonics (Nawrocki and Poprawa, 2006), sedimentology (Jaworowski, 1997; Modliński, 2010) and exploration for hydrocarbons (Podhalańska *et al*., 2016a, b).

The following features of the rock successions analysed were recorded in the course of detailed logging: lithology, grain-size according to the Wentworth's phi scale (Tucker, 2003) determined by comparison with the grain-size standard (American-Canadian Stratigraphic), bed thickness classes according to Ingram (Tucker, 2003), primary sedimentary structures, secondary/post-depositional sedimentary structures, degree of bioturbation, presence of hydrocarbons. Vertical trends of sedimentary facies and facies complexes enabled the identification of sequences: (a) pos-

Table 1

Summary data on the boreholes from the Podlasie Zone discussed in this paper.

Borehole label	Cambrian divisions	Cambrian depth from (m)	Cambrian depth to (m)	Thickness (true) (m)	Core reco-very %	Rocks underlying	Rocks overlying
Krzyże-4	middle	448.50	545.00	96.50	100		Tremadoc
	lower	545.00	724.00	179.00		Ediacaran	
Łochów IG-1	middle	1634.00	1759.00	125.00	58		Arenig
	lower	1759.00	2112.80	353.80		Precambrian	
Łochów IG-2	middle	1922.40	2049.90	127.50	75		Tremadoc
	lower	2049.90	2398.00	348.10		Precambrian	
Mielnik IG-1	middle	1182.00	1247.00	65.00	100		Tremadoc
	lower	1247.00	1576.30	329.30		Ediacaran	
Okuniew IG-1	middle	3637.20	3888.90	251.70	79		Arenig
	lower	3888.90	4249.00	360.10		Proterozoic	
Siedliska IG-1	middle	2596.00	2796.20	200.20	100		Arenig
	lower	2796.20	3010.30	214.10		well bottom	
Wyszków IG-1	middle	1854.50	1963.10	108.60	83		Zechstein
	lower	1963.10	2373.30	410.20		well bottom	
Wrotnów IG-1	middle	1608.70	1717.50	108.80	25		Tremadoc
	lower	1717.50	2026.10	308.60		Proterozoic	

itive/fining upwards (F-U), characterized by fining grain-size or a succession of sedimentary structures suggestive of more or less gradual decrease in energy of the depositional environment; and (b) negative/coarsening upwards (C-U) characterized by coarsening grain-size or a succession of sedimentary structures, indicating increasing energy of the environment. Such sequences can also be controlled by changes in intensity of sediment supply, sea-level oscillations, lateral migration of environments or climate changes. Correlation between the measured borehole cores along two lines of cross-section, i.e., the northern and southern section (Fig. 2), reveals facies gradients across and along the basin margin extending in a NW–SE direction.

The state of preservation of the borehole cores discussed is variable, therefore much emphasis is placed on facies complexes as well as their vertical and lateral relations, because these reflect large-scale stages of basin evolution and indicate possible tectonic controls on sedimentation.

GEOLOGY AND LITHOSTRATIGRAPHY OF THE CAMBRIAN SUCCESSION IN THE PODLASIE BASIN

Lithostratigraphically, the Cambrian succession of the Lublin-Podlasie Basin is subdivided into four formations. In the ascending order, these are: the Włodawa Fm, the Mazowsze Fm, the Kaplonosy+Radzyń Fm and the Kostrzyń Fm (Fig. 3). From the viewpoint of sequence stratigraphy, the succession of these units forms a part of the 2-nd order sequence (Paczešna and Poprawa, 2005b), labelled “B” and defined by the following unconformities: (a) the basal, angular unconformity on the underlying Middle Neoproterozoic strata, which are classified as the sequence “A”, and (b) the upper, erosional unconformity that reflects a hiatus at the base of the overlying Ordovician strata. Sequence “B” has been subdivided into five depositional systems, two of which (B4 and B5) include the Cambrian suite (Fig. 3). The uppermost part of system B4 contains the oldest strata of the Cambrian succession, i.e., the Włodawa Fm that occurs at the Ediacaran-Cambrian boundary and is characterised by the presence of fine-grained sandstone beds with large-scale cross-bedding, interpreted as the infills of tidal channels. This unit also contains numerous heterolithic intervals of thin-laminated mudstone, claystone, siltstone, and sandstone. System B5 is represented by a succession of three formations: (1) Mazowsze; (2) Kaplonosy + Radzyń; (3) Kostrzyń (Fig. 3). The most characteristic sedimentary features of this system are cross-laminated, fine-grained sandstones and mudstones and the most common sedimentary structures are lenticular and flaser lamination. Ichnofossils (Paczešna, 2006; Podhalańska, 2008) and the sedimentary facies indicate deposition in a shallow-marine environment, namely in the shoreface and offshore regions. In general, it is considered that the sedimentation took place at the highstand of sea-level (Paczešna, 2006).

