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BURIAL AND THERMAL HISTORY OF THE LOWER PALAEOZOIC PETROLEUM SOURCE ROCKS AT THE SW MARGIN OF THE EAST EUROPEAN CRATON (POLAND)

**Dariusz BOTOR[1]*, Jan GOLONKA[1], Aneta A. ANCZKIEWICZ[2], István DUNKL[3],
Bartosz PAPIERNIK[1], Justyna ZAJĄC[1] & Piotr GUZY[1]**

[1] *AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection,
al. Mickiewicza 30, 30-059 Kraków, Poland; e-mails: botor@agh.edu.pl,
jgolonka@agh.edu.pl, papiern@geol.agh.edu.pl, zajac@agh.edu.pl, guzy@agh.edu.pl*
[2] *Institute of Geological Sciences PAS, 31-002 Kraków, ul. Senacka 1, Poland; e-mail: ndstruzi@cyf-kr.edu.pl,*
[3] *Geoscience Centre, University of Göttingen, Goldschmidtstrasse 3, Göttingen D-37077,
Germany; e-mail: istvan.dunkl@geo.uni-goettingen.de*
** Corresponding author*

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Abstract: Thermal maturity modelling was carried out in over sixty wells along the SW margin of the East European Craton (EEC). The burial and thermal history modelling of the EEC, using thermochronological data, allowed the construction of burial history maps showing its geological development in the Phanerozoic. These results have proved that the Ordovician and Silurian source rocks occurring at the SW margin of the EEC reached a maximum palaeotemperature in the Palaeozoic, mainly during Devonian–Carboniferous time and at the latest during the Silurian in the most westerly part of this margin, along the Teisseyre-Tornquist Zone. In Mesozoic and Cainozoic time, the Ordovician and Silurian strata generally were subjected to cooling or to very minor heating, certainly below the Variscan level. The maximum burial and maximum temperature of the Ediacaran–Lower Palaeozoic strata were reached during the Early Carboniferous in the Baltic Basin and during the Late Carboniferous in the Lublin area, and even in the Early Permian in the SE corner of the Lublin Basin. Thus, the main period of maturation of organic matter and hydrocarbon generation in the Ordovician and Silurian source rocks was in the Late Palaeozoic (mainly Devonian–Carboniferous) and in the westernmost zone along the Teisseyre-Tornquist line at the end of the Silurian.

Key words: Maturity modelling, shale gas, shale oil, burial history, thermal history, Palaeozoic, East European Craton.

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INTRODUCTION

The assessment of the time-temperature histories of sedimentary basins is crucial for predicting the distribution and quality of petroleum, coal and even some metal deposits (e.g., Botor, 2014; Botor and Anczkiewicz, 2015; Botor *et al*., 2017a, b, c, d, e, 2018). Moreover, the assessment of petroleum generation and migration processes for exploration is based mainly on analysis of the subsidence, burial and thermal history of the sedimentary basin investigated. These are prerequisites of any petroleum analysis during exploration for both conventional and un-conventional hydrocarbon deposits. The second basic group of data comes from the quality of organic matter (e.g., Hunt, 1996; Hantschel and Kauerauf, 2009). In Poland, significant shale gas exploration potential occurs in the Ordovician and Silurian black shales of the East European Craton (Poprawa, 2010; Golonka *et al*., 2017; Golonka and Bębenek, 2017). These Lower Palaeozoic source rocks are characterized by diversified organic matter content as well as by thermal maturity in the range of the oil and gas windows (Botor, 1997; Kosakowski *et al*., 1998, 1999; Botor *et al*., 2002, 2017a, 2019; Klimuszko, 2002; Skręt and Fabiańska, 2009; Kosakowski *et al*., 2010, 2016; Pletsch *et al*., 2010; Poprawa, 2010; Więcław *et al*., 2010; Wróbel and Kosakowski, 2010; Podhalańska *et al*., 2016). The study area is situated on the southwestern margin of the East European Craton (EEC) in the onshore segment (Fig. 1).

