

ORDOVICIAN–SILURIAN LITHOSTRATIGRAPHY OF THE EAST EUROPEAN CRATON IN POLAND

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Porębski, S. J. & Podhalańska, T., 2019. Ordovician–Silurian lithostratigraphy of the East European Craton in Poland. *Annales Societatis Geologorum Poloniae*, 89: 95–104.

Abstract: This paper deals with the lithostratigraphic correlation of the Ordovician–Silurian succession between the Baltic, Podlasie and Lublin basins, located on the SW slope of the East European Craton. The correlation is based on previous lithostratigraphic classifications, which are modified here to include the results of recent biostratigraphic and sedimentological work performed on several new wells. The authors propose to extend the Sasino Formation for the entire upper Darriwilian–lower Katian mudstone sheet that is traceable in all basins. It is recommended that the Jantar Bituminous Claystone Member (late Hirnantian–Aeronian) of the Pasłek Formation be elevated to the rank of formation and the name Pasłek Mudstone Formation be retained for the late Aeronian–Telychian, rhythmic alternations of black, laminated mudstones and greenish, bioturbated mudstones. Moreover, the authors suggest that the top of the Kociewie Formation (Sheinwoodian–Ludfordian) be placed at the upper boundary of the Reda Member (latest Ludfordian), which shows much wider lateral persistence than previously was thought.

Key words: Lithostratigraphy, Ordovician, Silurian, East European Craton.

Manuscript received 18 January 2019, accepted 16 April 2019

INTRODUCTION

The crystalline basement of the East European Craton (EEC) in Poland is overlapped in the subsurface by a Neoproterozoic–Lower Palaeozoic volcanic-sedimentary succession, which reveals three depocentres referred to as the Baltic, Podlasie and Lublin basins (Fig. 1; Poprawa, 2010). The succession is disconformably overlain in the north and south by Permian or Lower Devonian deposits, respectively, although a continuous Silurian-to-Devonian transition may be present in the northernmost Baltic Basin (Modliński *et al.*, 1994). The Lower Palaeozoic strata are largely undeformed except for in the western Baltic Basin, where they were involved in the thin-skinned fold-and-thrust belt of the Pomeranian Caledonides (Mazur *et al.*, 2016). Farther to the south, the western limit of these strata has been placed conventionally at the Teisseyre-Tornquist Zone, although they are likely to plunge beneath a 10-km-thick pile of younger sediments in central Poland (e.g., Dadlez *et al.*, 1995).

The Ordovician–Silurian succession of the EEC is interpreted as recording the transition from a passive margin into a Caledonian Foredeep, induced by the collision of East Avalonia with Baltica (Poprawa *et al.*, 1999). The succes-

sion originated on a W-sloping carbonate shelf ramp, merging down-dip into a broad mudrock belt (Modliński, 2010), which consists mainly of dark, graptolitic mudstones, interbedded with numerous bentonites, bioclastic limestones and early diagenetic carbonate concretions. In the Silurian strata, such rocks are accompanied by siltstones, calcisiltites, as well as rare lithic and feldspathic wackes (Jaworowski, 2000; Szczepański *et al.*, 2015). Because of their elevated total organic carbon (TOC) content (locally up to 10%), substantial thickness along a 700-km-long subcrop parallel to the strike and commonly deep burial levels, the Ordovician–Silurian mudstones recently have become the subject of intense multidisciplinary research, aimed at evaluating their potential for hydrocarbon generation and retention (e.g., Poprawa, 2010; Więclaw *et al.*, 2010; Podhalańska *et al.*, 2016; Golonka and Bębenek, 2017).

As a part of this effort, the authors present here a lithostratigraphic correlation chart of the Ordovician and Silurian succession between the Baltic, Podlasie and Lublin basins (Fig. 2). The correlation is based on the previous lithostratigraphic classifications, erected for the Ordovician by Mod-

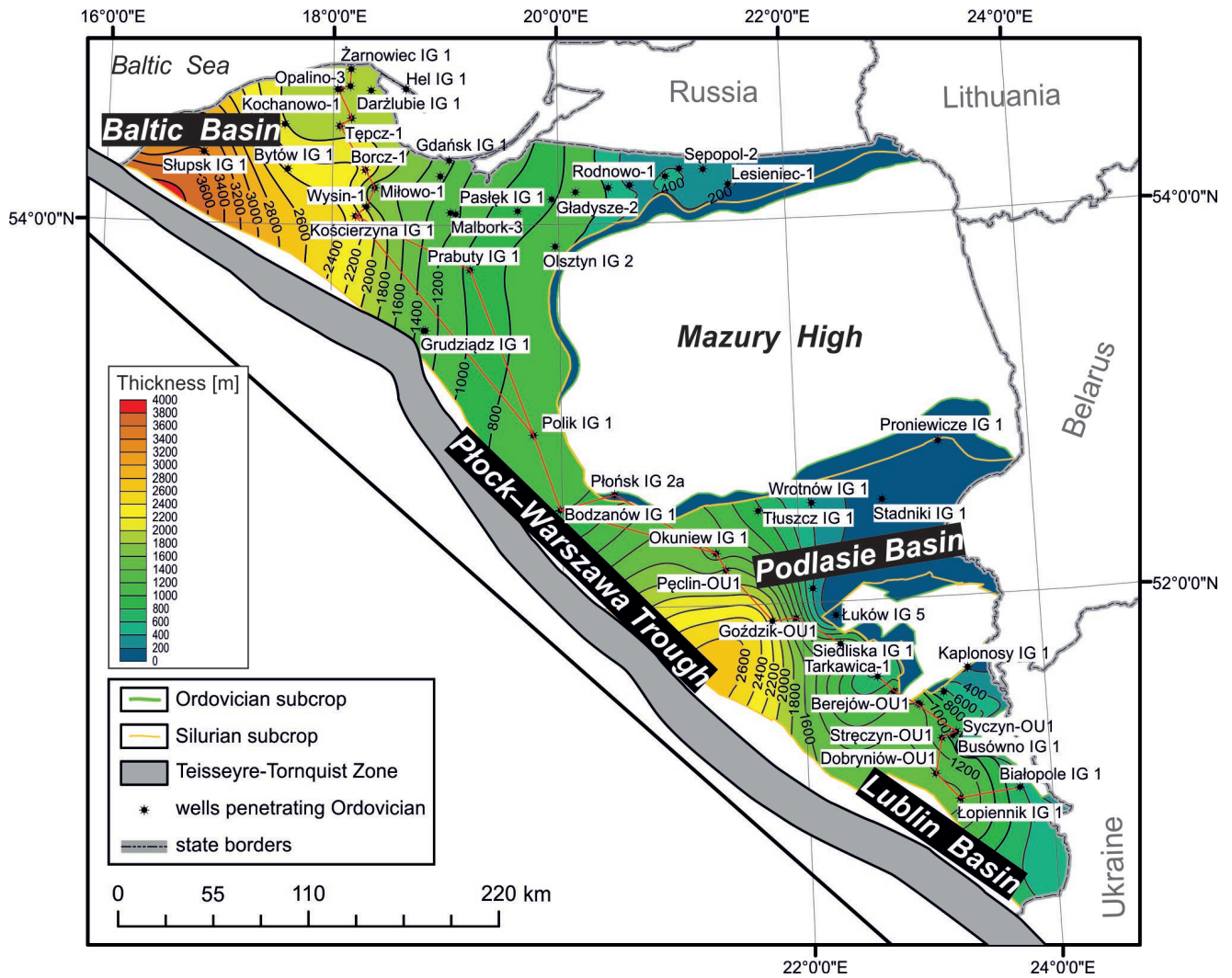
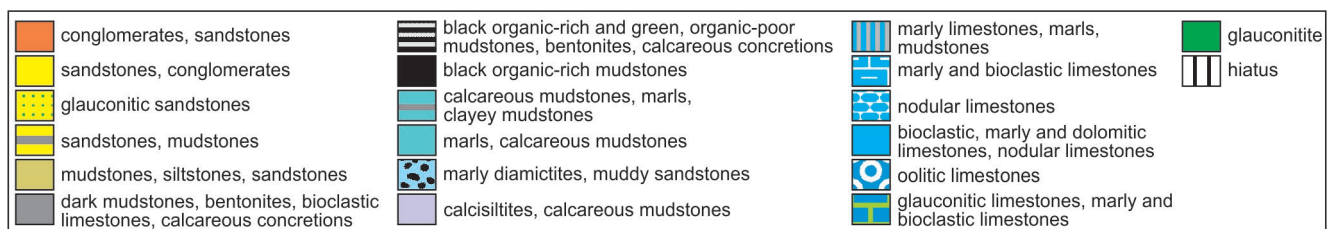


