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UNCONVENTIONAL HYDROCARBON PROSPECTS IN ORDOVICIAN AND SILURIAN MUDROCKS OF THE EAST EUROPEAN CRATON (POLAND): INSIGHT FROM THREE-DIMENSIONAL MODELLING OF TOTAL ORGANIC CARBON AND THERMAL MATURITY

Bartosz PAPIERNIK*, **Dariusz BOTOR**, **Jan GOLONKA** & **Szczepan J. PORĘBSKI**

AGH University of Science and Technology, Faculty of Geology,
Geophysics and Environmental Protection 30-059 Kraków, al. Mickiewicza 30, Poland
e-mails: papiern@geol.agh.edu.pl, botor@agh.edu.pl, jgolonka@agh.edu.pl, spor@agh.edu.pl
** Corresponding author*

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Abstract: Three-dimensional, structural and parametric numerical modelling was applied to unravel the unconventional hydrocarbon potential of a W-dipping, Lower Palaeozoic mudrock succession, which subcrops for some 700 km in the Baltic, Podlasie and Lublin basins across the SW margin of East European Craton in Poland. Input data comprised structural and thickness maps of Ordovician and Silurian strata and the results of thermal maturity (mean vitrinite-equivalent reflectance, % R_o) and total organic carbon (TOC, % wt.) modelling. A new, spatial interpretation of vitrinite-reflectance variability indicates that the regional, W-increasing thermal maturity pattern breaks into a series of domains, bounded by abrupt maturity variations. In total, 14 tectono-thermal domains were recognised and their boundaries traced to known and inferred faults, mostly of NW–SE and NE–SW orientations. On the basis of a combination of thermal maturity and total organic carbon levels (0.6% > R_o<2.4%, and TOC >1.5% wt.), good-quality, unconventional reservoirs can be expected in the Sasino Formation (Caradoc) and Jantar Formation (early Llandovery) in the central and western Baltic Basin. The Jantar Formation also is likely to be prospective in the western Podlasie Basin. Marginal-quality reservoirs may occur in the Sasino and Jantar formations within the Podlasie and Lublin basins and in the Pasłęk Formation (late Llandovery) across all basins. Poor- to moderate-quality, unconventional reservoirs could be present in the Pelplin Formation (Wenlock) in the Lublin and southern Podlasie basins. In spite of a considerable hydrocarbon loss during multiphase basin inversion, the Ordovician and Silurian mudrocks still contain huge quantities of dispersed gas. Successful exploitation of it would require the adoption of advanced fracking methods.

Key words: Lower Palaeozoic, shale gas, shale oil, Baltic Basin, Lublin-Podlasie Basin, total organic carbon, thermal maturity, structural-parametric model.

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INTRODUCTION

The growing interest in mudrocks that can act as both source and producible reservoirs of hydrocarbons has sparked renewed research interest in the Lower Palaeozoic mudstone-dominated successions of the East European Craton (EEC; Fig. 1). In particular, the Ordovician−Silurian mudstone belt, subcropping for some 700 km along the EEC, has become the main target in these efforts aimed at evaluation of its unconventional hydrocarbon potential (e.g., Poprawa, 2010a, b; Kiersnowski and Dyrka, 2013a, b; Porębski *et al*., 2013; Karcz and Janas, 2016; Podhalańska *et al.,* 2016; Dziadzio *et al*., 2017; Papiernik, 2017c; Papiernik *et al*., 2017a, b). Although initial production testing did not yield particularly encouraging results, it had preceded any exhaustive and regional assessment of the critical factors that govern the development of commercial, unconventional hydrocarbon accumulations (e.g., Passey *et al*., 1990; Slatt, 2011). Among such factors, the appropriate combination of total organic carbon content (TOC) and thermal maturity,

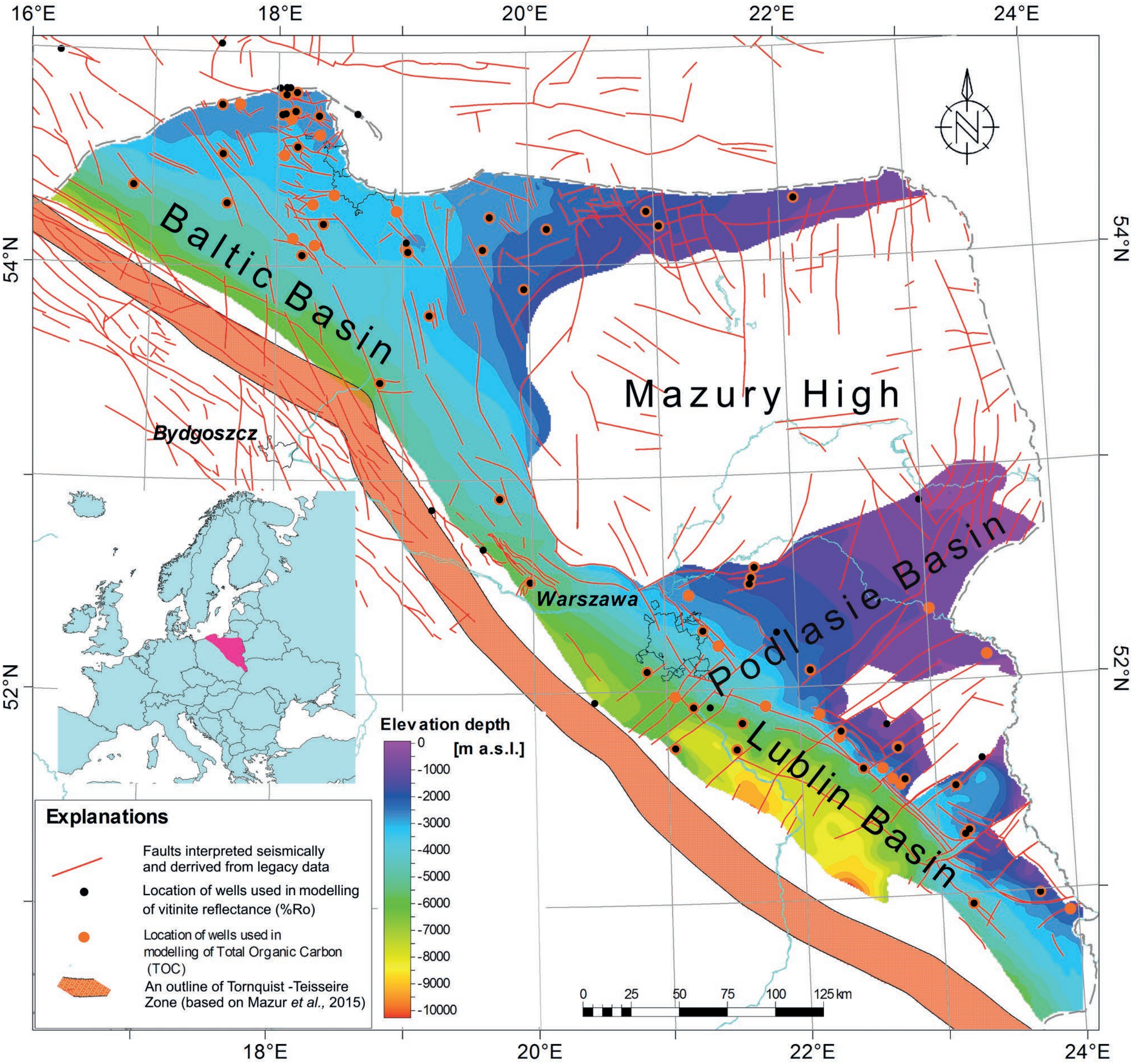

Fig. 1. Location of the Lower Palaeozoic basins in the Polish part of the East European Craton. Top-Ordovician map shown in the background.

here expressed as vitrinite reflectance (R_o), plays the main role one for any proper identification of potential pay zones. In this contribution, the authors used all available TOC determinations and modelled thermal maturity field, based on some 90 wells covering the western slope of the EEC in Poland (Fig. 1) to identify potential pay zones. The analytical results, placed within a 3D stratigraphic and structural framework, have provided a new regional basis for the credible mapping of zones, showing elevated potential for the presence of shale oil, condensate and gas in the Ordovician and Silurian mudrocks.

GEOLOGICAL SETTING

Basin development

The crystalline basement of the EEC dips in a homocline westwards and is onlapped by an E-thinning wedge of the Neoproterozoic–Lower Palaeozoic, undeformed to generally weakly deformed strata. These strata accumulated hydrocarbons mainly in three major depocentres that are referred to as the Baltic, Podlasie and Lublin basins (BB, PB and LB, respectively) separated in the east by the Mazury High (Poprawa, 2010a; Fig. 1). In the westernmost Baltic Basin, the basin fill is affected by the fold-and-thrust belt of the Pomeranian Caledonides (Mazur et *al*., 2016). Farther to the south, the western limit of these strata conventionally is placed at the NW–SE-trending Teisseyre-Tornquist Zone, beyond which they disappear beneath a 10-km-thick overburden of Upper Palaeozoic−Cainozoic in central Poland.

The basins originated during late Ediacaran rifting, which was followed by the Cambrian−Ordovician post-rift thermal sag of a passive-margin stage and finally by Caledonian flexural subsidence (Poprawa *et al*., 1999; Poprawa and Pacześna, 2002; Poprawa, 2006a; Krzywiec *et al*., 2018). During the rift phase, the basin was filled with volcanic rocks, mainly trap basalts, as well as continental to shallow-marine, clastic sediments During the post-rift phase, the Cambrian siliciclastic shelf (Jaworowski, 1997) evolved into Ordovician carbonate shelf ramp, merging westwards into black, graptolitic mudstones (Modliński, 2010). Since the Late Ordovician and throughout the Silurian, oblique collision of Avalonia with Baltica led to development of the extensive flexural basin along the western slope of the EEC (Poprawa *et al.*, 1999, 2018; Lazauskiene *et al.*, 2002; Poprawa, 2006b; Mazur *et al.*, 2015, 2018; Golonka *et al.*, 2017, 2019). The Caledonian foredeep is filled with a >4,000-m-thick mudstone-dominated succession with a minor contribution of carbonates and coarser siliciclastic components (Jaworowski, 2000). The succession is unconformably overlain by Devonian−Carboniferous sediments in the Lublin Basin and Permian strata farther to the north. The contemporary depth of burial of the Early Palaeozoic complex in the EEC ranges from ~600 to ~1,200 m below sea level.

Lithostratigraphy

The existing lithostratigraphic classification of the Ordovician–Silurian mudrocks on the western slope of the EEC (Modliński, 1984; Drygant *et al.*, 2006; Modliński *et al.*, 2006; Modliński and Szymański, 2008; Podhalańska *et al.*, 2010) was modified recently by Porębski and Podhalańska (2017, 2019) in order to emphasize the basin-wide persistence of many fine-grained units and, thus, their high mapping potential (Fig. 2). Lithologically, these units consist mainly of black, organic-rich, graptolitic mudstones, dark grey, argillaceous to locally, calcareous-clayey and dolomitic-clayey mudstones, and greenish-grey, bioturbated, argillaceous mudstones, which are interbedded with numerous bentonites, bioclastic limestones and early diagenetic carbonate concretions (Dziadzio *et al.*, 2017; Kędzior *et al.*, 2017). The mudrocks occur as major, mappable tongues and sheets, which wedge out cratonwards into marlstones and nodular limestones in the outer carbonate ramp.

The oldest tongues comprise the Słuchowo Mudstone Formation (Floian) and Płonka Mudstone Formation (Dapingian–early Darriwillian?), up to 15 and 5 m thick, respectively, the poorly represented record of which appears limited to the Baltic Basin. These tongues are followed upwards by a limestone complex, the maximum basinward extension of which is represented by the Kopalino Formation (late Dapingian–early Darriwillian) in the western Baltic Basin. The overlying Sasino Mudstone Formation (late Darriwillian–early Katian), up to 60 m thick, forms a basin-wide sheet that is traceable into the Lublin Basin (Dziadzio *et al.*, 2017). This sheet grades upwards into the marly Prabuty Formation (late Katian–Hirnantian), 50 m thick, in the western Baltic Basin and its limestone equivalents to the east and southeast (Fig. 2).