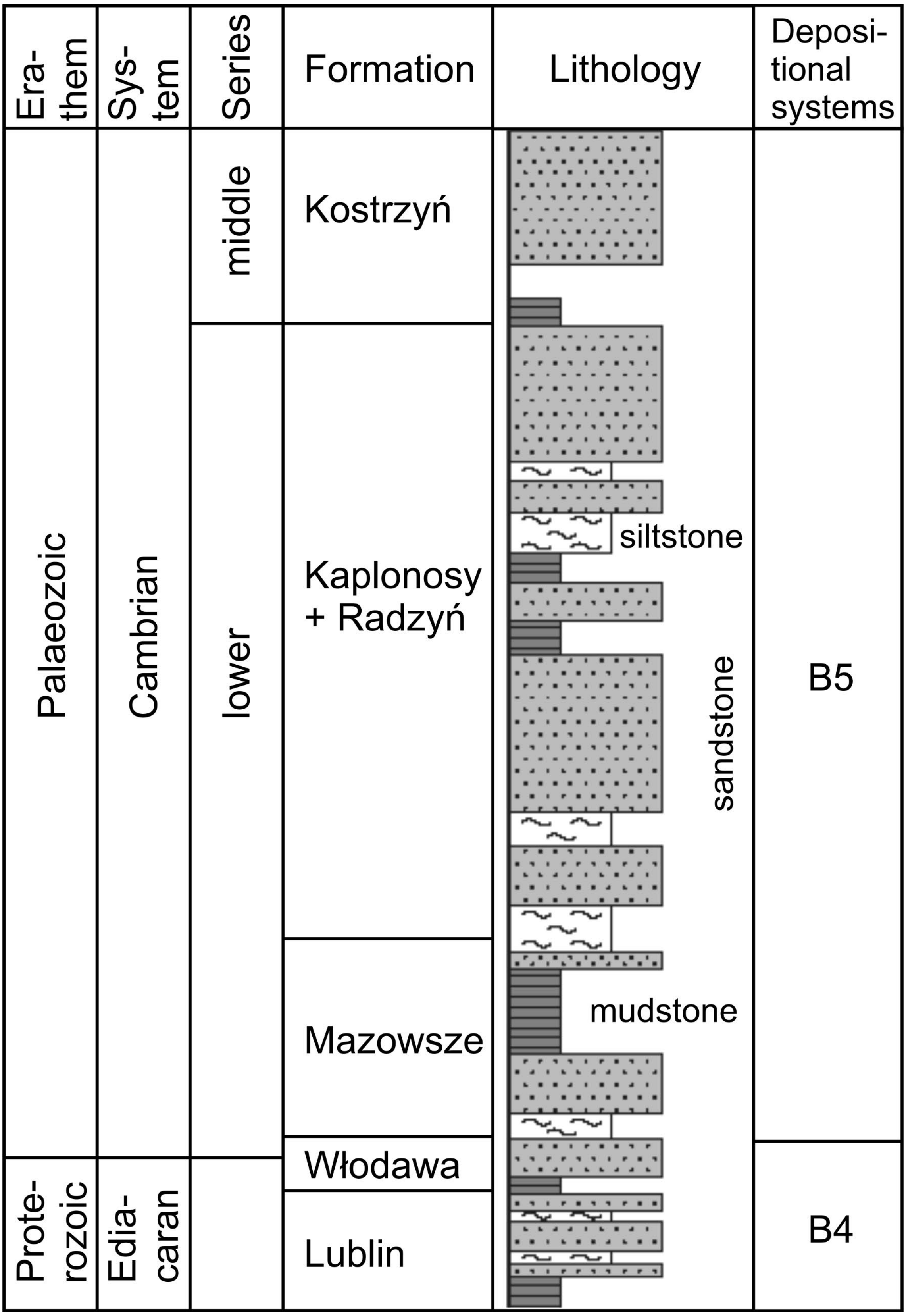

Fig. 3. Stratigraphic subdivision of the Cambrian succession in the Podlasie and Lublin zones (after Pacześna and Poprawa, 2005a; Wendorff, 2017).

SEDIMENTARY FACIES IN THE MEASURED SECTIONS AND THEIR INTERPRETATION

Sedimentary facies of the Cambrian strata defined on the basis of lithology and sedimentary structures (Tab. 2) are described below and their selected examples are illustrated in Figures 4–7. Each interval of the measured section that is characterised by a specific facies is termed a facies complex and successions of them are shown in Figures 8 and 9. Facies complexes are rarely uniform in composition; therefore, a complex type is defined with reference to the predominant (modal) facies. Subordinate facies are mentioned and commented upon in the descriptions and considered at the stage of interpretation of the depositional processes that shaped the facies complex. Mixed facies are assigned to a separate class, i.e., "heterolithic" strata. In this way, both the major and subordinate features that characterise the sedimentary environments documented in the measured sections are considered. The description of each facies is supplemented by an interpretation of sedimentary environment that it represents and an example of its occurrence in the measured sections. The interpretations of sedimentary facies, facies complexes and the analysis of their sequences presented in the forthcoming sections reflect the observations and concepts published by several authors (e.g., Reineck and Singh, 1980; Reading, 1986; Einsele, 1992; Tucker, 2003; Wendorff, 2005; Sheppard, 2006; Catuneanu, 2007; Nichols, 2009; Longhitano *et al*., 2012; Longhitano, 2015).

Conglomerate (G)

Ge – extraformational conglomerate

Extraformational conglomerates contain clasts derived from beyond the sedimentary basin and occur in one section only, i.e., in the basal part of Łochów IG-2, where it rests upon erosional surface, defining the lower boundary of the Cambrian succession. This occurrence is interpreted as a result of deposition by high energy currents – either storm-related or formed by rip-currents, transporting fluvially derived beach gravels.

Gi – intraformational conglomerate

Intraformational conglomerates most often contain tabular mudstone clasts 1–2 cm thick and 4–6 cm across, set in a sandstone matrix (Fig. 4A). The proportion of clasts is usually <50%. They are usually angular, but locally slightly rounded, can be deformed and represent the lithotype that occurs in underlying intervals of the stratigraphic succession. Intraformational conglomerate beds usually range from thin to medium in thickness, are most often massive, but locally display large-scale, high-angle cross-bedding (Sx type; Fig. 4A), occasionally trough cross-bedding; bioturbation structures are absent.

Occurrence: The Gi facies occurs only in the oldest, basal part of the succession transected by the Łochów IG-1 and Widowo IG-1 wells (Fig. 4A).

Interpretation: Deposition by high-energy currents eroding a partly lithified muddy substratum, locally still prone to plastic deformation. Sand beds containing interlayers of this mudstone were eroded simultaneously. Therefore, the sandy matrix of Gi conglomerates consists of both autochthonous sand, eroded locally within the basin, together with mud and allochthonous sand, derived from land. Massive beds were deposited rapidly *en masse,* probably during floods, possibly within channels or at the mouths of channels. Cross-bedded conglomerates originated either as dunes, which are bed-forms resulting from prolonged flow and transportation by traction, or as channel-infill sets, related to lateral accretion due to channel migration. In general, the Gi facies reflects the conditions of erosion and deposition by currents of high energy separated by periods, or zones of low energy, reflected in the deposition of episodically eroded, muddy sediments.

Sandstone (S)

Structural and textural variations of the arenaceous sediments enable the definition of four sedimentary facies.

Ss – massive sandstone

Massive sandstone is usually medium- and fine-grained, locally coarse and rarely with an admixture of coarse sand grains (Fig. 4B). The fine- and very-fine grained variety is well sorted, whereas the coarser type is often very poorly sorted and can contain fine mudstone grains. Bed thickness varies in a broad range from thin to very thick; some beds are stacked, reaching even 3 m in thickness. Faint parallel bedding and/or lamination as well as hummocky cross-lamination occur locally. The massive sandstone facies forms complexes reaching up to 50 m in thickness (e.g., Wyszków IG-1), which contain a few intercalations, less than 70 cm thick, of thin layers of very fine-grained sandstone associated with mudstone, both very intensively bioturbated (Fig. 4C). Sandstone beds of this facies may also contain mudstone intraclasts (Fig. 4D, lower part and centre), very thin (5–10 cm) interlayers of parallel laminated mudstone (Fig. 4D, upper part), or in places also heterogeneous interbeds of current-ripple-laminated sandstone and mudstone.

Occurrence: Facies Ss occurs in six out of seven sections where it forms complexes observed most often in the lower part of the succession, is a part of the negative, positive or mixed sequences, and most often occurs associated in stratigraphic successions with facies Sh, less commonly with Hw. On the other hand, rare interbeds within facies Ss are represented by Sl (e.g., Okuniew IG-1, depth 4220 m).

Interpretation: Poorly sorted sandstone results from rapid deposition from quickly decelerating currents carrying large volume of sand, i.e., flows of high capacity. Local occurrences of parallel lamination indicate the events of high-energy flows (upper flow regime), and occasional appearances of hummocky cross-stratification reflect storm events. On the other hand, bioturbation structures ranging from moderately frequent to very intense indicate periods of quiescence, which are also documented by thin complexes of thin-bedded, very fine-grained sandstone, interbedded with mudstone. In general, conditions of transportation and deposition were very inhomogeneous, ranging from storm-related flows of high energy to periods of quiescence. The abundance of infauna also varied from low to

Fig. 4. Sandstone facies in the basal part of the Cambrian succession (760–768.7 m) in borehole Widowo IG-1. **A**. Intraformational conglomerate (facies Gi) containing intraclasts of grey mudstone above which rests large-scale cross-bedded sandstone (Sx); 768.7 m. **B.** Very poorly sorted massive sandstone (Ss) succeeded by large-scale cross-bedded sandstone (Sx) tangential in the bottom part and containing double mudstone laminae ("mudstone couplets"), indicative of tides (sequences of beds shown in A and B are considered by Pacześna, 2006 and 2014 as infills of tidal channels); 763 m. **C.** Mudstone lamina with ichnofossils seen in bedding-parallel cross-section (core diameter the same as in A); 768.9 m. **D.** Massive sandstone (Ss) containing mudstone granules and small mudstone clasts interpreted as desiccation flakes washed off the dried-out mudflat surface (core diameter the same as in A); 760 m. Modified from Wendorff (2017).