The burial and thermal history of the Ediacaran–Lower Palaeozoic strata on the SW margin of the EEC is unclear, owing to significant hiatuses in the lithostratigraphic profile (Fig. 2) that allow various scenarios of petroleum generation (e.g., Majorowicz *et al*., 1983, 1984; Burzewski *et al*., 1998; Kosakowski *et al*., 1998, 2010; Botor *et al*., 2002, 2017d; 2019; Lazauskiene *et al*., 2002; Karnkowski, 2003a, b; Poprawa and Grotek, 2005; Wróbel *et al*., 2008; Poprawa *et al*., 2010; Poprawa and Żywiecki, 2005; Poprawa 2007b, c, 2008b, 2011b; Botor, 2016, 2018). Consequently, depending on the timing of petroleum generation, hydrocarbon resources could have had different chances of preservation until the present day.

Up to now, no thermochronological study has been carried out in this part of Poland. Particularly, there are no thermochronological data (e.g., fission tracks and/or helium dating of apatite /zircons) in the Polish part of the EEC that could allow the establishment of heating-cooling paths for a given rock. Two major thermochronological methods that are widely used are apatite fission track analysis (AFT) and apatite and zircon (U-Th)/He analysis (AHe, ZHe, respectively). The methods applied are effectively sensitive to the temperature range ca. 60–120 °C (AFT) and ca. 150–200 °C (ZHe) /ca. 40–70 °C (AHe); this allows the investigation of the final cooling periods of the rocks at shallow, crustal levels. A summary of these methods can be found in Reiners and Ehlers (2005) and Botor and Anczkiewicz (2010), while the laboratory details are given in Botor and Anczkiewicz (2015) and Botor *et al.* (2018).

However, some earlier papers give important clues on the thermal history of the SW margin of the EEC, but outside of Poland. Hansen (1995) presented an AFT study on Bornholm Island, documenting the Variscan overprint on the Lower Palaeozoic strata during the Carboniferous Period. Środoń and Clauer (2001) and Środoń *et al*. (2009) documented the diagenetic overprint due to heating in the Devonian–Early Carboniferous of the western part of the Baltic Basin. Środoń *et al*. (2013) also documented a Carboniferous heating event in Lower Palaeozoic data from Podolia (western Ukraine). In this paper, the present authors reveal the burial and thermal history of the EEC in the light of thermochronological data. However, a detailed thermochronological study of the SW margin of EEC area is to be published elsewhere; only the most important points related to thermal maturity modelling are presented here. The paper, here presented in English, is a significantly modified version of the book chapter by Botor *et al.* (2017e), so far available only in the Polish language.

METHODS

Maturity modelling was carried out using 1-D PetroMod ver. 11 software (Hantschel and Kauerauf, 2009). The modelling employed data on the burial history, comprising the