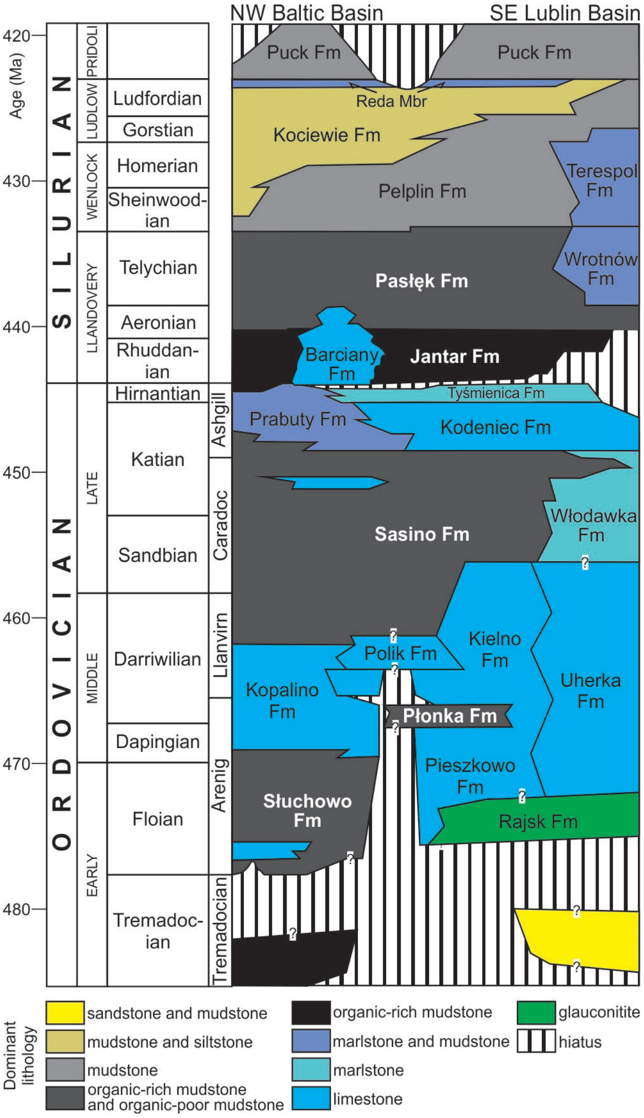

Fig. 2. Ordovician−Silurian lithostratigraphy in the Polish part of the East European Craton (based on Porębski and Podhalańska, 2017, 2019).

The overlying Jantar Mudstone Formation (Porębski and Podhalańska, 2017, 2019; late Hirnantian–middle Aeronian) is up to 18 m thick in the Baltic Basin and dominated by black, organic-rich, argillaceous mudstones. This formation is traceable, albeit discontinuously, into the Lublin Basin (Dziadzio *et al.*, 2017). Similar black, organic-rich mudstones, interbedded with greenish-grey, bioturbated mudstones, constitute the Pasłęk Mudstone Formation (Porębski and Podhalańska, 2017, 2019; late Aeronian–Telychian), which is a persistent, basinwide unit, up to 60 m thick, showing onlapping contacts in the Lublin Basin (Dziadzio *et al.*, 2017). The Jantar and Pasłęk formations intertongue locally in the Baltic Basin with nodular limestones, belonging to the Barciany Limestone Formation. The Pasłęk Formation gives way upwards to mainly dark grey, laminated, argillaceous to locally calcareous and dolomitic mudstones of the Pelplin Formation (Sheinwoodian–Ludfordian) forming a laterally persistent body, up to 400 m thick, across all basins. To the northwest and upwards, such mudstones become gradationally interbedded with laminated siltstones, calcisiltites and rare sandstones, all together distinguished as the Kociewie Formation (middle Sheinwoodian–Ludfordian). The calcisiltic Reda Member (latest Ludfordian), up to 34 m thick, caps this formation over much of the study area (Porębski and Podhalańska, 2019) and forms a prominent seismic-correlation marker. The Kociewie Formation is 50 to >3,000 m thick and shows base getting younger diachronously towards both east and southeast (Mazur *et al.*, 2018). The Silurian terminates with the Puck Formation (Pridoli), 0 to almost 1,600 m thick, which is dominated by variegated calcareous mudstones.

Petroleum targets

The Baltic Basin is the site of oil and condensate production, mainly from middle Cambrian conventional reservoirs. In the Polish Baltic Basin, the middle Cambrian sandstones are major reservoir horizons of oil and gas deposits, exploited in the central offshore part of this basin (Karnkowski and Górecki, 1993; Domżalski *et al*., 2004; Pletsch *et al*., 2010). Oil and gas deposits occur in the middle Cambrian quartzose sandstones, varying in thickness from 60 to 120 m. Sandstone porosity ranges from 1–15% and permeability from 10 mD–300 mD. Gas is methane-dominated (70–90 vol. %) and contains admixtures of higher gaseous hydrocarbons (6–25 vol. %), nitrogen, and carbon dioxide. Condensate concentrations vary between 100 g/m^3 of high-methane gas and >250 g/m^3 of other gases. Oil from the Baltic Basins is light, low in sulphur and asphaltenes, but rich in the gasoline fraction. Some oils reveal features intermediate between gasolines and the lightest oils and classified as hydrocarbon condensates (Górecki *et al*., 1992; Domżalski *et al*., 2004; Pletsch *et al*., 2010). Nearly all petroleum traps in the middle Cambrian sandstones are fault-related anticlines and cross-fault structures, associated with faults (Stolarczyk, 1979; Górecki *et al*., 1992; Domżalski *et al*., 2004; Pletsch *et al*., 2010).

The Upper Palaeozoic strata in the Lublin Basin host oil and gas production from several small fields, located within Devonian carbonates and Carboniferous sandstones (Karnkowski and Górecki, 1993; Helcel-Weil *et al*., 2007; Karnkowski, 2007; Pletsch *et al*., 2010). Hydrocarbon accumulations (mainly gases) occur within fault-related traps, associated with NW–SE-trending anticlinal structures, which originated mainly during Late Carboniferous time. The main reservoirs are Namurian fluvial sandstones showing porosities of 1–22% and permeabilities of 1–400 mD, whereas the seals consist of interdistributary, prodelta and marine mudstones (Pletsch *et al*., 2010). So far, no commercial hydrocarbon accumulations were discovered in the Podlasie Basin. The unconventional potential of these basins is still under consideration.

Potential source rocks for hydrocarbons comprise marine shales, which have wide stratigraphic distribution and tend to show an overall southward onlap across the EEC (Poprawa, 2010a, b). These shales are enriched in oil-prone, low-sulphur type II kerogen and occur in Ediacaran–Lower Cambrian, Cambrian–Tremadocian, Upper Ordovician (mainly Caradoc) and Lower Silurian (Llandovery–Wenlock) strata (Pacześna *et al*., 2005; Pletsch *et al*., 2010; Więcław *et al*., 2010; Kosakowski *et al*., 2016; Podhalańska *et al*., 2016; Radkovets *et al.,* 2017; Yang *et al*., 2017). In the Lublin Basin, Devonian and Carboniferous source rocks also were identified (Botor *et al*., 2002; Karnkowski, 2007; Pletsch *et al*., 2010; Radkovets *et al*., 2017). The main targets of shale-gas and shale-oil exploration in the Baltic Basin are organic, carbon-rich intervals within the Sasino, Jantar and Pasłęk formations and, to a lesser degree, in the Pelplin Formation. However, the latter is of a considerable interest in the Lublin Basin. It is important to emphasise that the Variscan evolution of these two basins proceeded along different paths, resulting in the significantly higher degree of tectonic deformation and more extended network of faults and natural fractures in the Lublin Basin. Hence, the risk of gas release from the shale reservoirs is considerable in this area (Poprawa, 2010a, b). In the Baltic Basin, most of the major faults terminate within Silurian strata below the Reda Member of the Kociewie Formation and this enhances the potential for gas preservation in the area. Phases of late Devonian, late Carboniferous and early Permian erosion affected much of the Baltic and Podlasie basin fills, whereas a thick Devonian−Carboniferous succession is preserved relatively intact in the fault-block system of the Lublin Basin.

DATA AND METHODOLOGY

The results of new lithostratigraphic analyses completed in the GASGEOLMOD project (Dziadzio *et al*., 2017; Kędzior et *al.*, 2017; Podhalańska, 2017, 2019; Stadnik *et al.*, 2017, 2019; Wendorff, 2017), together with seismic interpretations (Cichostępski *et al.*, 2019; Kasperska *et al.*, 2019) and available archival data, were used for the construction of structural and thickness maps (Papiernik, 2017a, b; Papiernik and Michna, 2019). These maps and models use the traditional British chronostratigraphic divisions of the Ordovician and Silurian (Fig. 2), because still some 40% of the legacy well data require stratigraphic reinterpretation.

Structural framework

All available information was migrated onto a Petrel platform and provided input data for the 3D structural-parametric modelling of the Lower Palaeozoic strata. The framework geometry of the model is based on three seismically traced surfaces, representing the tops of the Silurian, Ordovician and Cambrian. The top-Ordovician marker proved to be especially useful for establishing the model geometry, as it is easily recognizable in well logs and seismic sections. Using this reference surface, the geometry of adjacent complexes was restored for the Ordovician (Sasino and Prabuty formations, undivided Tremadocian–Arenig complex) and Silurian (Jantar, Pasłęk, Pelplin, Kociewie and Terespol formations and undivided Ludlow–Pridoli complex). The geometry of the Sasino and Jantar formations was additionally constrained by the top of the Sasino Formation (‘top Caradoc’), although the authors are aware that this boundary is diachronous and spanning the *complanatus*–early *anceps* biozones of the Katian. The Pelplin, Kociewie and Terespol formations were restored together as the Wenlock complex. The top of the Precambrian was used as the geometrical closure of the structural model; however, Cambrian deposits were not included in parametric modelling.

Vitrinite reflectance

The structural framework described above was used for further parametric modelling. The first step involved the construction of a thermal maturity model, which is based on reflectance data for vitrinite-like matter (% R_o) from 54 onshore wells (Fig. 1; Tab. 1). The data come from both *Polish Oil and Gas Company* resources, released for the project BLUEGAS /GAZGEOLMOD /LUPZAS/13, and sources available in the public domain (e.g., Nehring-Lefeld *et al.*, 1997; Grotek, 1998, 2006, 2015; Swadowska and Sikorska, 1998; Pletsch *et al.,* 2010; Botor *et al.*, 2017a, b, 2019a, b). The vitrinite reflectance model was constructed solely for Lower Palaeozoic strata using original, in-house methodology (Papiernik *et al.*, 2016; Michna *et al.*, 2017; Papiernik 2017a, b; Papiernik and Michna, 2019). The results obtained are a combination of the regional, depth-dependent variability, described by a global function, and the relatively gradual, local variability of R_o, observed in individual boreholes and reflected in the very long ranges of semivariograms (Fig. 3). The resultant R_o model is as an arithmetic average of seven equi-probable stochastic realizations estimated with the use of Sequential Gaussian Simulation (Dubrule, 2003; Papiernik *et al.*, 2015; Papiernik and Michna, 2019). The distribution of potentially prospective zones in the Ordovician−Silurian mudstones was interpreted on the basis of the following, empirically-derived R_o intervals: <0.6% = immature deposits, >0.6 %–0.8% = oil window, >0.8 %–1.25% = liquid (condensate) window, >1.25%–2.4% = gas window, and >2.4% = overmature deposits (Figs 4, 5). Such a subdivision differs considerably from the classical one of Dow (1977) and that proposed by Jarvie *et al.* (2005) and Jarvie

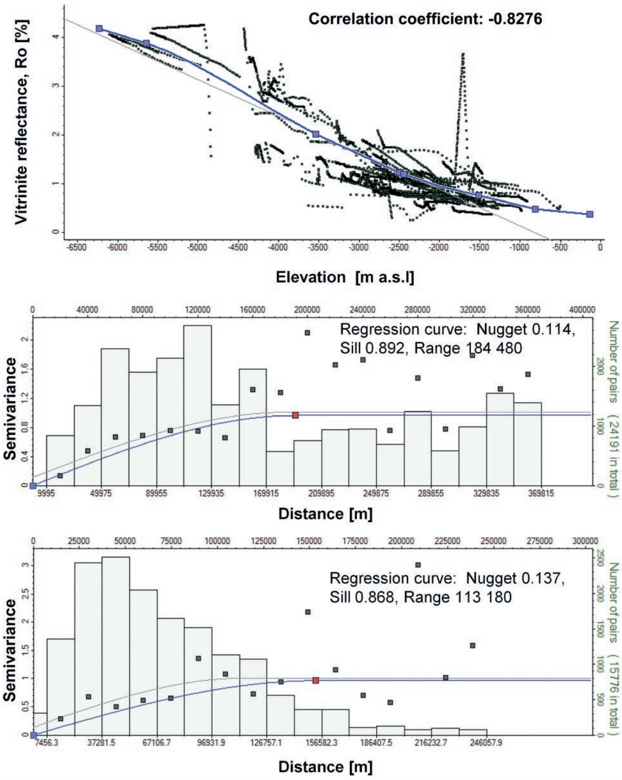

Fig. 3. Results of the process of data analysis that controls the process of modelling of vitrinite reflectance.