Fig. 1. Map showing the locations of wells that penetrated the entire thickness of the Ordovician–Silurian strata in the East European Craton. The red line marks the lines of section of each of the cross-sections shown in Figures 3 and 4.

Fig. 2. Lithostratigraphic subdivision of the Ordovician and Silurian successions in the East European Craton (modified from Porębski and Podhalańska, 2017; data sources are listed in the text). Ordovician–Silurian chronostratigraphy, graptolite zonation and correlation of the Ordovician and Silurian standard stages to the Baltic regional stages are after Cooper *et al.* (2012) and Melchin *et al.* (2012). The standard graptolite zonation is modified to include the local zones of Urbanek and Teller (1997) and Porębska *et al.* (2004). Hirnant. – Hirnantian; Lst – Limestone; Mdst – Mudstone; Mrst – marlstone; Mbr – Member.

Explanations:



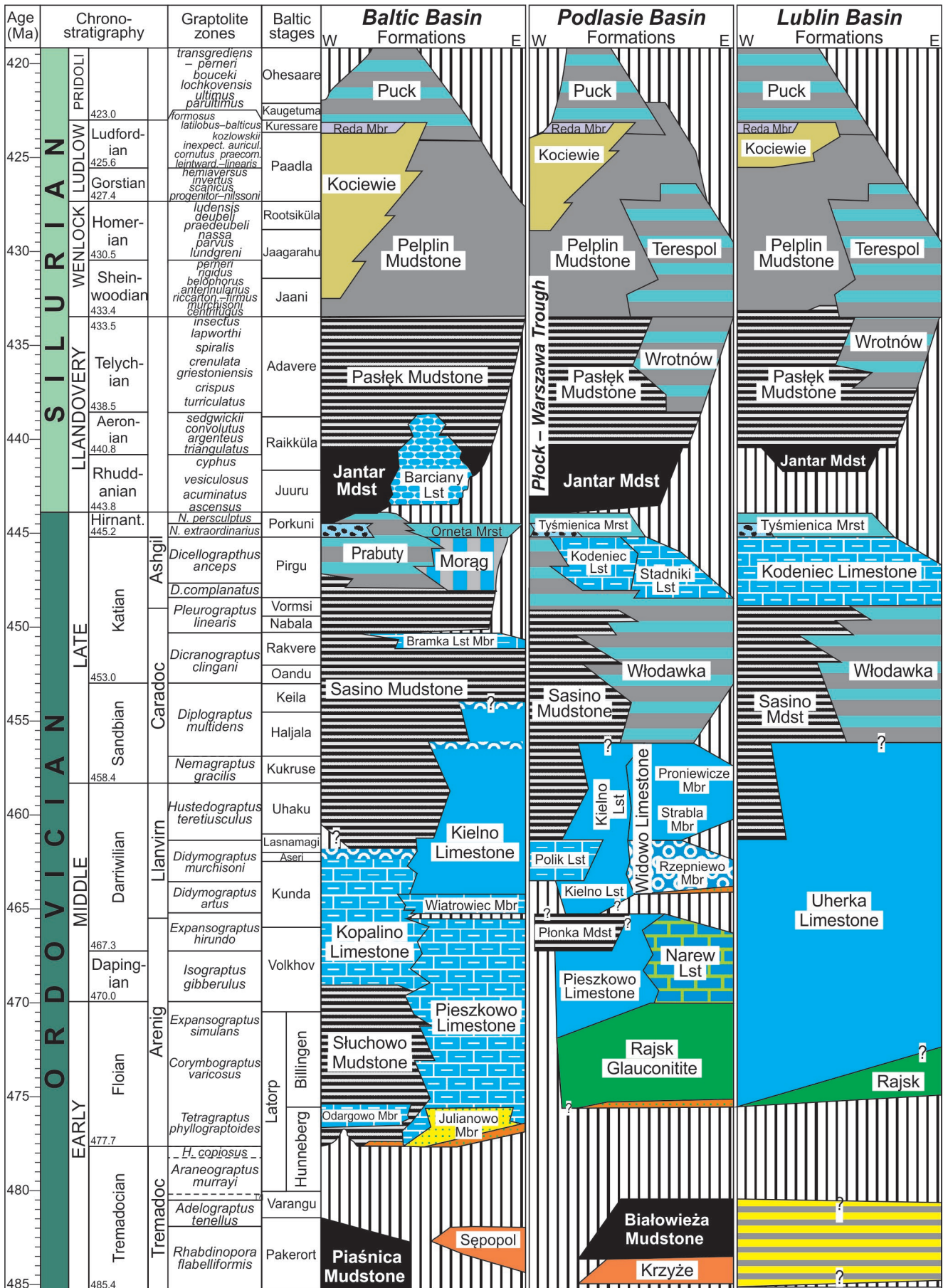


Fig. 2.