Fig. 5. Contrasting undisturbed and bioturbated facies. **A.** Large-scale high-angle cross lamination (Sx), Okuniew IG-1, 4110 m. **B.** Ms facies (locally Ml) undisturbed by bioturbation, Łochów IG-1, 2684 m. **C.** Mw and Ms facies heavily bioturbated; Łochów IG-2, 2716 m. Note: B and C represent heterolithic facies of mudstone with siltstone, in the literature usually classified as 'mudstone' and in the logs (Figs 8, 9) shown as 'mudstone + siltstone'. Modified from Wendorff (2017).

high. Considering the occurrences of massive ("structureless") sandstone beds, it should be noted that extremely well-sorted arenaceous sediment may not reveal traction-related structures, e.g., cross-lamination, which can be seen in X-rayed thin slabs only because of very high textural and mineralogical maturity. On the other hand, very intense bioturbation may also obliterate all primary sedimentary structures, but observations of lateral variation at a scale broader than that of the borehole core are required for such determinations.

Sh – planar parallel-laminated sandstone

Facies Sh is represented by medium and thin beds of fine- and very fine-grained sandstone; rarely medium- to coarse-grained. The lamination is defined by variations in grain-size, locally by admixtures of muscovite, glauconite or minute mudstone intraclasts. Such sandstone beds locally may contain thin intervals with current ripplemarks and intercalations of thin layers or laminae of mudstone. Hummocky cross-lamination is exceptionally rare.

Occurrence: Sh facies occurs in six out of seven sections shown in Figures 8, 9. In vertical sequences, its sediments

Fig. 6. Sandstone facies influenced by bidirectional and unidirectional currents. **A.** Bipolar cross-lamination (herring-bone cross-stratification), Okuniew IG-1, 4232.6–4239 m. **B.** sandstone with low-angle cross-lamination (Sl), Okuniew IG-1, 4118.3–4125.6 m. Modified from Wendorff (2017).

Fig. 7. Heterolithic facies. **A.** Sandy-muddy heterolithic deposits (Hw) – showing wavy lamination of very fine-grained sandstone component, Okuniew IG-1, 4154–4155 m. **B.** muddy-sandy heterolithic deposits (Hm) with lenses of very fine-grained sandstone, locally bioturbated, Okuniew IG-1, 4200–4202 m. Based on Wendorff (2017), modified.

most commonly form associations with complexes of facies Ss and Hw. On the other hand, within complexes of Sh facies, interbeds of Sx-type (tabular and trough cross-bedding) occur from time to time, e.g., in Wrotnów IG-1, at a depth of 2305–2322 m.

Interpretation: Deposition from traction by currents of high energy, in the upper flow regime. Rare occurrences of low-energy, unidirectional currents are reflected in current ripplemarks. Storm events are recorded very rarely and occasional periods of stagnation are indicated by suspension-related, hemipelagic mudstone layers.

Sl – sandstone with low-angle large-scale cross-lamination

Characteristically the Sl-facies sandstones possess cross-laminae/cross-beds dipping at an angle lower than 20° (Fig. 6B). They are usually very fine- and fine-grained, however locally may range from medium- to very coarse-grained. The lamination is defined by variations in grain size and concentrations of mudstone intraclasts, varying in size from very coarse sand to fine pebbles. The cross-laminae are planar and their set boundaries are in places erosional and inclined at a very low angle, relative to the dip amounts within the succeeding sets.

Occurrence: Facies Sl occurs in four of the seven sections discussed. In vertical successions, it most commonly underlies, or overlies, Ss and Hw facies intervals. Locally, it can occur as interbeds within Ss facies complexes (e.g., Okuniew IG-1; at depth intervals 4078–4107 and 4215–4338 m).

Interpretation: Transportation by traction by high-energy currents in the swash zone.

Sx – sandstone with large-scale, high-angle cross-lamination

Sandstones of the Sx facies are fine- and very fine-grained, rarely coarse-grained, the dip of cross-laminae exceeds 20°, laminae and bedding surfaces are planar or trough (Fig. 5A). The lamination is defined by variations in grain size and admixtures of very fine-grained mudstone intraclasts. Mudstone laminae often occur as couplets, separated by thin sandstone laminae. There are also reactivation surfaces, erosion surfaces and channel incisions. The intervals characterised by such features are thin or attain medium thickness.

Occurrence: Facies Sx is not common and a complex of significant thickness appears in only one section – Wrotnów IG-1. However, isolated occurrences, ranging