Table 1

List of wells used for preparation of 3D model of vitrinite reflectance (%R_o).

ID number	Name	ID number	Name	ID number	Name
1	Bartoszyce-IG1	19	Karnkowo-IG1	37	Pasłęk-IG1
2	Białogóra-3	20	Kochanowo-1	38	Piaśnica-2
3	Białopole-IG1	21	Kościerzyna-IG1	39	Polik-IG1
4	Bodzanów-IG1	22	Krowie Bagno-IG1	40	Potycz-1
5	Busówno-IG1	23	Kętrzyn-IG1	41	Prabuty-IG1
6	Bytów-IG1	24	Lubocino-1	42	Radzyń-IG1
7	Darżlubie-IG1	25	Lębork-IG1	43	Siedliska-IG1
8	Dębki-3	26	Maciejowice-IG1	44	Słupsk-IG1
9	Dębki-4	27	Malbork-IG1	45	Tarkawica-2
10	Gdańsk-IG1	28	Miłowo-1	46	Tłuszcz-IG1
11	Gołdap-IG1	29	Mszczonów-IG2	47	Warka-IG1
12	Grudziądz-IG1	30	Młynary-1	48	Wilga-IG1
13	Gródek-1	31	Nadarzyn-IG1	49	Łeba-8
14	Hel-IG1	32	Okuniew-IG1	50	Łochów-IG1
15	Henrykowo-1	33	Olsztyn-IG2	51	Łochów-IG2
16	Izdebno-IG1	34	Opalino-2	52	Łopiennik-IG1
17	Kamionki-IG3	35	Opalino-3	53	Żarnowiec-IG1
18	Kaplonosy-IG1	36	Parczew-IG10	54	Żebrak-IG1

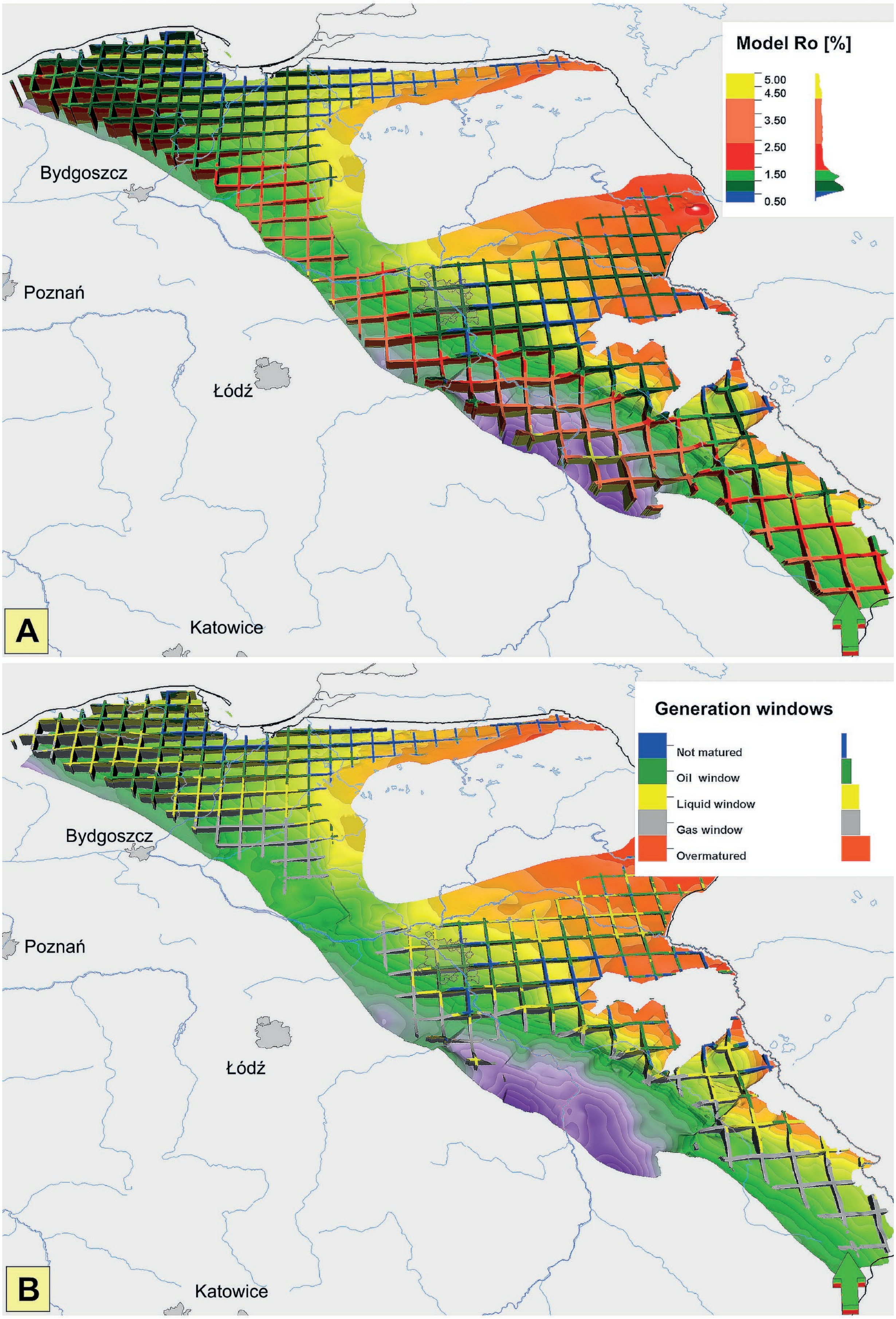

Fig. 4. **A**. Vitrinite reflectance model. **B**. Spatial distribution of hydrocarbon generation windows within % interval 0.6 %< R_o >2.4% for Silurian and Ordovician strata in the study area.

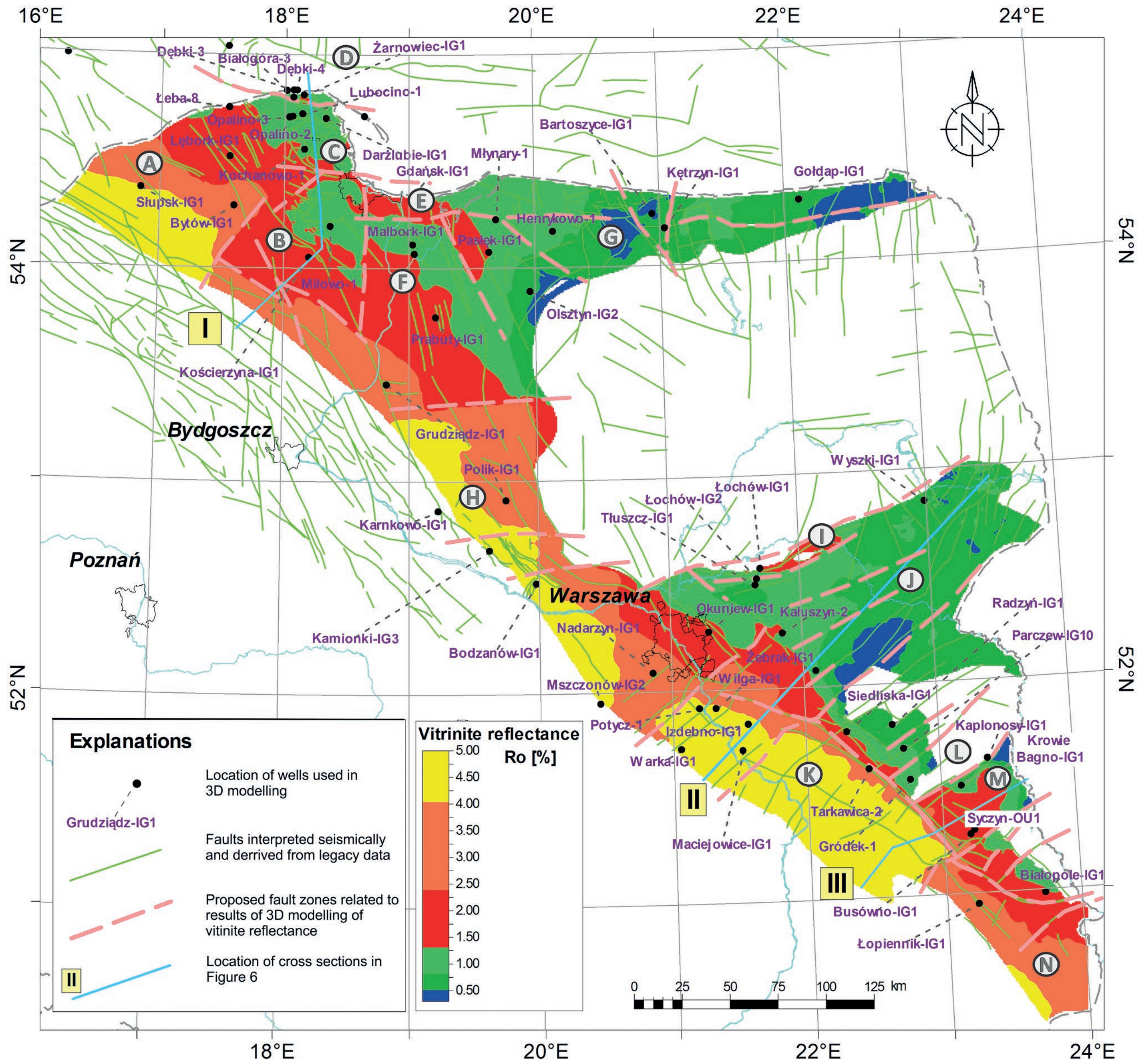

Fig. 5 Map of vitrinite reflectance extracted from R_o three-dimensional model, shown on the top of the Sasino Formation ('top-Caradoc surface'). Encircled letters mark tectono-thermal domains listed in Table 3.

(2015) for the Barnett Shale. However, the approach presented has already been proved useful in the Lublin Basin, where it was established empirically from a large set of geochemical data (Papiernik *et al.*, 2016).