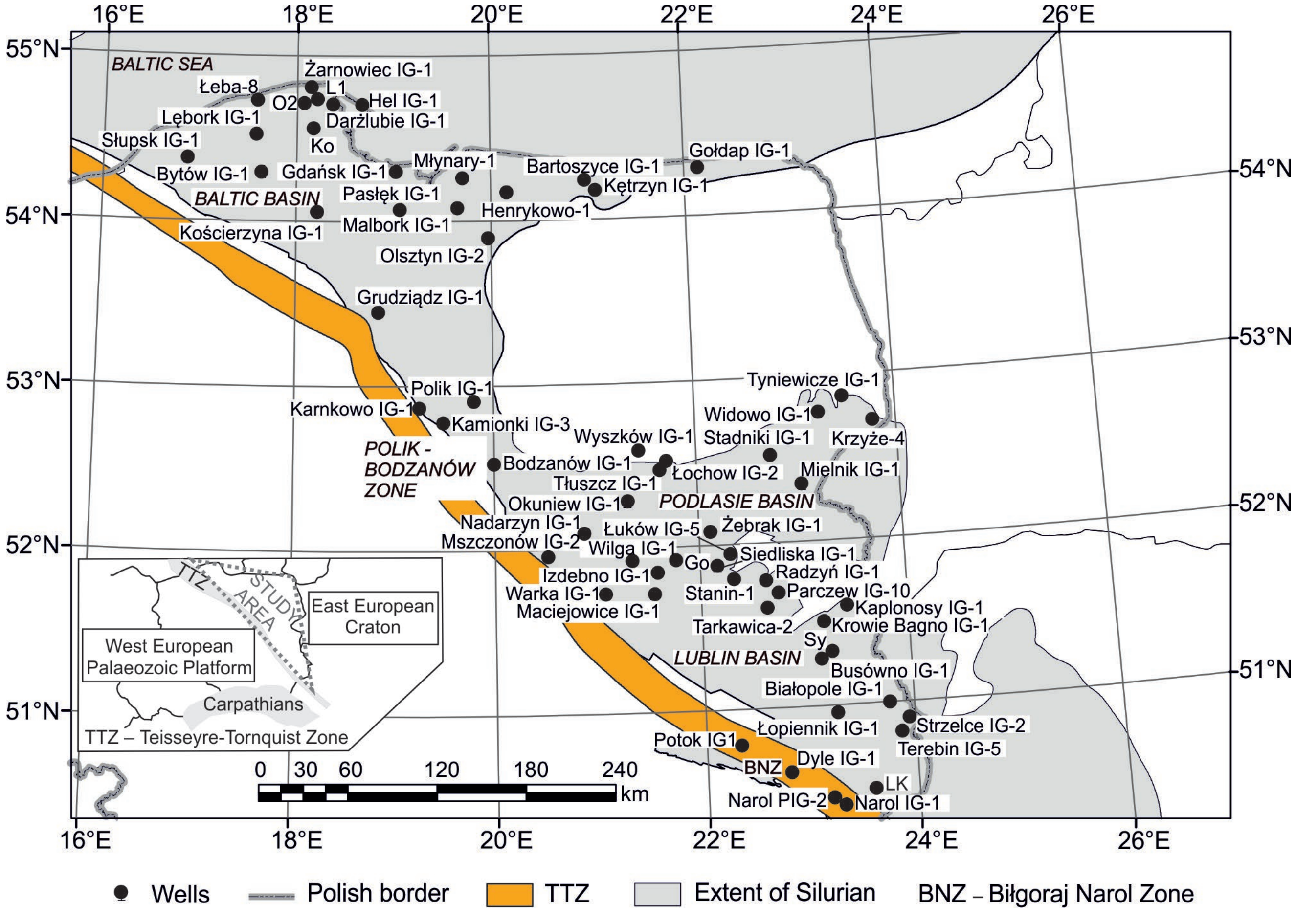

Fig. 1 Location maps of wells analysed on the SW slope of the East European Craton.

stratigraphy and thicknesses given in each well as petrophysical parameters for a particular lithology as well as the present temperature and thermal maturity. The development of maturity was calculated using the forward method, i.e. first the initial state of the system and definite, geological processes were assumed and then their effect on the pattern of thermal maturity in the well profile was determined. If discordance between calculated and measured maturity values occurred, then the procedure was performed again for changed parameters, until an optimum calibration was obtained. The petrophysical properties of the different lithologies employed in the modelling are given in Tab. 1. In the models of the present authors, thermal maturity was calculated, following the "Easy%R_o" method (Sweeney and Burnham, 1990). Further details of the methods are given by e.g., Botor and Kosakowski (2000) and Hantschel and