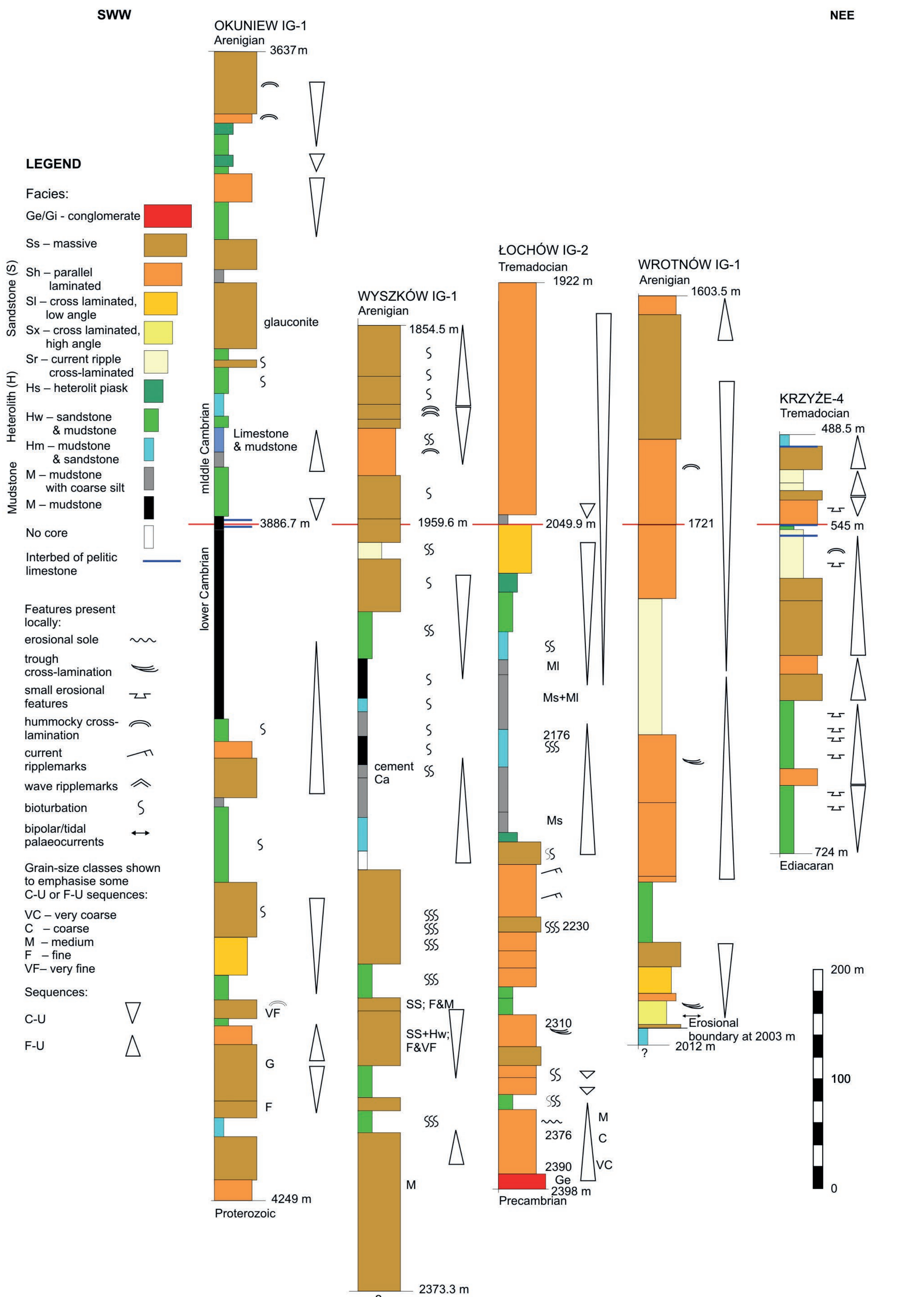

Fig. 8. Successions of facies and facies associations of the Cambrian strata in boreholes located in the Podlasie Zone – transect N (see Fig. 2). Modified from Wendorff (2017).

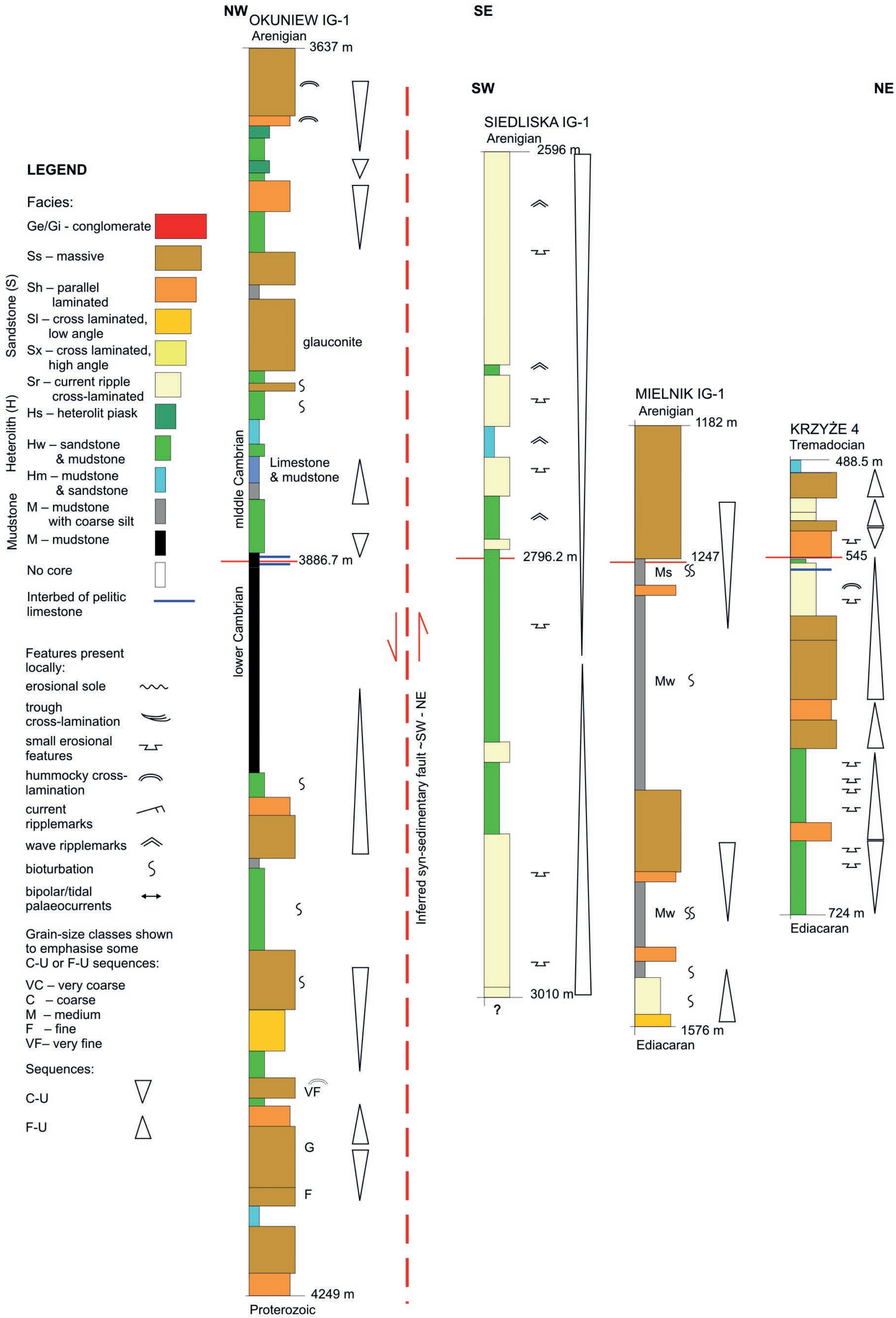

Fig. 9. Successions of facies and facies associations of the Cambrian strata in boreholes located in the Podlasie Zone – transect S, ca. perpendicular to the palaeoslope between boreholes Siedliska IG-1 and Krzyże-4 (see Fig. 2 for locations). Additional comparison between Okuniew IG-1 in the N and Siedliska IG-1 in the S, distributed along a line approx. parallel to the East European platform margin, supports interpretation of a synsedimentary perpendicular (SW–NE extending) hinge fault shown also in Figure 2. Modified from Wendorff (2017).

Table 2

Synthesis of sedimentary facies identified in the Cambrian successions from the Podlasie Zone discussed (see Tab. 1) and interpretation of their origins.