Total organic carbon

The total organic carbon trend was modelled here on the basis of TOC determinations from both the laboratory tests (~300 samples from 79 wells) and petrophysical well-log interpretations (43 wells), using the methods of Passey *et al.* (1990) and Bowman (2010). Both data groups were upscaled to well-scale models along a well path. These models were next unified *via* arithmetic averaging into a common TOC model. The resultant well-scale models (Tab. 2) reflect either log interpretation values, or core-based TOC content measurements, or the average of the two, where both data sets are present. Such an approach resulted in a uniformly distributed data set that is more reliable than those used in the past (Poprawa, 2010a, b; Kiersnowski and Dyrka, 2013a, b; Karcz and Janas, 2016) and fully suitable for the 3D modelling.

In order to define the spatial locations of the most prospective zones, the TOC volume was visualised only in cells that met the condition of $0.6\% < R_o < 2.4\%$, and TOC $> 1.5\%$. Moreover, a stratigraphic filter was applied allowing for graphical representation in the form of 3D geobodies displayed over the top-Cambrian marker as well as in a series of maps, showing the average TOC content for potential sweet spots in the Sasino, Jantar and Pasłęk formations and Wenlock succession. The TOC cut-off value of 1.5% applied is lower than that commonly used (2%; e.g.,

Table 2

Input wells and data types used for TOC modelling (data presence marked with +).

Id number	Well	Core data	Log data
1	Bartoszyce-IG1	+	+
2	Berejów-OU1	+	+
3	Białopole-IG1	+	
4	Bodzanów-IG1	+	
5	Borcz-1		+
6	Busówno-IG1	+	+
7	Bytów-IG1	+	
8	Będomin-1		+
9	Ciepielów-IG1	+	
10	Czachówek-1	+	
11	Darłowo-4	+	
12	Darżlubie-IG1	+	+
13	Dyle-IG1	+	
14	Dębe Wielkie-1	+	
15	Dębki-4	+	
16	Dębki-5K	+	
17	Dębki-6	+	+
18	Dębki-7K		
19	Dębki-8		+
20	Gdańsk-IG1	+	+
21	Goździk-1	+	
22	Goździk-OU1	+	+
23	Gołdap-IG1	+	+
24	Grudziądz-IG1	+	
25	Gródek-1	+	+
26	Hel-IG1	+	
27	Henrykowo-1	+	
28	Izdebno-IG1	+	
29	Jastarnia-IG1	+	
30	Kaplonosy-IG1	+	+
31	Kochanowo-1	+	+
32	Kock-IG1	+	
33	Kozaki-1	+	
34	Kościerzyna-IG1	+	
35	Krowie Bagno-IG1	+	+
36	Kętrzyn-IG1	+	+
37	Lubiny-1		+
38	Lubocino-1	+	+
39	Lubocino-2H	+	
40	Lębork-IG1	+	
41	Maciejowice-IG1	+	
42	Malbork-2		+
43	Malbork-IG1	+	+
44	Miłowo-1		+
45	Mielnik-IG1	+	
46	Mszczonów-IG2	+	
47	Młynary-1	+	
48	Nadarzyn-IG1	+	
49	Narol PIG-2	+	
50	Narol-IG1	+	
51	Niestępowo-1	+	+
52	Nowa Kościelnica-1	+	+
53	Okuniew-IG1	+	
54	Olsztyn-IG2	+	+
56	Opalino-3		+
57	Opalino-4		+
58	Osuchy-1	+	
59	Parczew-IG10	+	+
60	Pasłęk-IG1	+	
61	Piaśnica-2		+
62	Polik-IG1	+	
63	Potok-IG1	+	
64	Potycz-1	+	+
65	Prabuty-IG1	+	+
66	Radzymin-1	+	
67	Siedliska-IG1	+	+
68	Stanin-1	+	+
69	Strzelce-IG2	+	
70	Syczyn-OU1	+	+
71	Słupsk-IG1	+	+
72	Tarkawica-1		+
73	Tarkawica-2	+	+
74	Tarkawica-3		+
75	Terespol-1	+	
76	Tłuszcz-IG1	+	
77	Tępcz-1	+	+
78	Warka-IG1	+	
79	Wejherowo-IG1	+	
80	Wojcieszków-1		+
81	Wola Obszańska-10	+	
82	Wola Obszańska-9	+	
83	Wysin-1	+	+
84	Wyszków-IG1	+	
85	Łeba-8	+	
86	Łochów-IG1	+	
87	Łochów-IG2	+	
88	Łopiennik-IG1	+	+
89	Żarnowiec-8K	+	+
90	Żarnowiec-IG1	+	
91	Żebrak-IG1		

Charpentier and Cook, 2011; Tyson, 2012), in order to take into account the slightly increased averaging of TOC, imposed by the modelling rules.

RESULTS AND DISCUSSION

The structural model (Figs 1, 5, 6) provided a high-resolution, quantitative insight into the tectonic framework of the Lower Palaeozoic strata in the EEC and yielded critical constraints for the parametric modelling of vitrinite reflectance and total organic carbon contents. In particular, this modelling, guided by the 3D structural framework, significantly improved the picture of the thermal maturity field, whereas the confined imaging of the TOC model, filtered with the threshold values of TOC, R_o and a stratigraphy filter, helped to determine the locations of potentially prospective complexes (sweet spots).

Thermal maturity

A lot of research has demonstrated that the kerogen transformations in the Lower Palaeozoic strata of the EEC record a gradual increase in thermal maturity from low-temperature thermogenesis in the east to the overmature stage along the Teisseyre-Tornquist Zone (e.g., Kosakowski *et al*., 2010, 2016; Pletsch *et al.,* 2010; Poprawa 2010a, b; Więcław *et al.,* 2010, 2012; Carozzo *et al*., 2012; Grigo *et al*., 2014; Caricchi *et al.,* 2016; Botor *et al*., 2017a, b, 2019a, b; Poprawa, 2017). This is consistent with the homoclinal, westward dip of the Lower Palaeozoic strata in the EEC. Indeed, the thermally immature zones (R_o<0.6%) where oil generation did not take place, occupy the eastern part of the Baltic and Podlasie basins (Figs 4, 5). The overmature zones (R_o>2.4%) occur within the Lublin Graben (Fig. 5), the Płock-Warszawa Trough, and are spread over large parts of the Baltic Basin. However, the new R_o model presented here shows that this trend breaks into a series of local domains, which differ in thermal maturity and are likely to be bounded by deep-rooted faults of regional extent (see also Kiersnowski *et al*., 2014). In some areas, such pronounced R_o changes tend to occur across seismic-scale faults. In other regions and particularly where the seismic control is relatively poor, faults inferred from the abrupt R_o variations may depart significantly from the tectonic framework recognized so far (Fig. 5). The location of such faults is schematically marked in Figure 5 that shows the R_o variation in relation to the top of the Sasino Formation ('top of Caradoc').

In the Lublin Basin, the R_o-based fault-block model is in good agreement with all, major sub-Devonian faults trending NW–SE, such as the Kock Fault Zone, the Izbica Fault, and the Ursynów-Kazimierz Fault, as well as those aligned transversally to this trend, i.e., the Grójec, Hanna, Łosice, Święcica and Włodzimierz faults (Stolarczyk *et al*., 2004; Krzywiec *et al*., 2107a, b, c, 2018; Mazur *et al*., 2017; Tomaszczyk and Jarosiński, 2017). A similar fault pattern appears in the Podlasie Basin, where the model supports the existence of large, NW–SE-trending faults that were inferred by Stolarczyk *et al.* (2004) but were not shown on older tectonic maps (Pożaryski and Dębowski, 1983; Żelichowski and Kozłowski, 1983; Pożaryski and Karnkowski, 1992). Moreover, the data indicate, though less conclusively, that some NW–SE striking faults may extend from the Lublin Basin into the central part of the Podlasie Basin. A block-faulted structure appears also in the Płock-Warszawa Trough, where abrupt R_o changes especially enhance the transverse fault system . The most important in this system is an ENE–WSW-striking dislocation, situated south of the Grudziądz-IG1 well (Fig. 5). This dislocation, named here the Grudziądz Fault, seems to be the best candidate for a tectonic boundary between the Baltic and Podlasie basins.

In the Baltic Basin, the block tectonics, inferred from the R_o model and structural maps, differs substantially from the current, tectonic interpretations that are dominated by longitudinal faults (Pożaryski and Dębowski, 1983; Żelichowski and Kozłowski, 1983; Pożaryski and Karnkowski, 1992; Papiernik *et al.*, 2015; Kasperska *et al.*, 2019). In this interpretation, three major NW–SE-trending dislocation zones and a series of transverse faults divide the basin into twelve blocks, showing different burial and/or thermal maturation trends (Fig. 5A–N). Table 3 provides main characteristics of these blocks and similar tectono-thermal zones, distinguished in the segment of the EEC studied.

The fault-block structure postulated obviously was initiated during the late Vendian rifting, enhanced during the Caledonian flexing of the western margin of the EEC and further reactivated during the Variscan evolution of this margin. The latter is reflected in the Baltic Basin, not only by vitrinite reflectance changes, but also by the thickness variation of the Pridoli Puck Formation (Modliński, 2010; Papiernik and Michna, 2019), pointing to considerable post-Silurian erosion in the A, F and G domains (Tab. 3). Other minor-scale deviations from the R_o depth-dependent trend, observed in the B, C, D, E domains (Tab. 3), can be the complex result of many factors, such as local changes in post-Silurian sedimentation and erosion rates, minor-scale tectonic variability, or spatially confined thermal-field variability. It is noteworthy that in a recent study, based on gravimetric modelling, magnetic field imaging and seismic interpretations, Mikołajczak *et al.* (2018) have pointed to the existence of deep-rooted faults across the entire EEC segment studied here. Many of these faults are similar in location and orientation to those interpreted by the present authors at the borders of the A, B, C, D, E, F, G domains (Fig. 5; Tab. 3). Finally, the local variability of thermal maturation (Fig. 5) seems to be confirmed by the results of petroleum exploration in the Baltic Basin. Production tests, in spite of similar depth ranges, were much more successful on the concessions, located in the relatively high-maturity Słupsk-Lębork block (the Łebień LE-2H, LE-1, Gapowo B-1A, Lublewo LEP-1 and ST1H wells) than those located in the moderately mature Lubocino-Opalino-Kochanowo zone (Lubocino-1, Opalino-2, Kochanowo-1) and Kościerzyna-Miłowo block (Borcz-1, Miłowo-1; Poprawa *et al.*, 2018).

Potential prospect locations

The model of TOC content was created for the entire EEC (Fig. 7). This model, along with the thermal maturity results, provided crucial constraints for predicting potential

Table 3

Tectono-thermal domains interpreted as faulted blocks in Ordovician–Silurian strata of the Baltic Basin (BB), Podlasie Basin (PB) and Lublin Basin (LB). A−N refer to the locations of domains shown in Figure 5.

Domain	Location	Thermal maturity
A. Słupsk-Lębork Block	BB	relatively high maturity; local maturation trend
B. Kościerzyna-Miłowo Zone	BB	relatively less mature than the adjacent Słupsk-Lębork Block; individual depth-dependent R_o trend observed
C. Kochanowo-Opalino-Lubocino Zone	BB	relatively uniform, moderate maturity remaining in liquid window and smaller than that in surrounding domains
D. Łeba Block	BB	bordered from SW by Żarnowiec Fault and buried few hundred metres shallower than Block C, but slightly more thermally mature
E. Gdańsk-Młynary Zone	BB	more mature than expected, independent from regional depth trend and contrasting with adjacent zones B, F and G
F. Prabuty-Malbork Zone	BB	strongly faulted and thermally variable part of the Baltic Basin; displays systematic R_o increase towards SW
G. Henrykowo-Gołdap Zone	BB	low maturity; strongly scattered, individual burial dependency observed locally
H. Płock-Warszawa Trough	PB to BB transition	generally overmature, bordered to N by Grudziądz Fault and to S by Grójec Fault; possible western extension of Mazury High
I. Łochów-Tłuszcz Block	PB to MH transition	displays positive Ro anomaly, in contrast to recent burial trend of the Podlasie Basin
J. Podlasie Basin	PB	generally low maturity; depth-dependent regional variability
K. Lublin Graben	LB	generally overmature; obvious local burial dependence observed
L. Łuków-Wiszniów Horst	LB	regular depth-dependent $R_{o,}$ ranging from immature to gas window; local maturation trend observed
M. Włodawa Depression	LB	extensive occurrence of gas window and late liquid window; anomalously mature region displaying its individual depth dependency
N. Kumów Horst	LB	moderate maturity; local maturation trend

sweet-spot distribution in the Ordovician–Silurian infill of the Baltic, Podlasie and Lublin basins.