liński (1984), Modliński and Szymański (1997, 2008), Szymański and Modliński (2003) and Drygant *et al.* (2006), and for the Silurian by Modliński *et al.* (2006) and Podhalańska *et al.* (2010). The modifications to these classifications proposed here stem from recent biostratigraphic and sedimentological results acquired from several new and extensively cored wells and in particular those drilled in the Płock–Warszawa Trough (western Podlasie Basin) and in the Lublin Basin (Dziadzio *et al.*, 2017; Kędzior *et al.*, 2017; Podhalańska, 2017; Skompski and Paszkowski, 2017). In this contribution, the present authors have replaced the lithological designations “claystone” and “shale” in the lithostratigraphic names with the term “mudstone” because the latter better fits the observed range of fine-grained lithologies (see also the recommendations by Lazar *et al.*, 2015).

This contribution is a slightly modified version of the paper by Porębski and Podhalańska (2017) that was published in Polish.

ORDOVICIAN

The Ordovician succession is lithologically and stratigraphically bipartite. Its lower part comprises siliciclastic deposits of early Tremadocian age. In the Baltic and Podlasie basins, these deposits consist of black, organic-carbon-rich mudstones of the Piaśnica and Białowieża formations that are underlain to the east by conglomerates and sandstones of the Krzyże Formation (Modliński and Szymański, 1997). In the Lublin Basin, a possible time equivalent to these formations is represented by an unnamed, locally cored (in the Syczyn-OU1, Białopole IG 1 and Terebin IG 5 wells), thin-bedded alternations of hummocky-cross-stratified quartz arenites, dark mudstones and rare bentonites. This alternation documents deposition on a storm-dominated, lower shoreface (Kędzior *et al.*, 2017).

The late Tremadocian records a hiatus associated with an erosional unconformity, which seems to extend across the entire EEC in Poland and marks a change from the deposits of a siliciclastic shelf below to those of a mixed siliciclastic-carbonate ramp above. The shelf-ramp succession is of a Floian–Hirnantian age and displays an N-S-trending facies zonation (Modliński, 2010), with shallow-water carbonates accompanied locally by quartz arenites in the eastern, land-attached belt and black graptolitic mudstones in the western, offshore, deep shelf. This succession is relatively thin (ca. 30–100 m) and contains numerous indicators of reduced sedimentation, condensation and erosion, with associated stratigraphic gaps that are difficult to date, particularly in the carbonate rocks (Modliński and Szymański, 2008; Skompski and Paszkowski, 2017). The mudstones occur in three major tongues, which wedge out updip in the carbonates and appear to mark transgressions between periods of highstand and forced-regressive progradation of the carbonate ramp (Figs 2, 3).

Śluchowo Mudstone Formation (Floian)

The oldest mudstone tongue in the Floian–Hirnantian succession was distinguished as the Śluchowo Formation (Modliński and Szymański, 1997). It occurs only in the

western part of the Baltic Basin and is ca. 10 m thick (in the Lubocino-1 and Opalino-2 wells). The basal part of the Śluchowo Formation contains thin pods of glauconite-rich sandstones, conglomerates and breccias that are frequently cemented with palisade calcite (Skompski and Paszkowski, 2017). The bulk of this formation consists of dark grey and greyish green mudstones, which locally contain intercalations of ostracod coquinites and skeletal packstones, rich in echinoid, trilobite, brachiopod and mollusc bioclasts (Skompski and Paszkowski, 2017). South of the Kościerzyna IG 1 well, the Śluchowo Formation appears to either wedge out entirely, or pass into the Rajsk Glauconite Formation.

Plonka Mudstone Formation (Dapingian–early Darriwilian?)

The middle mudstone tongue was penetrated in few wells in the western Podlasie Basin (southern part of the Płock–Warszawa Trough) and distinguished as the Plonka Formation (Modliński and Szymański, 2008). In the Płońsk IG 2a well, this formation consists of dark grey, locally dolomitic mudstones, <5 m thick, which rest on Cambrian dolomitic limestones (Modliński and Szymański, 2008). In the Peclin-OU1 well, it appears to be represented by an as yet undated, 4-m-thick packet of dark grey and greenish grey, non-calcareous mudstones, locally containing marly nodules, that gradationally extends between the nodular limestones and marlstones of the Pieszkowo Formation below and the marly limestones of the Kielno Formation above (Kędzior *et al.*, 2017). Farther to the south, the Plonka Formation seems to pinch out at the top of the Rajsk Formation.

Sasino Mudstone Formation (late Darriwilian–early Katian)

The upper mudstone tongue comprises the Sasino Formation (Modliński and Szymański, 1997) and its lateral equivalent in the Lublin Basin, distinguished as the Udal Claystone Formation (Modliński, 1984). Both formations show a similar lithology that is dominated by black, dark grey and greenish grey, clayey to silty mudstones, intercalated with numerous, thin bentonites and locally bioclastic limestones and marlstones. The authors therefore merged these formations into a single lithostratigraphic unit under the name of the Sasino Mudstone Formation. This redefined Sasino Formation occurs as a persistent sheet across all basins, with its maximum thickness of ca. 60 m in the Płock–Warszawa Trough and the southernmost Lublin Basin. The base of the formation is sharp, often showing signs of transgressive erosion on the carbonates of the Kopalino, Polik, Kielno and Uherka formations and shows evidence of stratigraphic younging landwards within the *Didymograptus murchisoni* and *Diplograptus multidentis* zones. The top tends to be gradational into the calcareous mudstones and marlstones of the Prabuty Formation and its eastern equivalents. In the Podlasie and Lublin basins, the Sasino Formation grades laterally updip into the marlstones of the Włodawka Formation (Modliński and Szymański, 2008).