Class	Lithofacies	Sedimentary structures	Grain-size	Origin
Conglomerate	Ge – extra-formational	Massive	Pebbles	Pebbles from land; high energy of sed. environment
	Gi – intra-formational	Massive	4–6x1 cm; mudstone clasts	Intrabasinal erosion; high energy
Sandstone	Ss – sandstone	Massive (rare very thin mudstone wisps)	F, M, (C, VC)	Rapid deposition; high energy
	Sh – sandstone	Parallel lamination	F, VF (M, C, VC)	Traction, upper flow regime, planar bottom
	Sl – sandstone	Cross-lamination large-scale, low angle (<20°)	F, VF (M, C, VC, G)	Traction; swash zone
	Sx – sandstone	Cross-lamination large-scale, high angle (>20°); contains rare, very thin mudstone wisps	F, VF, M, (C)	Traction, upper flow regime, dune deposition
	Sr – sandstone	Ripple cross-lamination	F, VF (locally some silt)	Traction, lower flow regime, deposition of small bed-forms; unidirectional or oscillatory currents (wave-induced)
Heterolith	Hs – sandy	Flaser lamination	VF, F	Alternating episodes of deposition from traction (sand) & suspension (mud). Hs – traction dominant; Hw – traction & suspension balanced; Hm – suspension predominant. The main factor: tides
	Hw – sandstone-mudstone.	Wavy lamination	VF, F	
	Hm – mudstone-sandstone.	Lenticular lamination	VF, F	
Mudstone	Mw	Mudstone & siltstone – wavy lamination	Clay & silt (coarse)	Mud – suspension; silt – traction (current ripplemarks)
	Ms	Mudstone & siltstone – lenticular lamination	Clay & silt (coarse)	Mud – suspension; subordinate silt – traction (rare current ripplemarks)
	Ml	Mudstone & siltstone – parallel lamination	Clay & silt (coarse)	Pulsating current: suspension of mud & silt)
	Mm	Mudstone – massive	Clay + silt	Mud – suspension
Bioturbated	Ssb	Bioturbation structures, grade 2–3	Sandstone	Bioturbation of facies defined above. Low-energy environment, well-oxygenated; abundance of food
	Hsb	Bioturbation structures, grade 2–3	Sandy heterolith	
	Hwb	Bioturbation structures, grade 2–3	Sandy-muddy heterolith	
	Hmb	Bioturbation structures, grade 2–3	Muddy-sandy heterolith	
	Mb	Bioturbation structures, grade 2–3	Mudstone	

in thickness from medium to thick, are observed in most sections as interlayers within Sl and Sh facies complexes (e.g., within parallel-laminated sandstones in Wrotnów IG-1, depth 1982–1980 m; Łochów IG-2, depth 2249 m and 2310–2311m).

Interpretation: Traction transportation by high-energy currents (upper flow regime) forming dunes and locally eroding. Reactivation surfaces and mudstone couplets indicate oscillations of tidal currents, associated with periodic shifts between traction and suspension. A sandy tidal flat or estuary are suggested as the most likely sedimentary environments.

Sr – small-scale, current ripple cross-laminated sandstone

Very fine- and fine-grained sandstone, which locally may occur together with coarse-grained siltstone, both form current ripplemarks that make up beds, ranging from very thin to medium thickness. Symmetrical (wave) ripplemarks and hummocky cross-lamination appear locally. Lamination of these structures is emphasised by variations in grain size, shape, sorting, mineral composition and/or the presence of mudstone interlamination. Bioturbation structures appear locally and play a minor role.

Occurrence: The complexes of Sr facies occur in four sections, i.e., Krzyże-1, and Wrotnów IG-1, predominate in Siedliska IG-1, and are subordinate in Wyszków IG-1. In the first three borehole cores it occurs within complexes of the Ss and Sh facies. In Siedliska IG-1, it forms six complexes, associated with heterolithic facies Hw, in the lower and upper parts of the succession. In the remaining three boreholes, intervals of it occur within complexes of Ss and Sh. Complexes of Sr may contain subordinate interlayers of facies Ml (laminated mudstone) in the borehole cores Wrotnów IG-1 (at depth 1760–1827 m), Wyszków IG-1 (1972–1981 m) and Krzyże-4 (548–574 m).

Interpretation: Deposition by unidirectional currents out of traction in the lower flow regime, resulting from the migration of small current-ripplemarks. Symmetrical and near-symmetrical ripplemarks result from reworking by wave-induced, oscillatory currents (e.g., Siedliska IG-1). The influence of storm events is reflected in the Krzyże-4 section in the appearance of hummocky cross-stratification. Interbeds of Ml facies mark periods of low energy and the deposition of argillaceous sediments out of suspension.

Considering the significance of the co-occurrences in the borehole cores analysed of facies Sh, Sl and Sx, a degree of uncertainty of their genetic interpretations should be taken into account because the core diameter reduces the field of view, thus imposing limitations not present in an outcrop, where larger-scale observations in 3D may be interpreted with greater confidence. For example, at such a limited scale of observation, lamina-sets of similar geometry may represent either low-angle cross-lamination, deposited in the swash zone, or a part of hummocky cross-lamination, or a distal, leeward part of dune cross-laminae, tangentially approaching and extending down-current of the underlying horizontally-laminated layer (Wendorff, 2005, 2017).

Heterolithic deposits (H)

The heterolithic facies is lithologically mixed, composed of varying proportions of very fine-grained sandstone and mudstone, characterised by different types of sedimentary structure. In general, they are classified as three stages of a *continuum*, defined by varying relations between rhythmically alternating sand (transported by traction) and cohesive mud, deposited out of suspension (Reineck and Singh, 1980). These stages are represented by three subfacies:

Hs – sandy, heterolithic deposits, characterised by flaser lamination, i.e., fine-grained, current-ripple-laminated sandstone with wisps of mudstone;

Hw – mixed sandy-muddy, heterolithic deposits, typified by wavy lamination, which is composed of current ripplemarks forming continuous very thin layers with wavy-shaped tops that are separated by thin mudstone layers (Fig. 7A);

Hm – muddy, heterolithic deposits characterised by lenticular lamination in which mudstone contains solitary, isolated current ripplemarks (lenticles) of fine-grained sandstone (Fig. 7B).

Occurrence: Heterolithic facies complexes are most often composed of facies Hw, and rarely Hm, while Hs occurs extremely rarely and exclusively as thin units only in two sections, i.e., Łochów IG-2 and the uppermost part of Okuniew IG-1.

Interpretation: The three subfacies/stages reflect alternating periods of and proportions between deposition from traction and suspension, as follows: Hs – deposition mainly by traction, with a subordinate contribution of suspension; Hw – sedimentation during alternating episodes of traction and suspension, similar in efficiency; Hm – deposited during short intervals of supply of small amounts of sand, transported by traction over a muddy bottom. Tidal currents are considered to be the main agent responsible for the origin of such facies, but it may occur in other sedimentary environments as well (e.g., fluvial). However, taking into account the entire set of features of the sedimentary units discussed and especially the bi-directional/bipolar cross-bedding (Fig. 6A), it is suggested that the heterolithic facies considered in this paper are related genetically to a sedimentary environment, influenced by tidal currents.

Mudstone (M)

The pelitic sediments that belong to this category are composed of mudstone and mudstone, associated with different proportions of coarse siltstone that display sedimentary structures, partly similar to the heterolithic facies described above, namely:

Mw – mudstone and siltstone with wavy lamination;
Ms – mudstone and siltstone with lenticular lamination;
Ml – mudstone and siltstone parallel laminated;
Mm – mudstone massive.

Occurrence: Sedimentary rocks, representing these facies, appear only in the middle parts of the successions intersected by Łochów IG-2, Wyszków IG-1 and Okuniew IG-1. Characteristically, all are located in the westernmost part of the northern line of cross-section (Fig. 2).

Interpretation: The mudstone facies documents conditions of deposition ranging from suspension, associated with the subordinate influence of very weak traction currents periodically reworking silty material available in varying but always in small quantities (Mw, Ms, Ml), to stagnation and deposition from suspension. Subfacies Ml may reflect pulses of supply of muddy and silty material. Overall, except for Mm, all three other subfacies may represent distal, extremely low-energy equivalents of the heterolithic facies. Therefore, they may be distal, and probably deeper equivalents of the tidally influenced deposition, represented by the H facies.