Sasino Formation

Deposits, qualifying in the Sasino Formation as potential net pay, are widespread over the EEC where they cover an area of almost 19,000 km^2 (Fig. 8). These deposits are dominated by black, organic-rich argillaceous, locally siliceous (Baltic Basin), laminated mudstones, subordinately interbedded with massive and bioturbated mudstones and bentonites (Dziadzio *et al.*, 2017). The thickness of sweet spots averages 7.5 m and reaches 34 m. The TOC content of the net pay zone varies from 1.5% to 7.3%, averaging 2.5%, whereas the maximum TOC measured in core samples locally can exceed 10%. The Baltic Basin appears most prolific, where a vast prospective zone spreads between the Łeba-8 well in the northwest to the Kościerzyna-IG1 well in the southeast (Fig. 9). The mean TOC content is 4.2% (Fig. 9), whereas the maximum net-pay thickness of 34 m occurs in the northern part of this zone. Elevated TOC contents appear also between Elbląg and the Henryków-1 well, but they do not exceed 4% and are associated with much thinner intervals. The TOC maximum east of the Grudziądz-IG1 well could be a numerical artefact (Fig. 9).

A sweet spot, although less promising, appears in the Okuniew-IG1 – Łochów-IG1 area located within the central part of the Podlasie Basin, where the TOC content is 1.5–2%. In the Lublin Basin, prospective areas comprise the southwestern part the Łuków-Wiszniów Horst and locally in the Włodawa Depression (Tab. 3; Fig. 5), where TOC contents are 2.9% and <1.5%-2%, respectively (Fig. 9). In general, net-pay thicknesses in the Lublin and Podlasie basins do not exceed 10 m.

Jantar Formation

Deposits, forming net pay zones in the Jantar Formation, occupy a total area of 18,200 km^2 on the EEC (Fig. 10). These deposits are dominated by black, organic-rich argillaceous, in places silica- or carbonate-enriched, laminated to banded mudstones, which locally incorporate numerous ripple-scale calcisiltite lenses (Dziadzio *et al.*, 2017). According to modelling results, sweet-spot thicknesses vary up to >27 m and average 7.6 m. The TOC content in net-pay zones ranges from 1.5%–10.7% and averages 2.9%. Organic carbon-rich zones within the Baltic Basin are confined mostly to its central part, where the best-quality net-pay rocks average >4.5% in TOC in the Miłowo region and attain ~26 m in thickness in the Lubiny area. In this basin, the net-pay area in the Jantar Formation is considerably smaller than in a similar area, documented for the Sasino Formation (Fig. 11).

Probably, the richest source rock of the Jantar Formation occurs in central part of the Podlasie Basin (Fig. 11), where

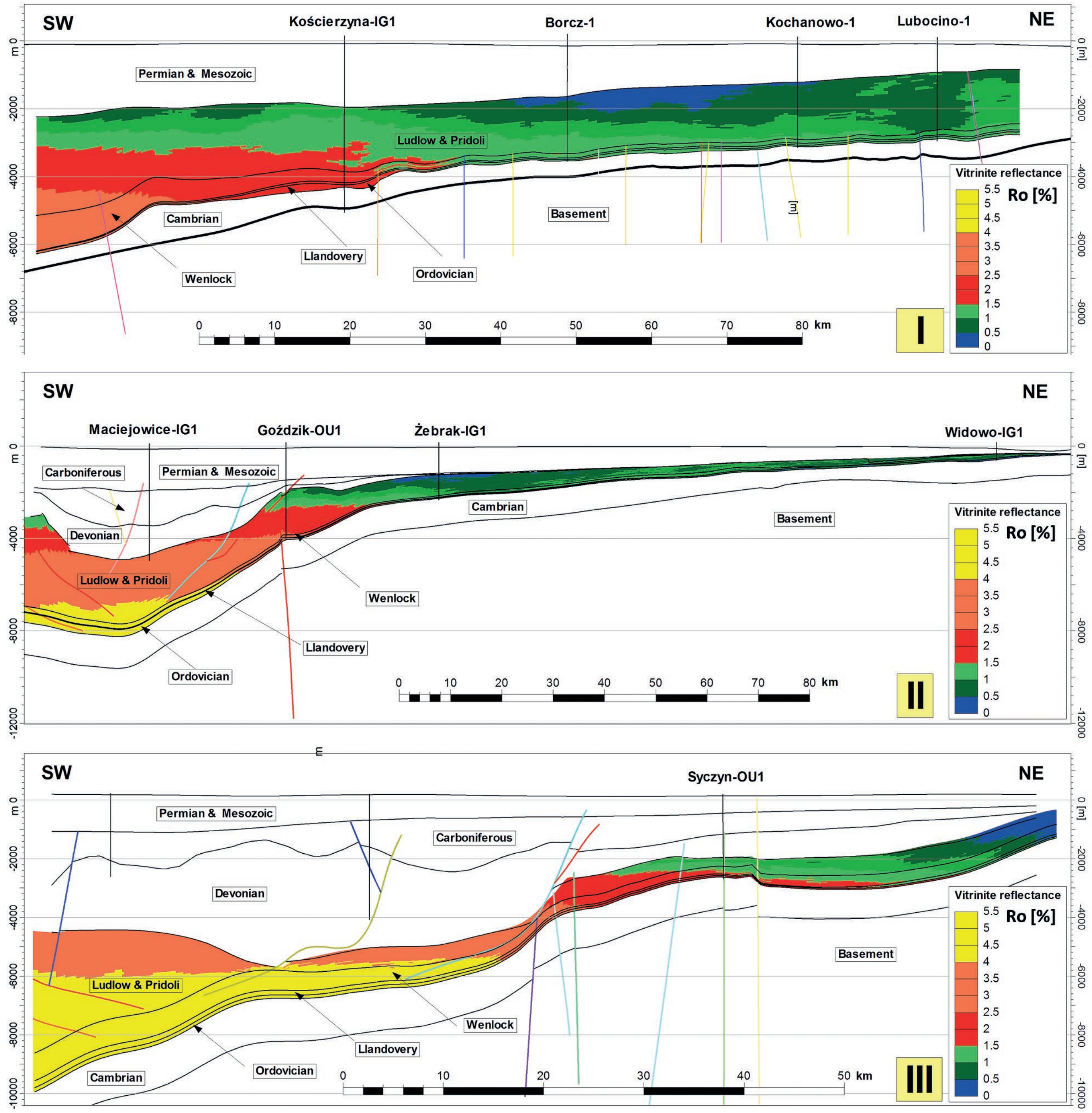

Fig. 6. Cross-sections showing the vitrinite reflectance of the Silurian and Ordovician deposits in (**I**) central Baltic Basin, (**II**) central Podlasie Basin and (**III**) through the Lublin Graben and Włodawa Depression in the Lublin Basin. The cross-sections are based on the 3D model of Ro.

TOC contents reach 6–8%. However, this value may be overestimated as the model is based on scattered laboratory measurements, derived from the legacy wells only. Net-pay thicknesses (up to 12 m in the Pęclin OU1 well) tend to be small. In the Lublin Basin, local sweet spots can be present near the Siedliska-IG1 well in the Łuków-Wisznió w Horst as well across the Włodawa Depression (Tab. 3; Figs 5, 13). The TOC content is up to 5.3%, whereas the thickness does not exceed 11 m. Core data indicate that the Jantar Formation in the southern Lublin Basin tends to form discontinuous, pod-like occurrences with the maximum thickness of source rocks not exceeding 4.5 m (Dziadzio *et al.*, 2017).

Pasłęk Formation

The common cm-scale intercalations of organic-poor, bioturbated mudstones among organic-rich mudstones lower the quality of potential source rocks in the Pasłęk Formation (Dziadzio *et al.*, 2017). A net-pay zone occupies an area of 5,800 km^2 and show thickness variations of up to 28 m and averaging 7 m (Fig. 12). The TOC is in the range of 1.5–5% and averages 1.85%. A small and low-quality prospective zone appears in the eastern part of the Baltic Basin in the Pasłęk-IG1–Henryków-1 and Kętrzyn-IG1 areas, where TOC and thickness attain 3.5% and 28 m, respectively. In the Lublin and Podlasie basins, potential sweet-spot zones are even less widespread. Their thickness reaches 10 m

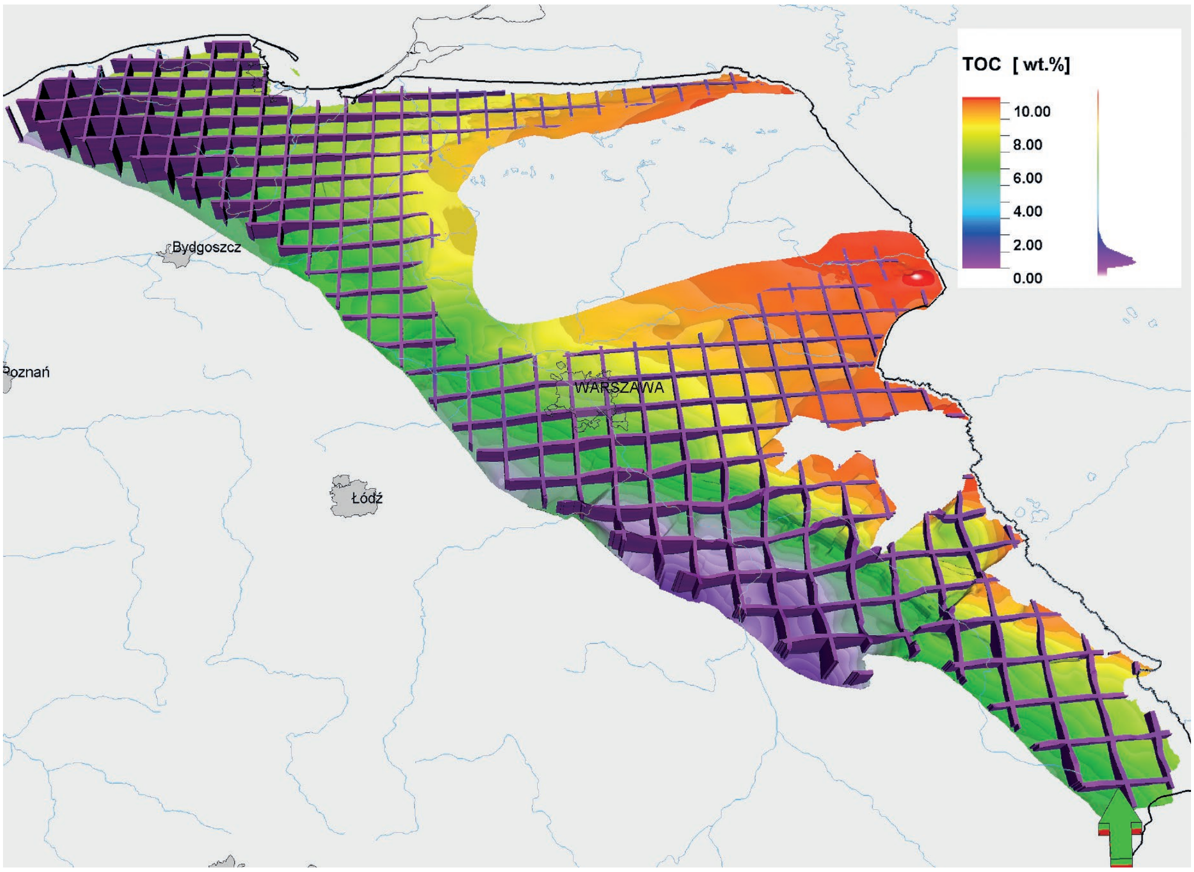

Fig. 7. Fence diagram showing the regional 3D model of total organic carbon distribution in Silurian and Ordovician strata of the study area.