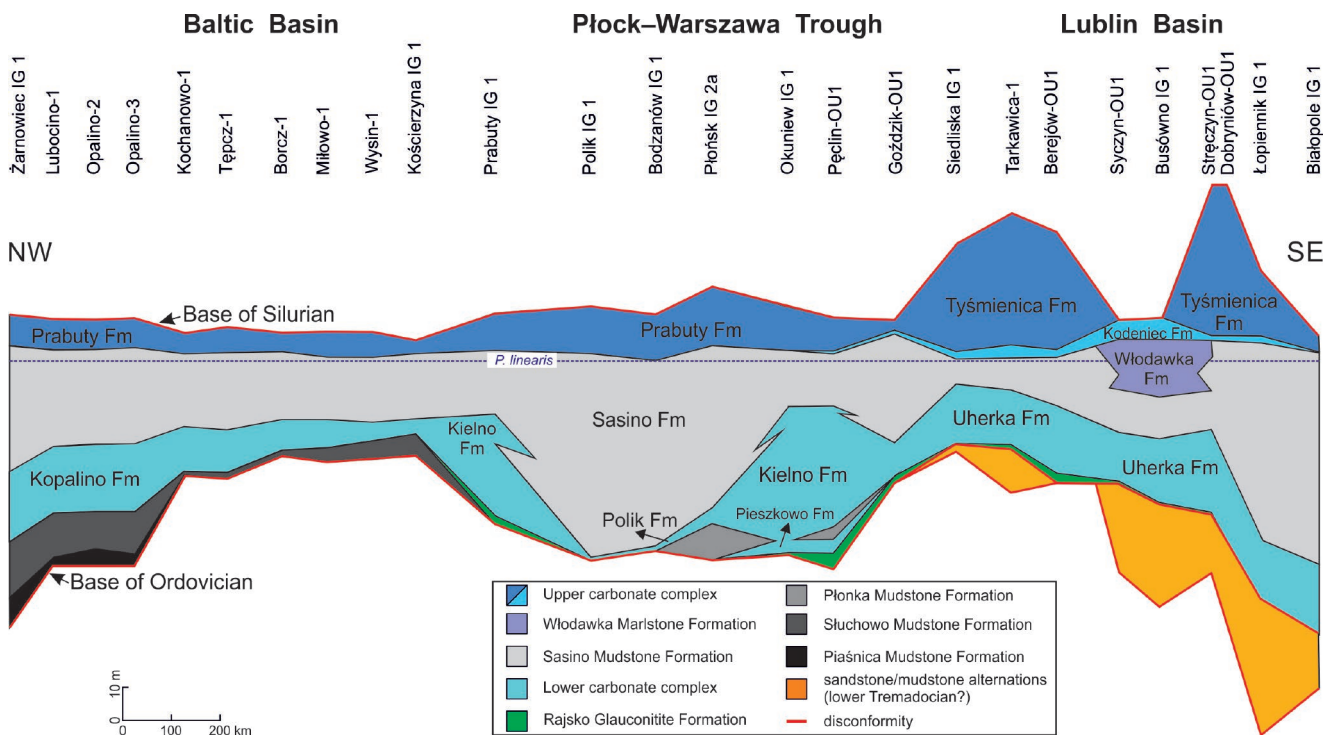


Fig. 3. Strike-oblique cross-section showing the distribution of Ordovician lithostratigraphic units. The section is flattened at the gamma-ray maximum within the *Pleurograptus linearis* Biozone.

Carbonate complexes

The Ordovician carbonate rocks were subdivided into a number of formations (Fig. 2). However, many of these units display a local or problematic areal distribution, which causes problems in the regional correlation and mapping of them. Hence, these rocks have been grouped here into two informal complexes that are separated by the siliciclastic mudrocks of the Sasino Formation and its lateral marly equivalent, represented by the Włodawka Formation in a cratonward direction (Figs 2, 3). Each complex shows a relatively high lithological integrity and is basinwide in extent.

Lower carbonate complex

The lower carbonate complex (Floian–earliest Sandbian) is up to 40 m thick in the southeast and thins to 4–18 m in the northwest. It begins in the east with a thin (0.5–5 m), locally discontinuous unit, composed of glauconitites, glauconite- and locally chalcedony-cemented conglomerates/brecias, sandstones and limestones. This transgressive unit was defined as the Rajska Glauconitite Formation (Floian) in the Podlasie Basin (Modliński and Szymański, 2008) and identified also in several new wells drilled in the Lublin Basin and southern part of the Płock–Warszawa Trough (the Berejów-OU1, Syczyn-OU1, Dobryniów-OU1, Pęcłin-OU1 and Goździk-OU1 wells). The Rajska Formation passes upwards into marlstones, marly and dolomitic limestones, dolomites and bioclastic, locally glauconitic, oolitic and nodular limestones, which were distinguished as the Uherka Limestone Formation in the Lublin Basin (Modliński, 1984) and the Narew, Widowo, Pieszkowo, Kielno and Polik limestone formations in the Baltic and Podlasie basins. The landward

(eastern) parts of the lower carbonate complex can be locally glauconitic (Narew Formation), or rich in oolitic facies (Widowo Limestone and Kielno Limestone formations), whereas nodular wackestones interbedded with marlstones and thin mudstones increase in abundance downdip. The latter lithologies predominate in the Kopalino Limestone Formation (Dapingian–early Darriwilian), which represents the most basinward segment of this complex penetrated in the western Baltic Basin. This formation is 2–20 m thick and occurs between the Słuchowo and Sasino mudstones (Modliński and Szymański, 1997), containing numerous omission surfaces and hardgrounds (Skompski and Paszkowski, 2017). The top of the Kopalino Formation occurs at the *Didymograptus purchisoni* Zone and records a surface that reflects a change from regression below to transgression above.

Upper carbonate complex

The upper carbonate complex (late Katian–Hirnantian) is up to 37 m thick in the southeast and decreases to ca. 3 m in thickness in the northwest. In the Lublin and Podlasie basins, the late Katian part of this complex is dominated by bioclastic, nodular and marly limestones and has been distinguished as the Kodeniec Limestone and Stadniki Limestone formations, respectively (Modliński, 1984; Modliński and Szymański, 2008). Their age equivalents in the eastern Baltic Basin comprise variegated, marly limestones and marlstones, interbedded rarely with calcareous and clayey mudstones distinguished as the Morąg Formation, which grades downdip into the even more marly and argillaceous Prabuty Formation. The Ordovician succession ends with Hirnantian marlstones and calcareous mudstones, forming a persistent

sheet across all the basins. This sheet consists of the Ornetá Marlstone Formation in the Baltic Basin and Tyśmienica Marlstone Formation farther southwards (Modliński, 1984; Modliński and Szymański, 1997) and throughout much of its extent is followed upwards by Llandovery black mudstones. It is noteworthy, however, that in the western Baltic Basin, the deposition of the black mudstones began already in late Hirnantian times (Modliński and Szymański, 1997).