Selected specific cases of facies and their relations

Occurrences of the facies and their relations observed in better preserved parts of some borehole cores shed additional light on development of the Cambrian facies. Three such cases are discussed below.

Facies Ms at Łochów IG-2 in a depth range of 2179–2154 m

This facies is represented by siltstone, mostly coarse-grained, interbedded with mudstone and locally intensely bioturbated. The siltstone is light grey, with current-ripple cross-lamination, and often occurs as isolated ripplemarks and lenses. Beds composed of ripple-cross-laminated cosets show locally sharp bases and upper boundaries that are either sharp or gradational into the overlying, light-grey mudstone.

Interpretation: The siltstone was deposited by currents of very low energy, locally continuing over a considerable period, locally short-lived or transporting silt that was in short supply. Stagnation periods are recorded by suspension-related, massive mudstone layers. Some beds are the products of very highly diluted turbidity currents, possibly stirred by storms in a more proximal and shallower part of the basin or supplied by short periods of flooding and increased intensification of river discharge.

Facies Ss at Wyszków IG-1 in a depth of 2148–2198 m

Fine-grained sandstone, locally very poorly sorted, medium- to coarse-grained, locally intensely bioturbated, in places with indistinct parallel lamination, forming very thick beds or bed sets up to 3 m in thickness. Thin (5–10 cm) beds of laminated mudstone are very rare. Locally, very strongly bioturbated intervals occur, 50–70 cm thick, composed of thin beds (10 cm) of very fine-grained sandstone, interbedded with very thin mudstone layers (5 cm).

Interpretation: Very poor sorting of the Ss facies sandstone, in conjunction with locally preserved parallel lamination and intense bioturbation of the fine-grained interbeds indicate that the entire thick interval initially could have been laminated (Sh or Sl), but the structure was obliterated by bioturbation.

Basal part of Wrotnów IG-1 profile

A complex of Ss facies overlies an erosional boundary and is succeeded by sandstone with high-angle, bidirectional (bipolar) cross-lamination (herringbone-type cross-stratification; Fig. 6A).

Interpretation: Sedimentary structures and position in the succession reflect marine transgression and the associated deposition of mega-ripplemarks and/or dunes, controlled by flow and ebb of the tide.

SEQUENCES OF FACIES COMPLEXES AND FACIES ASSOCIATIONS

Sedimentary sequences in the sections discussed below are subdivided into two groups, each distributed along a different transect, approximately perpendicular to what is inferred to be the general NW–SE extension of the basin margin; these are: (i) – sections distributed along the northern transect, i.e., Krzyże-4 – Wrotnów IG-1 – Łochów IG-2 – Wyszków IG-1 – Okuniew IG-1 (Figs 2, 8); (ii) - sections distributed along the southern transect, i.e., Krzyże-4 – Mielnik IG-1 – Siedliska IG-1 (Figs 2, 9); Figure 9 also contains the Okuniew IG-1 section for comparison of facies relations in a direction approximately parallel to the palaeoslope strike.

Northern transect

The thickness of the succession increases gradually towards the west, i.e., distally relative to the margin of the East European Platform. Each section, from Wrotnów in the east to Okuniew in the west, contains a symmetrical megasequence of the facies complexes. Namely, the central part, typified by complexes of Hs, Hm, M, representing sedimentary environments of the lowest energy, and facies Sr at Wrotnów, overlies and is succeeded by strata that represent facies deposited in conditions of much higher energy (Ss, Sh, Sl, Sx). The latter locally contain subordinate interbeds of the Hw facies.

Interpretation: The above relations of thickness and facies development reflect a gradual increase in the marine accommodation space towards the west, i.e., the distal region of the basin, and away from the craton margin. Such increase of the accommodation space must have been related to a gradual increase in subsidence rate westward. The thinnest succession, only one-third of the Okuniew IG-1 sequence, occurs in the Krzyże-4 borehole and does not show vertical megasequences, characteristic for the remaining sections, which indicates stratigraphic condensation.

Southern transect

The general trend of lateral thickness increase towards the west is similar in the southern transect (Fig. 9), but the rate of this increase is about 50% lower than along the northern transect. As well, lateral facies gradients show a different pattern, being great between Krzyże-4 and Mielnik IG-1 and changing completely to fine-grained sandstone facies Sr and sandy heterogeneous strata farther to the west. Such changes indicate the predominance of sandstone beds deposited by traction in the lower flow regime and a contribution of traction alternating with that of suspension. The succession in Mielnik IG-1 is characterised by an extreme facies contrast, as massive sandstone complexes (Ss) are associated with mudstone layers, containing interbeds of siltstone (Mw). These two successions are symmetrical, similar to the sequences of the northern section.

Interpretation: The thickness and facies relations in the southern transect indicate a gradual increase in the accommodation space to the west i.e., away from the Craton margin, but of much lower rate than in the northern area (Fig. 8). However, extreme contrasts between the succeeding facies in the Mielnik IG-1 section indicate great changes in the conditions of deposition, whereas Okuniew IG-1 borehole documents much less variable conditions.

DISCUSSION

Facies, their associations and depositional environments

The coastal zone and the adjacent shallow-marine environment are subdivided, depending on the influence of waves into: (a) the backshore, extending beyond the influence of the storm waves and high tides, and including beach-berm and back-beach dune sediments; (b) the foreshore, periodically submerged and emergent, depending on the intensity of tides and waves, encompassing the intertidal zone and reaching down to the base of the swash zone; (c) the shoreface, extending from the base of the swash zone or low tide level to the base of the mean fair-weather wave base and subdivided further into upper (surf zone), intermediate (breaker zone), and lower shoreface (oscillatory wave zone) on the basis of the bedforms reflecting a gradual decrease in the intensity of reworking by waves and currents; and (d) offshore, down to the storm wave base (Reynolds, 1995; Catuneanu, 2007; Nichols, 2009). Marginal-marine environments, influenced by tides, are characterised by highly variable facies, genetically related to muddy and/or sandy tidal flats, tidal channels, tidal creeks and barrier bars.

On the basis of the sedimentary facies, their associations and vertical sequences observed in the measured sections, the following environments of deposition of the Cambrian strata present in the Podlasie Zone of the basin are interpreted below (following Reineck and Singh, 1980; Reading, 1986; Einsele, 1992; Catuneanu, 2007; Nichols, 2009) and illustrated with examples of the most characteristic occurrences:

1. Backshore – no facies representing this environment were recorded.
2. Foreshore to upper shoreface is characterised by the associations of facies Sx, Sl, Sh, among which swash zone sediments (Sl) are important. Example: Łochów IG-2 – the coarsening-upwards (negative) sequence in the uppermost part of the section, below and above the boundary between the lower and upper Cambrian strata.
3. Upper shoreface is represented by associations of sandstone facies Sx, Sl and Sh, containing subordinate proportions of Sr interbeds. Example: Łochów IG-2 – the sequence above depth marker 2230 m typified by the predominant Sh and Sr facies complexes.
4. Intermediate shoreface is characterised by mainly fine-grained sandstones, locally medium-grained, laminated Sl, Sr, and subordinately Sx as well as sandy heterolithic deposits Hs. Example: Łochów IG-2, facies association in the depth range 2260–2376 m (Hs interbedded with sandstone facies).
5. Lower shoreface is identified by fine-grained sandstones and mudstones, forming the facies associations Sh and Sr with subordinate Sl, and mudstone heterolithic deposits Ml.
6. Offshore environment was generally calm, but occasionally influenced by storm waves and characterised by the deposition of mudstone and heterolithic facies: Mw, Ms, Ml, Mm with Hw, Hm. Sediments very frequently are bioturbated (grades 2 and 3); sporadic strong storm events are indicated by hummocky cross-lamination. Example: Łochów IG-2, central part of the succession.
7. Tidal-flat associations in the sections analysed are lithologically variable, depending on the character of the environment and the sediment type. The deposits of sandy tidal flats are characterised by bipolar palaeocurrent directions (herringbone cross-bedding) and Sx facies sandstone beds with reactivation surfaces, as well as sandstone-mudstone laminae couplets in cross-laminated sets. Example: The lowest part of the section Wrotnów IG-1. On the other hand, sandy-muddy heterolithic deposits with gutter casts may indicate energy oscillations from sandy traction, preceded by intense small-scale erosion events and followed by deposition out of suspension, which may indicate lower shoreface or deposition in a back-barrier area.