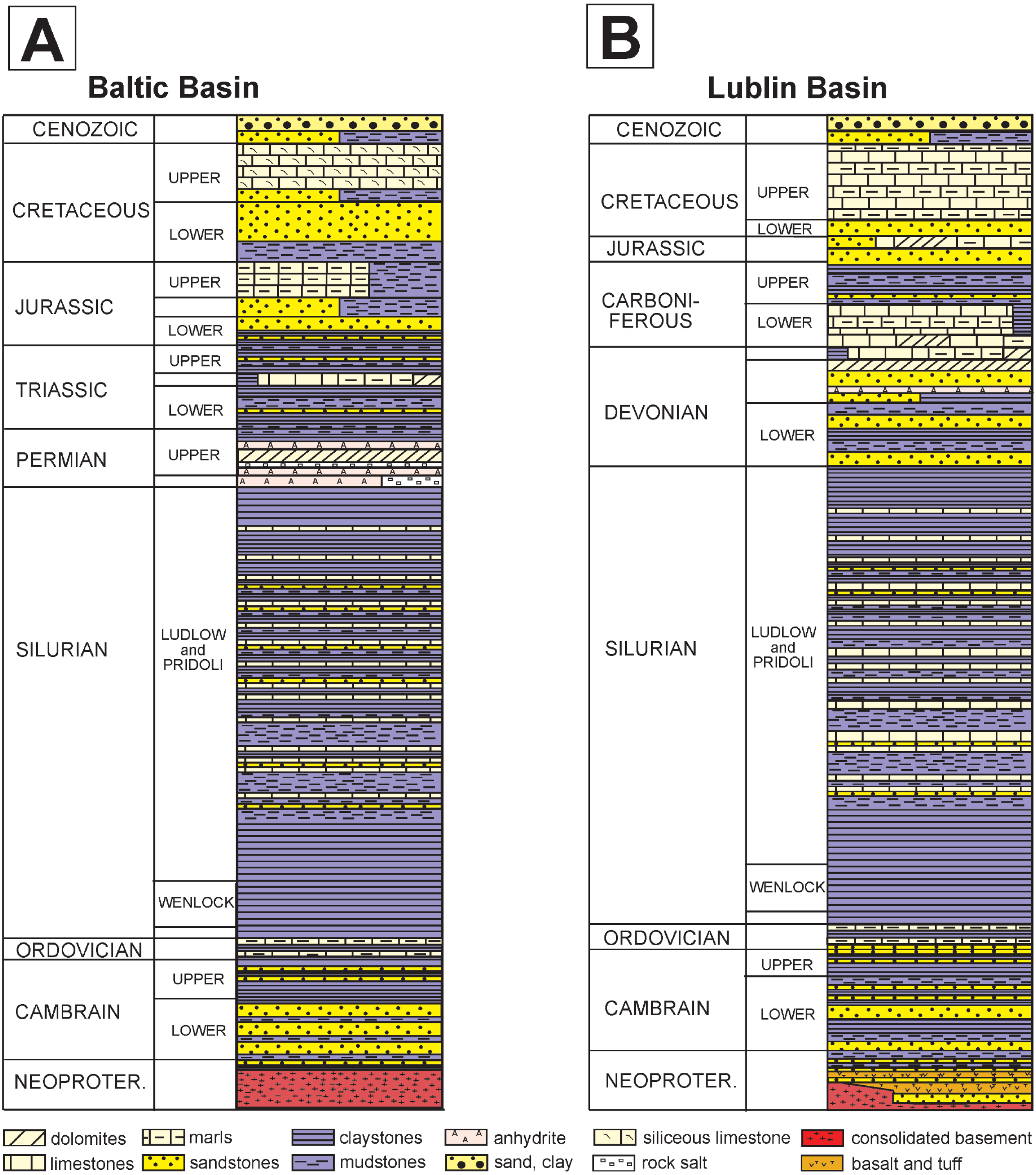

Fig. 2. Simplified lithostratigraphic profiles for the Baltic Basin (**A**) and the Lublin Basin (**B**). Modified after various sources, including Żelichowski (1987), Dadlez *et al.* (1995), Porzycki and Zdanowski (1995), Marek and Pajchlowa (1997), Botor *et al.* (2002), Matyja (2006), Podhalańska and Modliński (2006), Poprawa (2010), and Waksmundzka (2010).

Table 1.

Petrophysical properties of different types of lithologies used in this modelling.