The Prabuty and Tyśmienica formations contain discontinuous intercalations, 0.05–6.5 m thick, of poorly sorted, gravelly, muddy quartz wackes to granule-bearing and sandy mudstones, which are rich in *Hirnantia* brachiopod fauna, diamictic textures and a variety of soft-sediment deformations. These intercalations occur in the trilobite *Mucronaspis mucronata* Zone, corresponding to the early Hirnantian *Normalograptus extraordinarius* graptolite Zone (Podhalańska, 2009), and are interpreted as being laid down from floating and grounding ice (Modliński, 1982; Porębski *et al.*, 2019).

SILURIAN

A north-south-trending facies belt persisted through Silurian times in the EEC (Modliński, 2010). However, the post-Hirnantian deglacial transgression, superimposed upon increasing flexural subsidence, led to the cratonward expansion of the mudrock and carbonate belts and resulted in a dramatic thickness increase of the Silurian infill, attaining >4000 m in the western Baltic Basin. Modliński *et al.* (2006) introduced the Pasłęk Claystone Formation to encompass a Llandovery mudstone succession, 15–70 m thick, in the Baltic Basin. The formation begins with black, bituminous claystones that pass upwards into dark grey claystones, laminated with greenish, grey green and black claystones and interbedded locally with calcareous claystones, thin marls, marly limestones and bentonite laminae (Modliński *et al.*, 2006, p. 788). The Jantar Bituminous Claystone Member forms the basal layer of this formation and consists of black, pyrite-rich, bituminous, argillaceous claystones, intercalated with dark grey, calcareous claystones and infrequent, thin interbeds and nodules of dark grey, marly limestones (Modliński *et al.*, 2006). In a subsequent report, Podhalańska *et al.* (2010) extended the Pasłęk Formation into the Podlasie and Lublin basins. Dziadzio *et al.* (2017) showed that the organic-rich mudstones of the Jantar Member are spread, albeit discontinuously, as far south as the Stręczyn-OU1 well in the latter basin.

For practical reasons, the present authors have elevated the Jantar Member to the rank of formation. In this context, it is worth emphasizing that in a number of reports produced for the hydrocarbon industry, rock properties, for instance, – total organic carbon (TOC), are listed separately for the Jantar Member and the Pasłęk Formation. However, it is often unclear whether the values obtained for former unit were counted also for the latter (as one might expect), or omitted, which would have falsified the statistics for the property in the Pasłęk Formation. The proposed solution removes such uncertainties and, more importantly, it results in the separation of two lithostratigraphic units, which are lithologically different and mappable on an interbasinal scale (Dziadzio *et al.*, 2017). Moreover, the Jantar Formation is character-

ized by high TOC values and hence is easily identifiable on well logs.

Jantar Mudstone Formation (late Hirnantian–Aeronian)

The bulk of the formation consists of black, organic-rich, clayey mudstones, which are laminated and non-bioturbated. In the western Baltic Basin, they locally begin already in the late Hirnantian *persculptus* Zone and rest conformably on the grey marlstones and calcareous mudstones of the Prabuty Formation. However farther to the east, the Jantar Formation tends to overlap erosively various formations of the uppermost Ordovician (Fig. 2), with the associated hiatus spanning the early Rhuddanian *ascensus* Zone (Podhalańska, 2003; Modliński *et al.*, 2006). In the Płock–Warszawa Trough (in the Peclin-OU1 and Goździk-OU1 wells), the Jantar Formation is of Rhuddanian–Aeronian age and overlies marly sediments of the Tyśmienica Formation. In the Lublin Basin, the basal contact of the Jantar Formation tends to be sharp to erosional and attributed to a transgressive ravinement (Porębski *et al.*, 2013), which is accompanied by a hiatus spanning the *ascensus–vesiculosus* zones. In all basins, the top of the formation appears as a gradational transition into the overlying Pasłęk Formation and has been placed at the base of the first intercalation of a greenish grey, bioturbated mudstone. In the cores that have been dated biostratigraphically so far, this boundary falls invariably within the *triangulatus* Zone of the early Aeronian (Fig. 2). In Pomerania, the Jantar Formation occurs as the fill of a linear, NNW–SSE-trending depocentre, 12–18 m thick, whereas in the Lublin Basin it occurs in a series of discontinuous pods, 1–6 m thick (Fig. 4; Dziadzio *et al.*, 2017). In the eastern Baltic Basin, the formation intertongues locally with dark, nodular and marly limestones of the Barciany Formation (Modliński *et al.*, 2006).

Pasłęk Mudstone Formation (late Aeronian–Telychian)

The characteristic feature of the Pasłęk Formation is a zebra-like colour banding, due to the alternation of millimetre- to decametre-thick layers of black to dark grey, laminated, clayey mudstone and greenish grey, clayey mudstone showing a variable, though generally high degree of bioturbation (Uchman, 2017). Both mudstone facies tend to be non-calcareous and contain rare lenses and laminae composed of quartz-feldspar silt, calcisiltite and finely comminuted shell detritus. The top of the formation is gradational and taken to occur at the top of youngest layer of a bioturbated mudstone. Graptolite dating constrains the age of this boundary as falling within the *centrifugus* to *murchisoni* zones of the earliest Sheinwoodian (Modliński *et al.*, 2006; Podhalańska *et al.*, 2010). The Pasłęk Formation occurs as a basinwide sheet, up to 60 m thick in the Baltic Basin, thinning to 2 m and overlapping the Ordovician substratum in the Lublin Basin (Fig. 4). At the easternmost reaches, the Pasłęk Formation grades into marlstones and limy mudstones of the Wrotnów Formation in the Baltic and Lublin basins (Podhalańska *et al.*, 2010).