Cambrian sedimentation in the Podlasie Basin

In general, the sedimentary features and facies described above as well as their interpretations remain in agreement with the opinions expressed by previous authors (Pacześna and Poprawa, 2005a, b) that the Cambrian strata in the region analysed represent a "shallow-marine, siliciclastic, brackish depositional system". On the other hand, this study reveals some new features and relationships with implications for the perception of the interplay between tectonic and sedimentary processes and lateral variations in sediment dispersal systems.

Pacześna and Poprawa (2005b, p. 569) suggested that the sea-level rise was not eustatic but controlled by local factors "unrelated to the geotectonic mechanisms of basin development". However, considering variations of the sedimentary successions discussed, lateral facies gradients and the interpreted sedimentary environments summarised in Figure 10, this problem merits closer scrutiny.

Section Krzyże-4, located in the eastern extremity of the area discussed, contains a succession 240 m thick, whereas the Okuniew IG-1 profile, located 170 km to the west, is three times thicker (Fig. 8). By comparison with all other sections, the greater part of the Krzyże-4 succession contains proximal sandy facies (Ss, Sh, Sr), heterolithic deposits dominate in the lower part, and the vertical facies trend defines an asymmetrical, negative (C-U) megasequence, with the grain size generally coarsening upwards. This coarsening-upwards megasequence consists of mainly fining-upwards (positive), smaller-scale sequences, and such

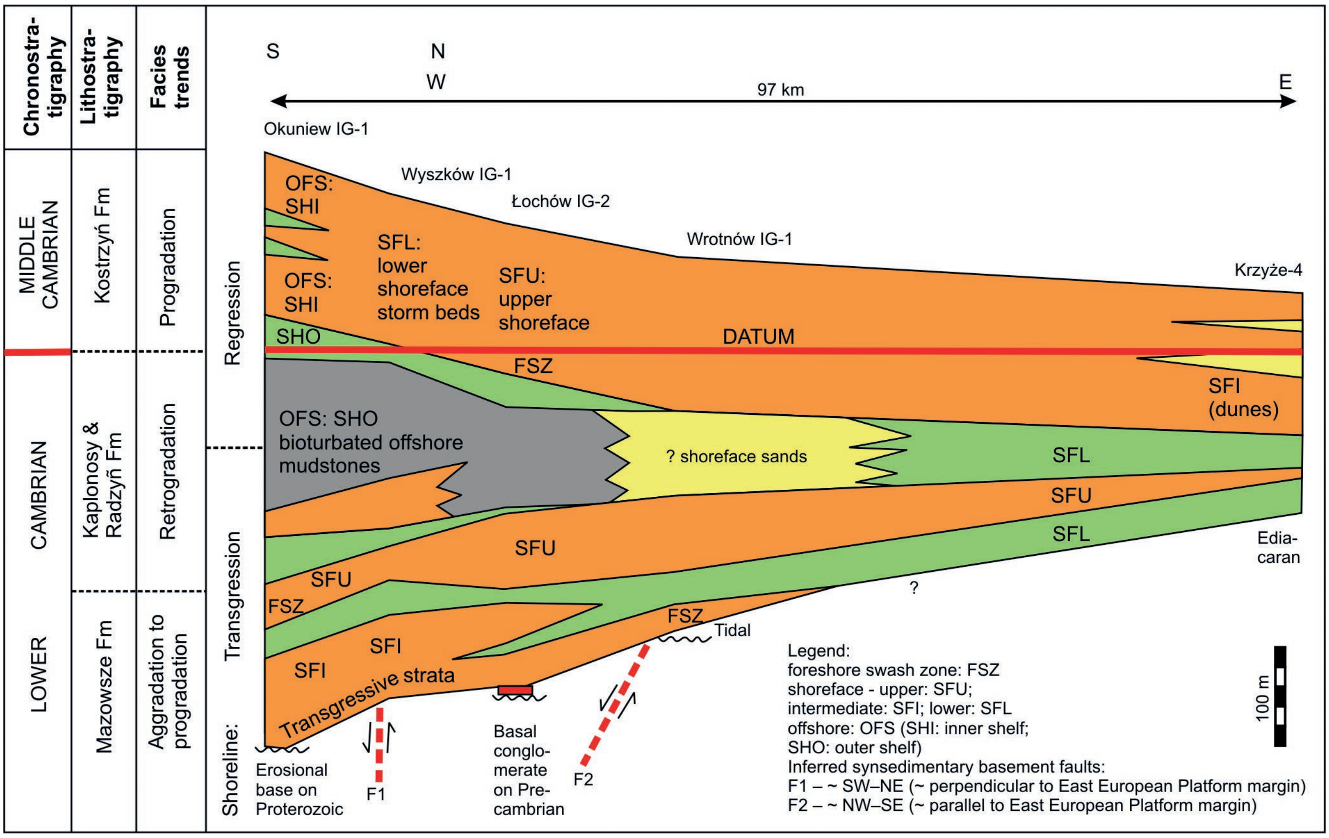

Fig. 10. Generalised pattern of facies associations correlated along N transect (see Figs 2, 8), showing a transgressive trend followed by a regressive succession (both with facies oscillations), clearly developed in the distal sections in the SW (Okuniew IG-1 – Łochów IG-1) and passing laterally into condensed eastern section in the proximal area (Krzyże-4). Interpretation of Wrotnów IG-1 section is tentative because of incomplete preservation of this borehole core.

a trend remains in sharp contrast to other sections, because more than half of their thickness is composed of coarsening-upwards (negative) sequences. By comparison with other sections, this one is a stratigraphically condensed succession of middle shoreface deposits in the lower part and upper shoreface deposits in the upper part.

In the N transect (Figs 8, 10), the thickness of the Cambrian succession gradually increases westward and the facies complexes in each borehole core form symmetrical megasequences: the lower, positive sequence (F-U), which reflects marine transgression, passes upwards into a negative one (C-U), recording the subsequent marine regression. Considering energy levels, the environment during the transgression oscillated between high- and very low-energy levels in the shoreface foreshore, shoreface and offshore zones. The approximate symmetry of the F-U and C-U megasequences in thickness and the rhythmic occurrences of the facies associations in them indicate similar variations in the intensity of terrigenous sediment supply and the capacity of the environments for its redistribution during both transgression and regression. However, the greater variety in vertical facies arrangements in the lower-transgressive part of the succession (Figs 8, 10) than in the upper-regressive part reflects oscillations in the transgressive stage and a more steady regressive trend.