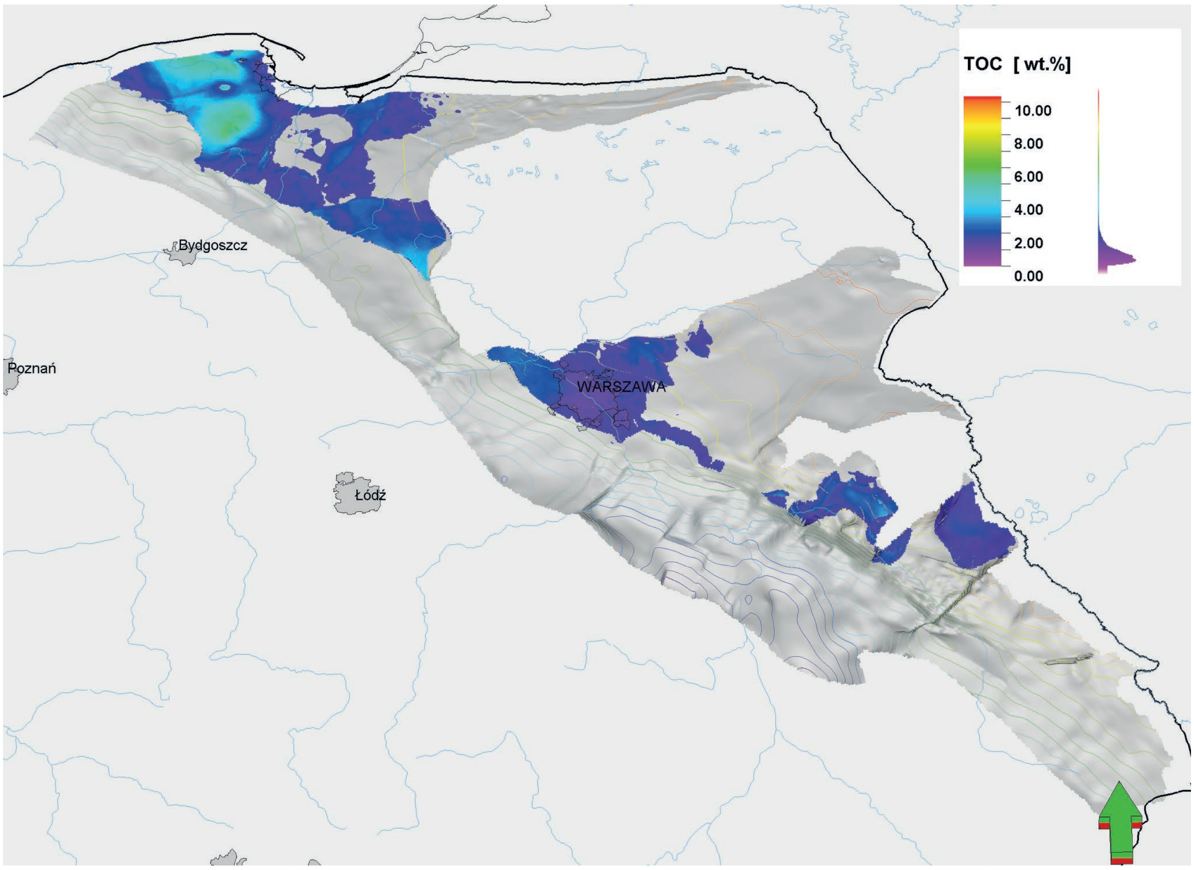

Fig. 8. Three-dimensional model of TOC content in the Sasino Formation (Llanvirn−Caradoc). The part of the model, where 0.6% $<R_o<$2.4%and TOC>1.5%, is displayed over the top-Cambrian surface.

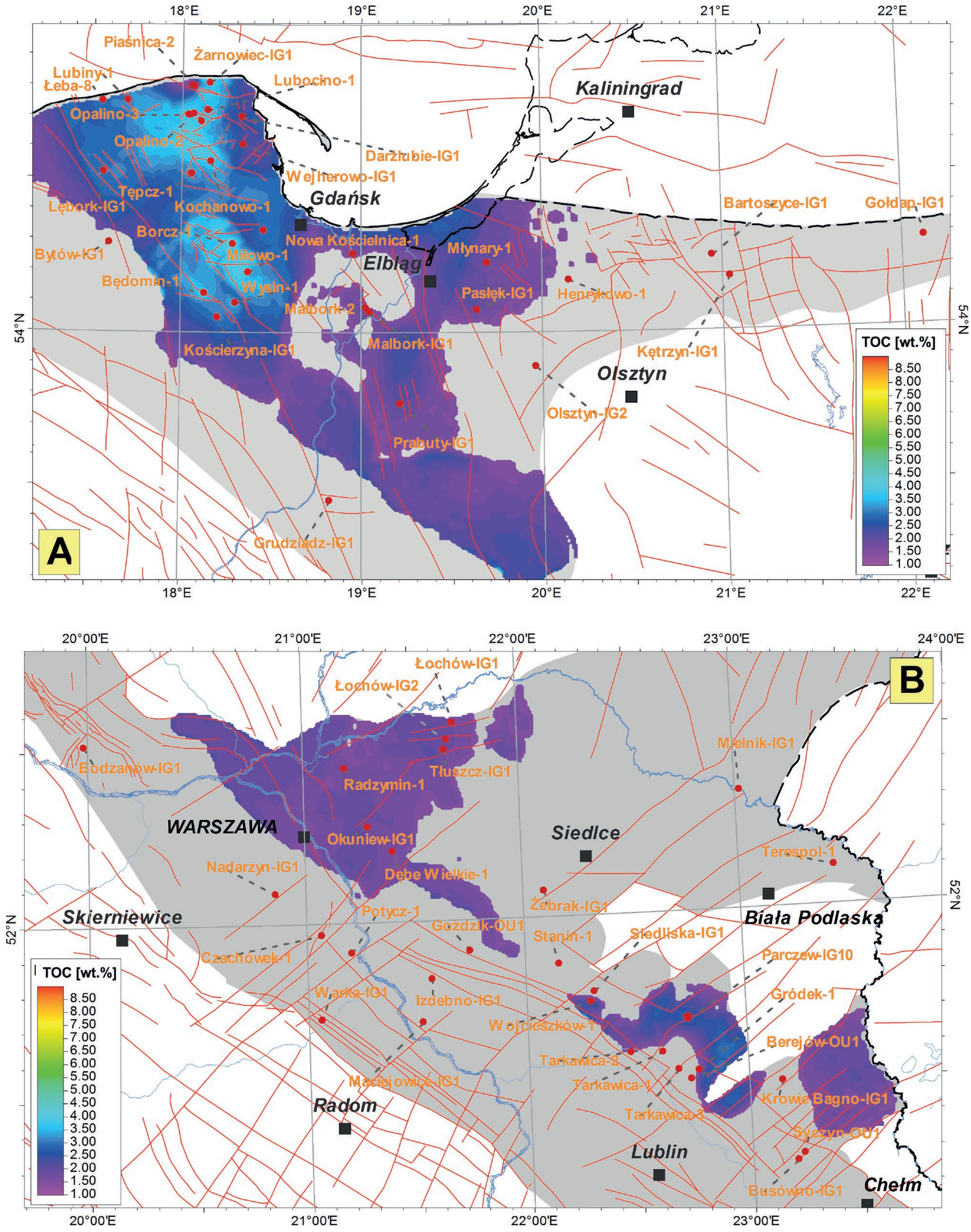

Fig. 9. Map showing the average TOC content [wt. %] in the Sasino Formation (Llanvirn–Caradoc) deposits in (**A**) the Baltic Basin and (**B**) the Lublin and Podlasie basins. Average TOC values were calculated for the model volumes, where 0.6% <R_o<2.4%and TOC >1.5%.

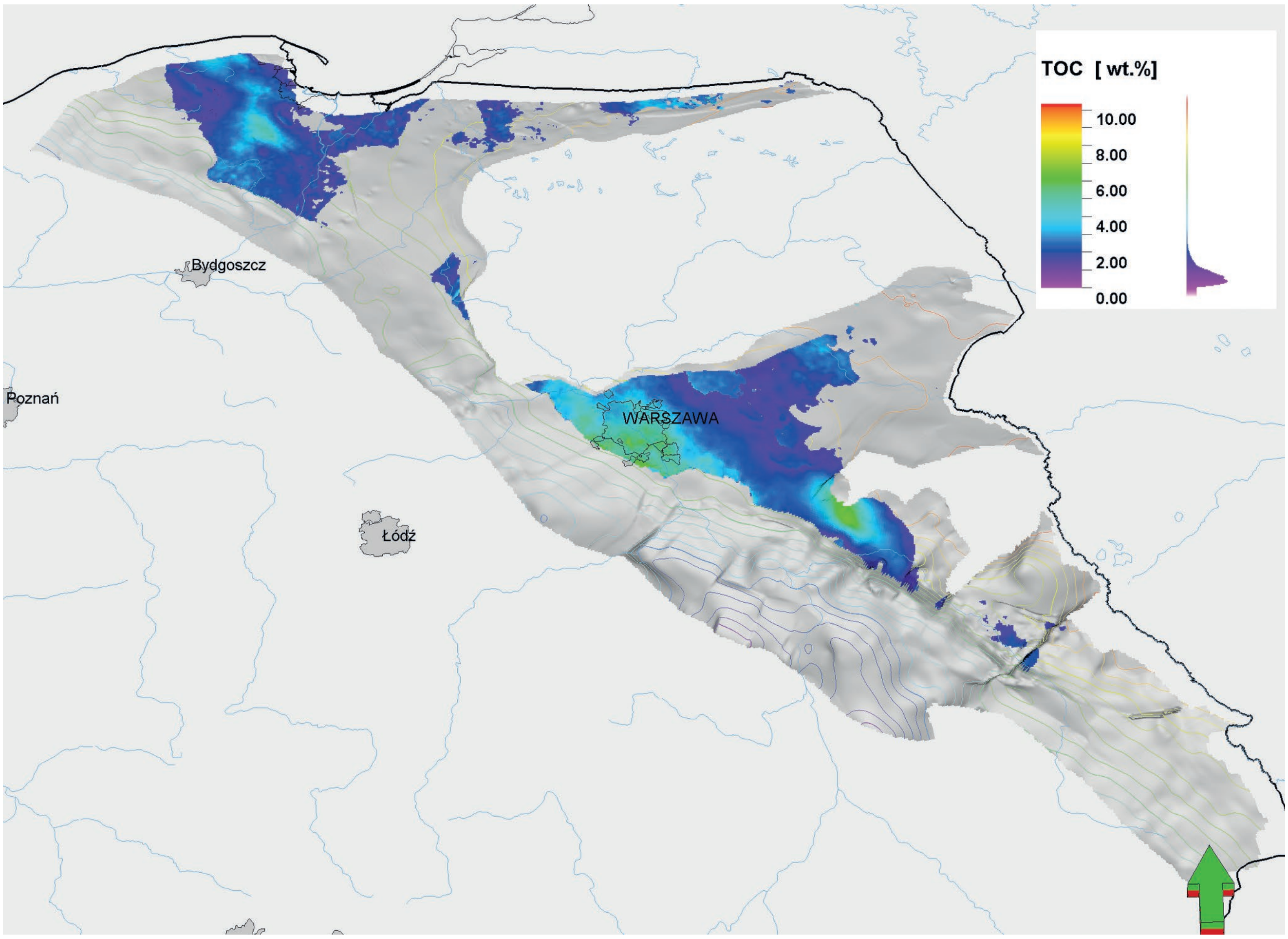

Fig. 10. Three-dimensional model of TOC content in the Jantar Formation (early Llandovery). The part of model, where 0.6% <Ro<2.4%and TOC> 1.5% displayed over the Cambrian top surface.