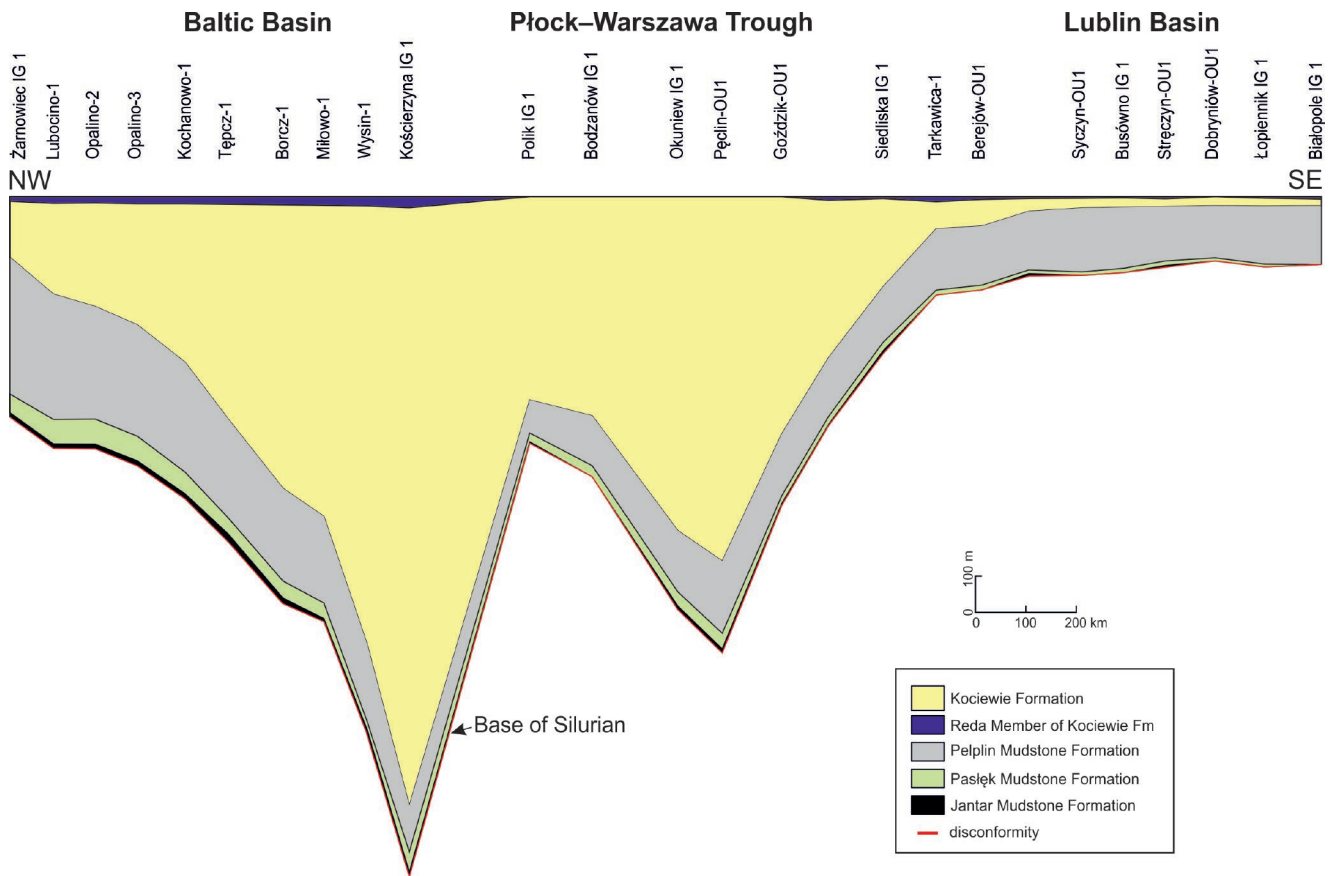


Fig. 4. Strike-oblique and strike-parallel cross-section showing the distribution of Silurian lithostratigraphic units; the Puck Formation is not shown. The section is flattened at the top of the Kociewie Formation (= top of the Reda Member).

Pelplin Mudstone Formation (Sheinwoodian–Ludfordian)

The Pasłek Formation is followed by the Pelplin Formation, which was defined in the Baltic Basin (Modliński *et al.*, 2006) and subsequently traced into the Podlasie and Lublin basins (Podhalańska *et al.*, 2010). The dominant lithology of the Pelplin Formation comprises dark grey, massive to locally laminated, argillaceous mudstones, interbedded with calcareous-clayey and dolomitic-clayey mudstones, numerous early diagenetic carbonate concretions and centimetre-thick bentonites. Siliciclastic and calcisiltic lenses and laminae, thin lags of shelly detritus and bioclastic limestone beds form common intercalations that increase in abundance upwards in the formation through two to three shoaling-up cyclothems of wide lateral persistence (Dziadzio *et al.*, 2017). The Pelplin Formation is ca. 150–400 m thick and thins generally southeastwards. It grades upwards and laterally to the north into the silt-rich Kociewie Formation and passes laterally in the eastern Lublin and Podlasie basins into the marly and calcareous Terespol Formation (Podhalańska *et al.*, 2010).

Kociewie Formation (middle Sheinwoodian–Ludfordian)

The Kociewie Formation, originally defined in the Baltic Basin (Modliński *et al.*, 2006) and traced into the Podlasie

and Lublin basins (Podhalańska *et al.*, 2010), is typified by the abundance of both siliciclastic and calcareous siltstone laminasets and bedsets within grey, clayey and silty mudstones, weakly cemented with calcite or dolomite. Intercalations of bioclastic limestones, early diagenetic carbonate concretions and bentonites are common, whereas those of fine- to medium-grained sandstones, represented by lithic and arkosic wackes (Szczepański *et al.*, 2015), are relatively rare. The base of the formation is strongly gradational into the Pelplin mudstones and in the absence of cores difficult to recognize. Where cores are available, the boundary should be placed at the base of the first thicker (say 0.5 m thick) siltstone laminaset in the grey mudstones.

The base of the Kociewie Formation is clearly diachronous and younging both cratonwards (Modliński *et al.*, 2006) and southwards along the strike (Mazur *et al.*, 2018). Silt-dominated sedimentation began during the early Sheinwoodian in the western Baltic Basin (Jaworowski, 2000; Modliński *et al.*, 2006), arrived during the *nassa-leintwardinensis* biochrones of the late Homerian–early Ludfordian in the Płock–Warszawa Trough, and reached the southern Lublin Basin (in the Berejów-OU1 and Dobryńów-OU1 wells) in the *praecornutus–cornutus* biochrones of the Ludfordian (Mazur *et al.*, 2018).