The lower boundary of the Cambrian succession ranges from transitional to the underlying Precambrian strata (Figs 8, 10) in the westernmost (and most distal) section at Okuniew IG-1 to an erosional unconformity paved with a basal conglomerate, the base of which marks a hiatus and marine transgression at Łochów IG-2, farther to the east. Such a lateral change indicates a palaeogeographical position of the shoreline between the present-day locations of Wyszków IG-1 and Łochów IG-2 at the beginning of the Cambrian transgression.

The initial stage of deposition in the sections of the northern transect is characterised by (Fig. 8):

1. at Wrotnów IG-1 – a negative sequence (C-U), erosional boundaries, tidal (bipolar) currents, trough cross-stratification, high-angle cross-stratification;
2. at Łochów IG-2 – a basal conglomerate overlying the erosional boundary on the Precambrian strata, very coarse-grained sandstone facies evolving upwards into medium-grained, lamination generally parallel, but containing numerous erosional surfaces and trough-cross-bedding that appears a little higher in the succession;
3. at Wyszków IG-1 and Okuniew IG-1 – a vertical trend of grain-size in massive sandstones, ranging from medium-grained with granules, decreasing upwards to fine- and very fine-grained, rarely with a medium-grained admixture.

Therefore, the lowest parts of these sections are typified by the most proximal subfacies, related to the early stages of the Cambrian transgression. On the other hand, laterally transitional facies gradients are lacking (e.g., the basal conglomerate is present in only one section), which, in association with variations in thickness, indicates that synsedimentary faulting related to the extensional tectonics that affected the rifted margin of the East European Craton may have been responsible for this relationship. Consequently, it is proposed that, parallel to the Platform margin, a normal extensional fault (or fault zone), oriented NWN–SES, exists in the basement rocks and was active during deposition between Krzyże-4 and Łochów IG-2 (Fig. 10). In this context, the Krzyże-4 section is located in the most tectonically stable part of the depositional area. In the same vein, a change in thickness of the facies associations and of the entire succession between Okuniew IG-1 and Wyszków IG-1 indicates another syndepositional fault zone, probably oriented W–E.

The southern transect displays a slightly different lateral variation of facies and their succession (Fig. 9). It is quite natural that the Mielnik IG-1 section consists of facies distal by comparison with the one at Krzyże-4. However, internally it shows much greater contrasts in facies pattern than the sections of the northern transect. A thin transgressive interval, represented by a positive (F-U) succession, beginning with coarse-grained sandstone at the base, is overlain by alternating complexes of facies deposited in high-energy (Ss) and low-energy (Mw) environments. This indicates multiple, rapid shifts between the shoreface and the very quiet offshore. The suite observed in the borehole core from Siedliska IG-1 consists entirely of deposits that represent low-energy environments, i.e., very fine-grained current-ripple cross-laminated sandstones (Sr) and sandy heterolithic deposits with wavy lamination (Hs) and common symmetrical, wave ripplemarks. They are interpreted as indicators of the lower shoreface zone. The influence of a transgressive maximum in the middle of the succession, followed by a regression, was noted in both of the sections Mielnik IG-1 and Siedliska IG-1, similarly to the sections of the northern transect.

Sections Siedliska IG-1 and Okuniew IG-1 (Fig. 9) provide a comparison between both transects, approximately along strike of the palaeoslope. Relations between the accommodation space in the NW and SE sectors of the basin indicate an approximately 50% higher subsidence rate and more efficient supply in terrigenous detritus in the north than in the south. These relations are interpreted here as being a consequence of syndepositional activity of a hinge fault (or a fault zone), extending approximately from NE to SW between the two transects, with the displacement increasing towards the SW and the NW block downthrown more than the SE one (Fig. 9). This observation is at variance with the suggestion advanced by Pacześna and Poprawa (2005b) that the sea-level rise at the time of deposition of the strata discussed was controlled by local factors, "unrelated to the geotectonic mechanisms of basin development", because the differences in facies development between the two transects shown above imply the influence of syndepositionally active tectonic discontinuities on sedimentation (Figs 2, 9, 10).

CONCLUSIONS

In general, the results of this work remain in agreement with previous publications, in some cases supporting them, in some others broadening them, but also shedding new light on several important details. This is especially relevant to the problems of sedimentary features, sequences, and the influence of rift tectonics on sedimentation.

The main points presented and discussed above may be summarised as follows:

1. The variability of depositional processes and conditions is reflected in 14 sedimentary facies and their associations that represent conditions of a generally shallow-marine deposition in the following zones: the swash zone, the upper, intermediate and lower shoreface, and the offshore.
2. The conditions in the easternmost part of the basin were different from the rest of the area, being determined by the position upon a tectonically stable part of the East European Craton. The subsidence rate there was at its lowest, which resulted in a condensed succession at the Krzyże-4 well. Its internal organisation is different from all the remaining sections that represent a more or less open marine basin farther to the west, where block tectonics contributed to eustatic changes in sea level.
3. The influence of tidal currents, clearly recorded in the basal part of the succession (especially in the Widowo IG-1 and Wrotnów IG-1 wells), becomes much less obvious up the sequence.
4. Sediments of the open part of the marine basin extending generally to SW and W are characterised by (a) depositional facies controlled by depth and local interplay between erosion and sedimentation, (b) medium-scale sequences determined by short-term variation in sea level that could have been influenced by local block subsidence and its interplay with varying rates of sediment supply and deposition, and (c) facies megasequences controlled by long-term sea-level changes, resulting in the lower Cambrian marine transgression, followed by a regressive trend of the middle Cambrian.
5. At the beginning of the transgression, the marine palaeoshoreline probably was located near the Łochów IG-1 well, because there the lower Cambrian strata begin with a basal conglomerate overlying an erosional surface and a hiatus, whereas a stratigraphic transition between the underlying Precambrian and the succeeding Cambrian strata occurs further to the west, in the Okuniew IG-1 well.
6. Lateral variations in facies complexes indicate that a synsedimentary normal (extensional) longitudinal fault (or faults) striking NW–SE, i.e., parallel to the SW-dipping palaeoslope of the East European Platform margin, controlled the opening of the accommodation space and evolution of the basin. Lateral changes in thickness of the depositional complexes indicate that longitudinal faults, or fault zones (F1 and F2 in Fig. 10) continued to influence local subsidence throughout the deposition of the entire Cambrian succession, mainly in the western part of the depositional area. However, a slightly more uniform facies distribution and thickness

of the Kostrzyń Formation, may indicate an increase in influence of regional subsidence at a late stage of deposition.

7. A NE–SW-oriented hinge fault, or a fault zone, oriented more or less perpendicular to the East European Platform margin, is interpreted as a zone separating two depositional domains (Figs 2, 10). The domain extending NW of the fault experienced ca. a 50% higher rate of accommodation space increase (synsedimentary subsidence) and more intense sediment supply than the SE domain. Another similarly oriented, but less prominent fault zone is envisaged between the Wyszków IG-1 and Okuniew IG-1 wells.
8. Locally occurring sandstone bodies and channel-fill facies may be considered as prospective targets in hydrocarbon exploration.

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