(the Łuków-Wiszniów Horst), whereas TOC generally does not attain 2% and displays a maximum of ~4% SE of the Tarkawica-2 well (Fig. 13).

Wenlock

Potential net-pay zones of Wenlock source rocks are essentially confined to the central part of the Podlasie and Lublin basins (Fig. 14), where these rocks belong to the Pelplin Formation. Local anomalies observed in the Baltic Basin are very small and they can be negligible. Sweet spots in in the former basins covers area of ca. 7500 km^2 that is centred in the Łuków-Wiszniów Horst and the Włodawa Depression (see Tab. 3; Fig. 5). The sweet-spot thickness here attains 150 m and averages ~40 m. The mean TOC content is ~1.75%; however, TOC values higher than 2.2% can be observed only in a narrow zone, extending between the Siedliska-IG1 and Gródek-1 wells (Fig. 15). In general, these sweet spots reveal poor-quality source rocks, which suffered from the significant dilution of organic matter by a terrigenous component. The only advantage of this location is the relatively high net thickness of potentially productive rocks.

Hydrocarbon expulsion

Botor *et al.* (2017b, 2019b) have shown that hydrocarbon expulsion from the Lower Palaeozoic strata of the EEC commenced already in the Silurian and lasted until the end of the Carboniferous. According to other works, generation phases continued even much later (e.g., Poprawa, 2010a, b). However, the late Variscan and Late Cretaceous inversion may have resulted in a considerable hydrocarbon loss (Poprawa, 2010a, b; Botor *et al.,* 2017a, b, 2019a, b); hence, the presence of large, unconventional reservoirs seems unlikely. In spite of this loss, the Ordovician and especially Silurian complexes of the EEC still contain huge quantities of dispersed gas (Papiernik *et al.*, 2017a, b). The highest potential for hydrocarbon retention exists in TOC-rich complexes, where considerable primary porosity, organic porosity and absorption properties can be expected (Papiernik *et al.*, 2017a, b; Botor *et al.*, 2017b). Unfortunately, the enormous dispersion of gas prevents exploitation of these deposits, using fracking methods that currently are applied.

It is worth emphasizing that the evaluation of the potentially prospective zones based on 3D integrated mod-

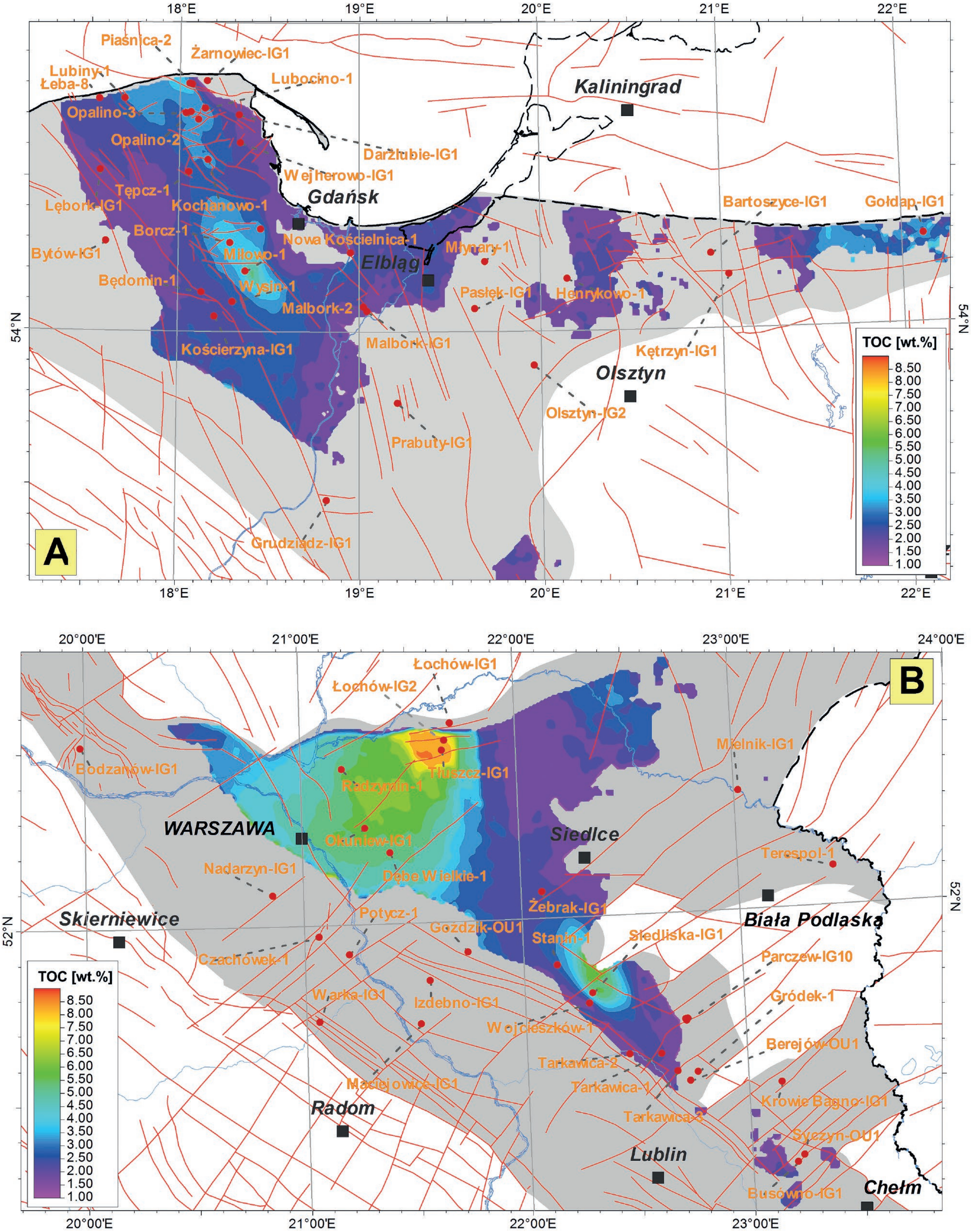

Fig. 11. Map showing the average TOC content [wt. %] in the Jantar Formation in (A) the Baltic Basin and (B) the Podlasie and Lublin basins. Average TOC values were calculated for the model volumes, where 0.6% <Ro<2.4%and TOC >1.5%.

elling of organic carbon content and thermal maturity is still in an early stage in the complex workflow required in any successful prospecting for unconventional hydrocarbon reservoirs. In particular, the TOC model of the present authors is based on relatively little input data and only eleven TOC-content logs acquired with the use of modern well-logging tools were available. In the case of upgrading from regional, basin-scale prospecting to the appraisal phase, a more credible evaluation of the quality and distribution of prospective zones requires the use of relevant data from all wells drilled in the area after 1990. Emphasis should be given to correlation between 3D seismic images and geophysical well-log data using different seismic inversion methods (e.g., Papiernik *et al.*, 2016; Vernik, 2016; Cichostępski *et al.*, 2017, 2019; Kasperska *et al.*, 2017, 2019). Moreover, gaining further, detailed insight into the complex relationships between petrophysical, geomechanical and hydrodynamic properties of gas-bearing mudrocks is the only way to develop new artificial-stimulation methods that would ensure commercial gas inflows from such reservoirs.

CONCLUSIONS

The new interpretation of vitrinite reflectance data indicated that the thermal maturity pattern of the Lower Palaeozoic strata of the East European Craton differs significantly from the gradual, west-increasing trend, advocated in earlier reports. This trend breaks into a series of domains, bounded by abrupt variations in maturity, which most likely occur across deep-rooted dislocations of regional extents. In total, 14 tectono-thermal domains have been distinguished in the segment of the EEC studied and their boundaries were traced to known and inferred faults.

On the basis of a combination of thermal maturity with total organic carbon content, good-quality, unconventional reservoirs can be expected in the Sasino Formation (Caradoc) and Jantar Formation (early Llandovery) in the central and western parts of the Baltic Basin. The Jantar Formation is likely to be prospective also in the western Podlasie Basin, although this conclusion is based on scarce input data. Marginal-quality reservoirs occur in in the Sasino and Jantar formations in the Podlasie and Lublin ba-

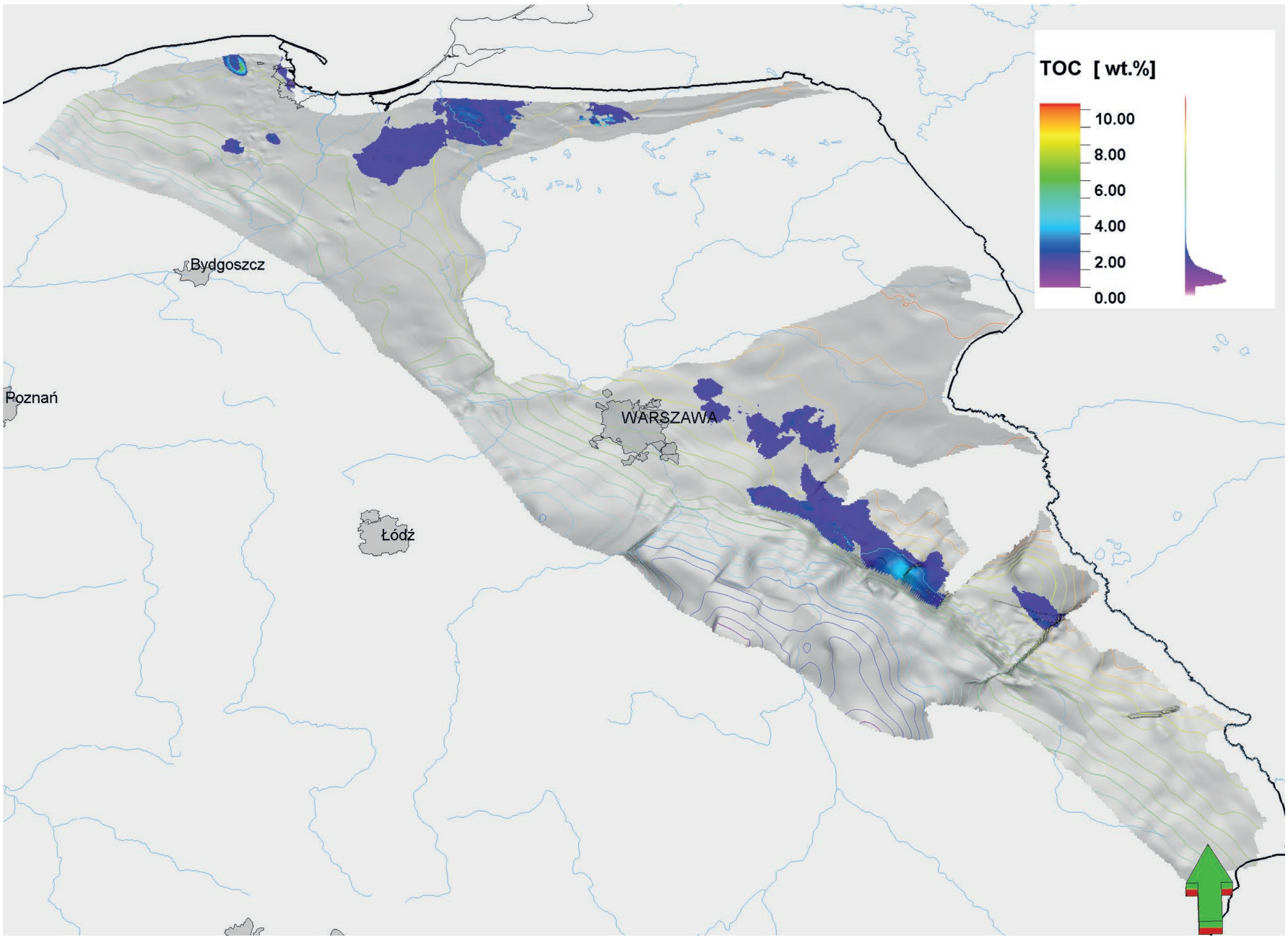

Fig. 12. Three-dimensional model of TOC content in the Pasłęk Formation (late Llandovery). The part of the model, where 0.6% <R_o<2.4%and TOC >1.5%, is displayed over the top-Cambrian surface.