In the Baltic Basin, the uppermost part of the Kociewie Formation was distinguished as the Reda Member, up to 34 m thick, which consists of calcareous mudstones and marly limestones, spanning the *kozłowskii–latilobus–balticus*

zones of the latest Ludfordian (Modliński *et al.*, 2006). The Reda Member is correlated with a low-amplitude, “blocky” signature on gamma-ray logs and is traceable as far south as the Kościerzyna IG 1 well (Dziadzio *et al.*, 2017). A similar anomaly is also recognizable across much of the Lublin Basin, where it corresponds to a 4.5–5-m-thick unit, composed of laminated calcareous mudstones and calcisiltites and dated as the latest Ludfordian (Podhalańska, 2017). In the Berejów-OU1 and Syczyn-OU1 wells, this unit was affected by rotational sliding and slumping (Porębski *et al.*, 2013). Although the silt facies is continuous into the Pridoli, the top of the Kociewie Formation is accepted as being at the top of the Reda Member, because this boundary is easily recognizable in well logs and seismic sections across much of the EEC segment analysed here. The thickness of the formation reaches >3000 m in the Baltic Basin (Modliński *et al.*, 2006) and decreases to ca. 50 m in the southern Lublin Basin. The thickness maximum in the southernmost Baltic Basin (Fig. 4) may reflect a transverse (roughly E–W-striking) zone of Late Silurian growth faulting.

Puck Formation (Pridoli)

The Silurian succession ends with the Puck Formation (Modliński *et al.*, 2006; Podhalańska *et al.*, 2010), which consists mainly of grey and variegated, clayey to silty, argillaceous and calcareous mudstones, intercalated with carbonate concretions and bentonites. However, owing to discontinuous core record, the Puck Formation is poorly defined and its base is difficult to recognize in the areas, where the Reda Member is missing. Its top is a disconformity below the Devonian or Permian strata, although a continuous Silurian-to-Devonian transition may exist in the northernmost Baltic Basin (Modliński *et al.*, 1994).

CONCLUSIONS

The proposed modifications to the existing lithostratigraphic classifications of the Ordovician–Silurian strata on the SE slope of the East European Craton highlight the potential for long-distance correlation of some fine-grained units. The revised Sasino Mudstone Formation (upper Darriwilian–lower Katian) includes the Udal Claystone Formation, formerly distinguished in the Lublin Basin. It forms a persistent mudstone sheet separating two carbonate-dominated complexes.

The Jantar Bituminous Claystone Member of the Pasłek Formation (Llandovery) now is distinguished as the Jantar Mudstone Formation (late Hirnantian–Aeronian). This organic-rich unit is traceable as far south as the Lublin Basin, where it becomes discontinuous. The name Pasłek Mudstone Formation is here retained for the upper Aeronian–Telychian, thin-bedded alternations of black, laminated mudstones and greenish, bioturbated mudstones. The top of the Kociewie Formation (Sheinwoodian–Ludfordian) is placed at the upper boundary of the Reda Member (latest Ludfordian), which can be traced, albeit intermittently, into the Lublin Basin.

Acknowledgements

The research was funded by means of a Polish National Centre for Research and Development (NCRD) grant under the BLUE GAS – Polish Shale Gas programme – G1/GAZGEOLMOD/13. We thank Gabriel Ząbek for providing the map shown in Figure 1 and Monika Masiak and Josef Paul for their helpful comments.

REFERENCES

- Cooper, R. A., Sadler, P. M., Hammer, O. & Gradstein, F. M., 2012. The Ordovician Period. In: Gradstein, F. M., Ogg, J. G., Schmitz, M. D. & Ogg, G. M. (eds), *Geologic Time Scale 2012, Vols 1 & 2*. Elsevier Science Bv, Amsterdam, 489–523 pp.
- Dadlez, R., Narkiewicz, M., Stephenson, R. A., Visser, M. T. M. & Van Wees, J. D., 1995. Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. *Tectonophysics*, 411: 111–128.
- Drygant, D., Modliński, Z. & Szymański, B., 2006. Lithostratigraphical correlation of the Ordovician in the Biłgoraj–Narol area with deposits of the adjacent regions of the marginal zone of the East European Craton in Poland and Ukraine. *Przegląd Geologiczny*, 54: 219–227. [In Polish, with English summary.]
- Dziadzio, P. S., Porębski, S. J., Kędzior, A., Liana, B., Lis, P., Paszkowski, M., Podhalańska, T. & Ząbek, G., 2017. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węgłowodorów*. Wydawnictwo Arka, Cieszyn, pp. 232–277. [In Polish.]
- Golonka, J. & Bębenek, S. (eds), 2017. *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węgłowodorów*. Wydawnictwo Arka, Cieszyn, 502 pp. [In Polish.]
- Jaworowski, K., 2000. Facies analysis of the Silurian shale-siltstone succession in Pomerania (northern Poland). *Geological Quarterly*, 44: 297–315.
- Kędzior, A., Dziadzio, P. S., Lis, P., Liana, B., Paszkowski, M., Porębski, S. J. & Ząbek, G., 2017. Architektura facyjna ordowiku zachodniej części kratonu wschodnioeuropejskiego. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węgłowodorów*. Wydawnictwo Arka, Cieszyn, pp. 150–190. [In Polish.]
- Lazar, O. R., Bohacs, K. M., Schieber, J., Macquaker, J. H. & Demko, T. M., 2015. Mudstone Primer: Lithofacies variations, diagnostic criteria, and sedimentologic-stratigraphic implications at lamina to bedset scales. *SEPM Concepts in Sedimentology and Paleontology*, 12, 204 pp.
- Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Lewandowski, M. & Buffenmyer, V., 2016. Pomeranian Caledonides, NW Poland – A collisional suture or thin-skinned fold-and-thrust belt? *Tectonophysics*, 692: 29–43.