Lithology	Density (g/cm^3)	Compressibility (1/Pa)		Thermal conductivity (W/mK)		Heat capacity (cal/gK)	
		Minimum	Maximum	at 20 °C	at 100 °C	at 20 °C	at 100 °C
DOLOMITE	2.836	10	250	3.81	3.21	0.202	0.229
EVAPORITE	2.540	1	10	4.69	3.91	0.194	0.210
EVAPshaly	2. 585	10	100	3.87	3.31	0.200	0.221
LIMEdolom	2.752	10	180	3.18	2.82	0.198	0.226
LIMEmarly	2.707	10	300	2.63	2.41	0.201	0.235
LIMEsandy	2.695	20	700	2.93	2.62	0.190	0.219
LIMEshaly	2.700	10	550	2.51	2.31	0.203	0.237
LIMESTONE	2.710	10	150	2.83	2.56	0.195	0.223
MARL	2.687	10	940	2.23	2.11	0.208	0.248
SALT	2.160	1	4	5.69	4.76	0.206	0.212
SAND&LIME	2.685	15	400	2.93	2.54	0.186	0.215
SAND&SHALE	2.669	10	2800	2.65	2.38	0.197	0.236
SAND&SILT	2.665	10	1900	2.59	2.31	0.192	0.229
SANDcongl	2.663	10	330	2.93	2.63	0.184	0.217
SANDshaly	2.666	10	1400	2.78	2.37	0.190	0.226
SANDsilty	2.664	10	1200	2.97	2.64	0.188	0.223
SANDSTONE	2.660	10	500	3.12	2.64	0.178	0.209
SHALE	2.680	10	60000	1.98	1.91	0.213	0.258
SHALE&LIME	2.695	20	1500	2.39	2.24	0.208	0.246
SHALE&SAND	2.669	10	2800	2.65	2.38	0.197	0.236
SHALE&SILT	2.674	10	13000	2.09	1.97	0.207	0.251
SHALEcalc	2.688	10	5000	2.22	2.09	0.208	0.248
SHALEcarb	2.655	10	45000	1.50	1.43	0.212	0.258
SHALEcoal	2.474	10	16500	1.80	1.60	0.202	0.244
SHALEevap	2.630	10	7000	2.93	2.61	0.210	0.247
SHALEsand	2.674	10	9000	2.32	2.12	0.205	0.248
SHALEsilt	2.677	10	25000	2.05	1.94	0.210	0.254
SILT&SAND	2.665	10	1900	2.59	2.31	0.192	0.229
SILT&SHALE	2.674	10	13000	2.09	1.97	0.207	0.251
SILTsandy	2.666	10	3000	2.55	2.33	0.192	0.230
SILTshaly	2.675	10	15000	2.09	1.98	0.203	0.245
SILTSTONE	2.672	10	8000	2.14	2.03	0.201	0.242

In lithology types the following system was applied for abbreviations: LIMEdolom (first lithology in upper case and second in lower case): 70% limestone and 30% of dolomite; SAND&SHALE (both lithologies in upper case): 50% sandstone and 50% shale.

Kauerauf (2009). Published thermal maturity data were used for calibration of the models: vitrinite reflectance and organic particle reflectance in the case of the Lower Palaeozoic strata (Nehring-Lefeld *et al*., 1997; Grotek, 1998, 1999, 2005, 2006, 2015, 2016; Grotek *et al*., 1998; Swadowska and Sikorska, 1998), and Tmax from Rock-Eval pyrolysis (Kosakowski *et al*., 1998, 2010; Matyasik, 1998; Botor *et al*., 2002; Skręt and Fabiańska, 2009; Pletsch *et al*., 2010). Additionally, the present-day temperatures in boreholes were applied (Plewa, 1991, 1994; Górecki *et al*., 2006a, b).

GEOLOGICAL SETTING

The study area is located on the SW slope of the EEC, where the following geological units can be distinguished: the Baltic Basin in the northern part and Podlasie-Lublin Basin in the south (Fig. 1). Between them, there is the Polik-Bodzanów Zone, the geological history of which is not yet known in detail (e.g., Narkiewicz, 2007; Golonka and Bębenek, 2017; Golonka *et al*., 2017). The EEC margin is limited by the Teisseyre-Tornquist Zone (TTZ) (Fig. 1;