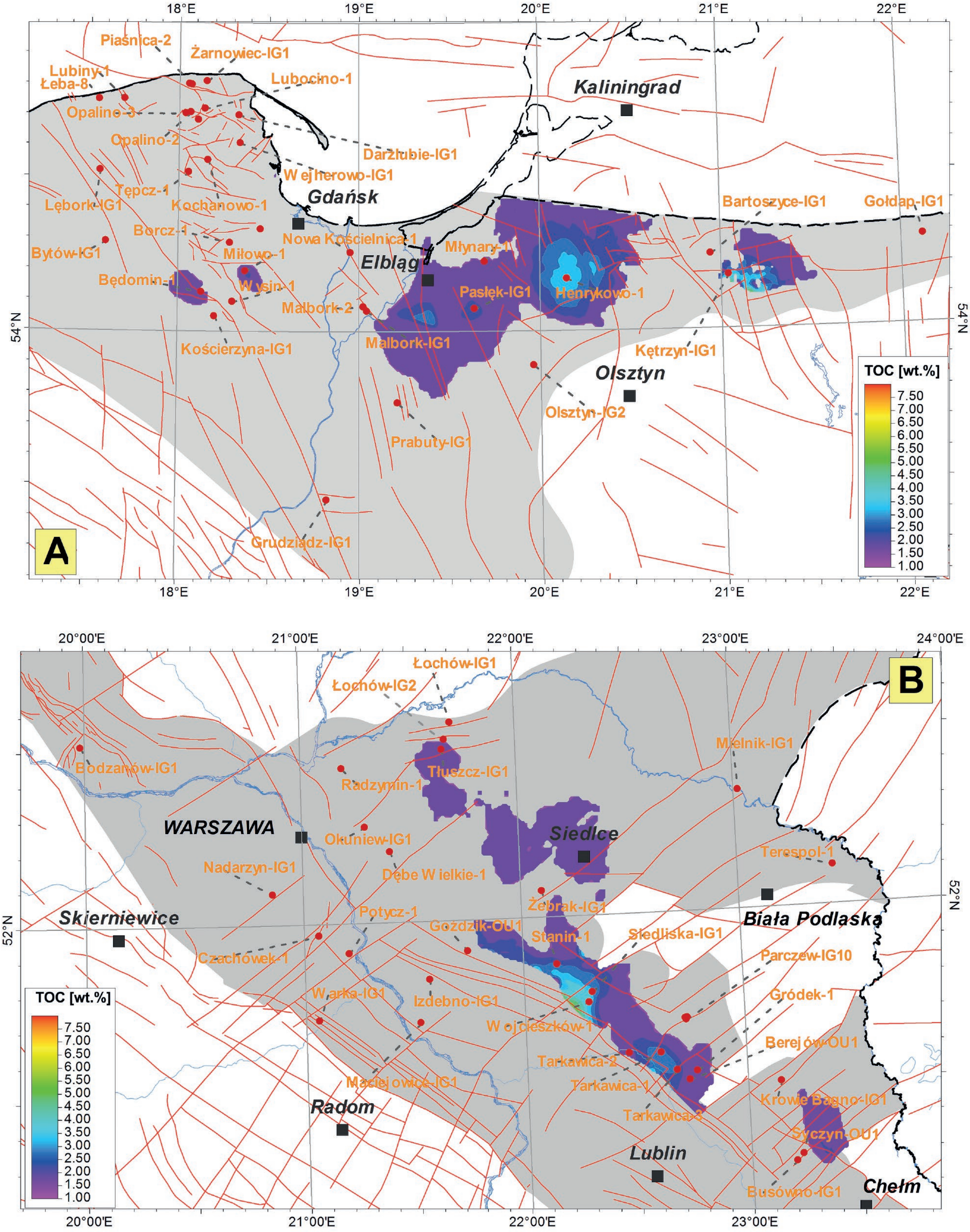

Fig. 13. Map showing the average TOC content [wt. %] in the Pasłęk Formation in (**A**) the Baltic Basin and (**B**) the Podlasie and Lublin basins. Average TOC values calculated for the model volumes, where $0.6\% < R_o < 2.4\%$ and TOC >1.5%.

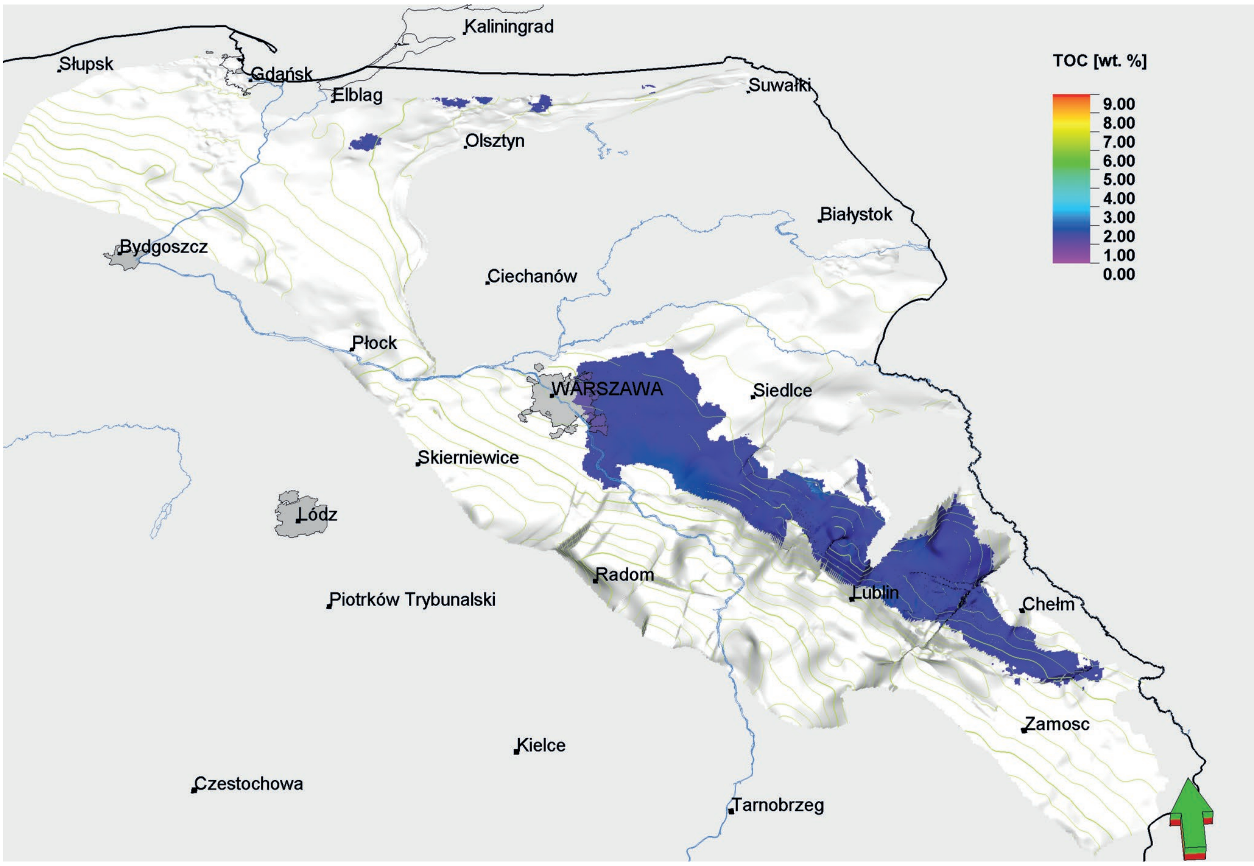

Fig. 14. Three-dimensional model of TOC content in the Wenlock deposits (Pelplin, Kociewie and Terespol formations, undifferentiated). The part of model, where 0.6% <R_o<2.4%and TOC >1.5%, is displayed over the top-Cambrian surface.

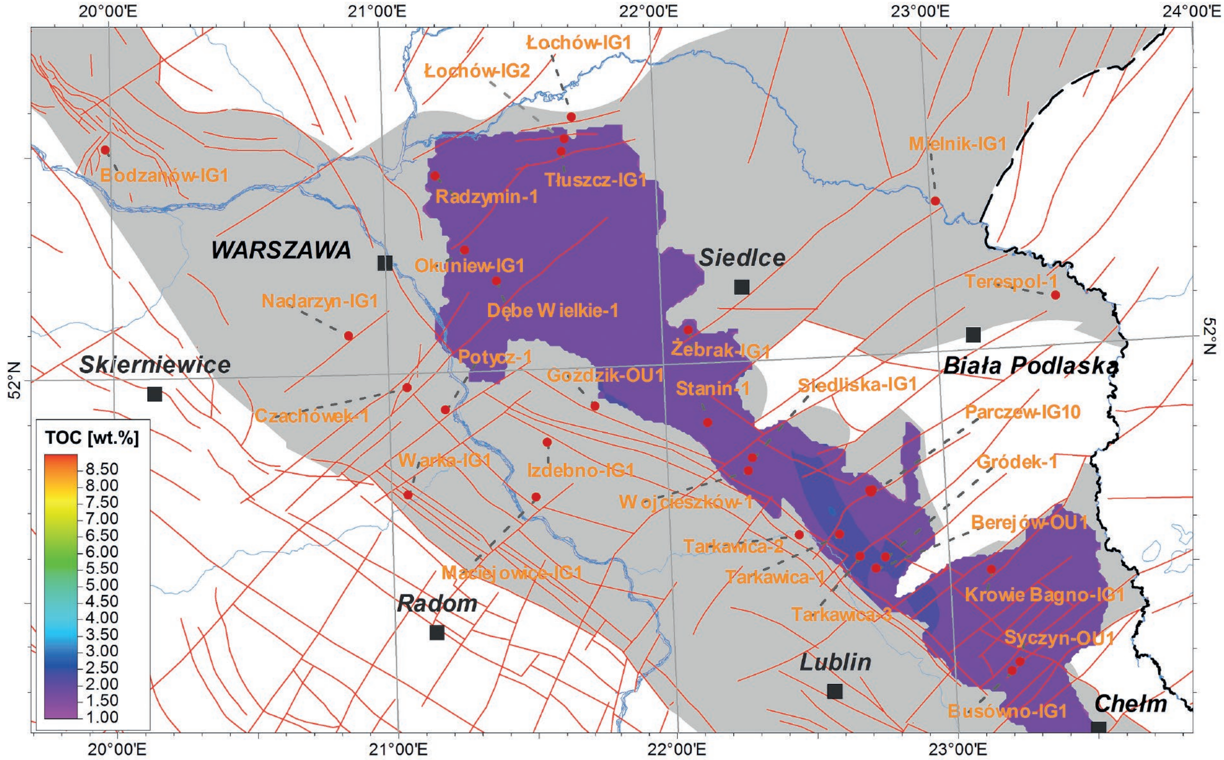

Fig. 15. Map showing the average TOC content [wt. %] in the Wenlock deposits (Pelplin, Kociewie and Terespol formations, undifferentiated) in the Lublin and Podlasie basins. Average TOC values were calculated for the model volumes, where 0.6% <R_o<2.4% and TOC >1.5%.

sins and the Pasłęk Formation (late Llandovery) across all basins. Poor- to moderate-quality reservoirs are likely to occur in the Wenlock (mainly Pelplin Formation) in the Lublin and southern Podlasie basins.

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