- Mazur, S., Porębski, S. J., Kędzior, A., Paszkowski, M., Podhalańska, T. & Poprawa, P., 2018. Refined timing and kinematics for Baltica-Avalonia convergence based on the sedimentary record of a foreland basin. *Terra Nova*, 30: 8–16.
- Melchin, M. J., Sadler, P. M., Cramer, B. D., Cooper, R. A., Gradstein, F. M. & Hammer, O., 2012. The Silurian Period. In: Gradstein, F. M., Ogg, J. G., Schmitz, M. D. & Ogg, G. M. (eds), *Geologic Time Scale 2012*, Vols 1 & 2. Elsevier Science Bv, Amsterdam, 525–558 pp.
- Modliński, Z., 1982. The development of Ordovician lithofacies and palaeotectonics in the area of the Precambrian platform in Poland. *Prace Instytutu Geologicznego*, 102: 1–66. [In Polish, with English summary.]
- Modliński, Z., 1984. Stratigraphy of post-Tremadocian Ordovician rocks in the Lublin region. *Kwartalnik Geologiczny*, 28: 1–16. [In Polish, with English summary.]
- Modliński, Z. (ed.), 2010. *Paleogeological Atlas of the sub-Permian Paleozoic of the East European Craton in Poland and neighbouring areas*. Państwowy Instytut Geologiczny, Warszawa. [In Polish, with English summary.]
- Modliński, Z., Nehring-Lefeld, M. & Ryba, J., 1994. The Paleozoic complex in the Polish part of the Baltic Sea. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 22: 227–234.
- Modliński, Z., & Szymański, B., 1997. The Ordovician lithostratigraphy of the Peribaltic Depression (NE Poland). *Geological Quarterly*, 41: 273–288.
- Modliński, Z. & Szymański, B., 2008. Lithostratigraphy of the Ordovician in the Podlasie Depression and the basement of the Płock-Warsaw Trough (eastern Poland). *Biuletyn Państwowego Instytutu Geologicznego*, 430: 79–112. [In Polish, with English summary.]
- Modliński, Z., Szymański, B. & Teller, L., 2006. The Silurian lithostratigraphy of the Polish part of the Peri-Baltic depression (N Poland). *Przegląd Geologiczny*, 54: 787–796. [In Polish, with English summary.]
- Podhalańska, T., 2003. Late Ordovician to Early Silurian transition and the graptolites from Ordovician/Silurian boundary near the SW rim of East European Craton (northern Poland). *INSUGEO, Serie Correlation Geologica*, 18: 165–171.
- Podhalańska, T., 2009. The Late Ordovician Gondwana glaciation – a record of environmental changes in the depositional succession of the Baltic Depression (Northern Poland). *Prace Państwowego Instytutu Geologicznego*, 193: 1–132. [In Polish, with English summary.]
- Podhalańska, T., 2017. Biostratygrafia ordowiku i syluru zachodniej części kratonu wschodnioeuropejskiego. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węglowodorów*. Wydawnictwo Arka, Cieszyn, Poland, pp. 116–143. [In Polish.]
- Podhalańska, T., 2019 (in press). Graptolite biostratigraphy and dating of the Ordovician-Silurian shale succession of the SW slope of the East European Craton. *Annales Societatis Geologorum Poloniae*, 89.
- Podhalańska, T., Modliński, Z. & Szymański, B., 2010. *Nowelizacja stratygrafii syluru brzeżnej części kratonu wschodnioeuropejskiego (obszar Lubelszczyzny i Podlasia)*. Narodowe Archiwum Geologiczne. Warszawa. [In Polish.]
- Podhalańska, T., Waksmundzka, M. I., Becker, A., Roszkowska-Remin, J., Dyrka, I., Feldman-Olszewska, A., Głuszyński, A., Grotek, I., Janas, M., Karcz, P., Nowak, G., Paczeńska, J., Roman, M., Sikorska-Jaworowska, M., Kuberska, M., Kozłowska, A., Sobień, K., 2016. Prospective zones for unconventional hydrocarbon resources in Cambrian, Ordovician, Silurian and Carboniferous rocks of Poland – integration of the research results. *Przegląd Geologiczny* 64: 1008–1021. [In Polish, with English summary.]
- Poprawa, P., 2010. Shale gas potential of the Lower Palaeozoic complex in the Baltic and Lublin-Podlasie basins (Poland). *Przegląd Geologiczny*, 58: 226–249. [In Polish, with English summary.]
- Poprawa, P., Sliupa, S., Stephenson, R. & Lazauskiene, J., 1999. Late Vendian – Early Paleozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis. *Tectonophysics*, 314: 219–239.
- Porębska, E., Kozłowska-Dawidziuk, A. & Masiak, A., 2004. The *lundgreni* event in the Silurian of the East European Platform. *Palaeogeography Palaeoclimatology Palaeoecology*, 213: 271–294.
- Porębski, S. J., Anczkiewicz, R., Paszkowski, M., Skompski, S., Kędzior, R., Mazur, S., Szczepański, J., Buniak, A., Mikołajewski, Z., 2019. Hirnantian icebergs in the subtropical shelf of Baltica: Evidence from sedimentology and detrital zircon provenance. *Geology*, 47: 284–288.
- Porębski, S. J. & Podhalańska, T., 2017. Litostratygrafia ordowiku i syluru. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węglowodorów*. Wydawnictwo Arka, Cieszyn, Poland, pp. 144–149. [In Polish.]
- Porębski, S. J., Prugar, W., & Zacharski, J., 2013. Silurian shales of the East European Platform in Poland – some exploration problems. *Przegląd Geologiczny*, 61: 1–9.
- Skompski, S. & Paszkowski, M., 2017. Węglany ordowiku i syluru pomorsko-lubelskiego obrzeżenia platformy wschodnioeuropejskiej jako stratygraficzny zapis wahań eustatycznych. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węglowodorów*. Wydawnictwo Arka, Cieszyn, pp. 191–226. [In Polish.]
- Szczepański, J., Anczkiewicz, R., Buniak, A., Kędzior, A., Paszkowski, M. & Porębski, S. J., 2015. Provenance signals in Early Palaeozoic sandstones in the Lublin Basin (SE Poland): From passive margin to collision suture. *Abstract Book of 31st IAS Meeting of Sedimentology, 22–25 June, 2015, Krakow, Poland*. Kraków, p. 514.
- Szymański, B. & Modliński, Z., 2003. Revision of the Silurian stratigraphy in selected boreholes from the Polish sector of the Baltic Depression (northern Poland). *Biuletyn Państwowego Instytutu Geologicznego*, 405: 109–138. [In Polish, with English summary.]
- Uchman, A., 2017. Paleoośrodowisko mułowców sylurskich z basenu lubelskiego i bałtyckiego w świetle analizy ichtologicznej. In: Golonka, J. & Bębenek, S. (eds), *Opracowanie map zasięgu, biostratygrafia utworów dolnego paleozoiku oraz*

- analiza ewolucji tektonicznej przykrawędziowej strefy platformy wschodnioeuropejskiej dla oceny rozmieszczenia niekonwencjonalnych złóż węglowodorów.* Wydawnictwo Arka, Cieszyn, pp. 278–296. [In Polish.]
- Urbanek, A. & Teller, L., 1997. Graptolites and stratigraphy of the Wenlock and Ludlow Series in the East European Platform. *Palaeontologia Polonica*, 56: 23–57.
- Więclaw, D., Kotarba, M. J., Kosakowski, P., Kowalski, A. & Grotek, I., 2010. Habitat and hydrocarbon potential of the lower Paleozoic source rocks in the Polish part of the Baltic region. *Geological Quarterly*, 54: 159–182.