e.g., Guterch and Grad, 2006; Mazur *et al*., 2015, 2018). In NE Poland, which is the study area of this work, Neoproterozoic, Palaeozoic, Mesozoic and Cainozoic strata occur above the Precambrian crystalline basement (Fig. 2; e.g., Nawrocki and Poprawa, 2006; Modliński, 2010). The thickness of the Ediacaran to Lower Palaeozoic section increases towards the west. An extensive system of basins, defined as the peri-Tornquist Ocean basins, developed on the SW margin of the EEC (from Scandinavia to the Black Sea area) in Neoproterozoic to Early Palaeozoic time (Šliaupa *et al*., 1997, 2006; Poprawa *et al*., 1999; Nawrocki and Poprawa, 2006). The development of these basins was closely related to the tectonic processes occurring west of the EEC margin that is presently located in the Trans-European Suture Zone (TESZ, Torsvik *et al*., 1990, 1993, 1996; Oliver *et al*., 1993; Meissner *et al*., 1994; Nikishin *et al*., 1996; Tanner and Meissner, 1996; Maletz *et al*., 1997; Šliaupa *et al*., 1997, 2006; McCann, 1998; Poprawa *et al*., 1999; Poprawa, 2006a, b, 2017). During the Late Neoproterozoic–early Cambrian, rifting processes developed along the entire SW margin of the EEC. Rifting was documented by (1) tectonic subsidence curves, in which subsidence syn-rift phase was clearly visible, (2) rift magmatism, and (3) extensional tectonic grabens (Nikishin *et al*., 1996; Šliaupa *et al*., 1997, 2006; Poprawa *et al*., 1999; Lassen *et al*., 2001; Poprawa and Pacześna, 2002; Poprawa, 2017; Krzywiec *et al*., 2018). Almost contemporaneous rifting along the Orsza-Wołyń Zone resulted in the development of a triple junction in the Podlasie-Lublin Basin (Poprawa and Pacześna, 2002). In the post-rift stage, the SW margin of the newly formed Baltica continent, became a passive margin (Nikishin *et al*., 1996; Poprawa *et al*., 1999, 2018; Poprawa, 2006a, b, 2017). The post-rift phase is documented by a decreasing rate of tectonic subsidence, facies development, and lateral expansion of the basin (Šliaupa *et al*., 1997, 2006; Pacześna, 2006; Poprawa *et al*., 1999, 2018; Poprawa, 2006a, b, 2017).

In the Late Ordovician and Silurian, a systematic increase in subsidence rate occurred, creating convex-type subsidence curves which are typical for the foreland basin stage (Nikishin *et al*., 1996; Šliaupa *et al*., 1997, 2006; Poprawa *et al*., 1999, 2018; Poprawa and Pacześna, 2002; Mazur *et al*., 2016) also supported by seismic data interpretation (e.g., Krzywiec *et al*., 2014). Therefore, the Silurian development is assumed to have been a flexural foredeep, caused by the formation of the Caledonian collision zone. (Poprawa, 2006a, b). The diachroneity of the foredeep basin development along the SW margin pf Baltica is consistent with a model of oblique collision of Avalonia and Baltica (Poprawa, 2017; Poprawa *et al*., 2018; Mazur *et al*., 2016, 2018). This is documented by tectonic subsidence curves, the asymmetric geometry of basin, which was a regional flexure towards west, adherent to the Caledonian collisional zone, the very high maximum rate of accumulation of detrital material, and locally also sedimentary onlap of the structure along western margin of the EEC (Šliaupa *et al*., 1997; Poprawa *et al*., 1999, 2018; Poprawa, 2006a, b, 2017; Šliaupa *et al*., 2006). In the Ediacaran to Early Palaeozoic, the extent of Baltica was much further towards west than the present-day TTZ, which is supported by gravimetric and seismic studies as well as clastic provenance characteristics (Krzemiński and Poprawa, 2006; Mazur *et al*., 2015, 2016; Krzywiec *et al*., 2018). The Ediacaran to earliest Devonian sedimentary cycle was terminated with an erosional event, which is seen as a regional unconformity. The Devonian to Carboniferous subsidence of the SW part of the EEC is documented in the Podlasie-Lublin Basin (Żelichowski, 1987; Narkiewicz *et al*., 1998, 2007, 2011, 2015;Narkiewicz, 2007; Narkiewicz and Narkiewicz, 2008; Krzywiec, 2009; Krzywiec *et al*., 2017a, b), whereas in the Baltic Basin, it is assumed on the basis of comparison to adjacent areas (Narkiewicz *et al*., 1998; Matyja, 2006; Podhalańska and Modliński, 2006). Generally, the foreland basin entered a shallow-marine and a continental stage during the Early Devonian. Taking into account the facies development of the Devonian to Lower Carboniferous strata in the Koszalin-Chojnice Zone (Trans-European Suture Zone), as well as in the strata of the eastern part of the Baltic Basin including Lithuania and Latvia, the presence of strata of the same age in the study area might be assumed. However, such Devonian strata exist at the present day in the Podlasie-Lublin Basin, where they are covered by the Viséan–Westphalian carbonate-siliciclastic sequence. In the Baltic Basin, the Devonian to Lower Carboniferous deposits, were completely removed, whereas in the Podlasie-Lublin Basin, partially removed during late Variscan (late Carboniferous to Early Permian) uplift and erosion, caused mainly by tectonic stress induced by strike-slip translation and/or collisions in the Trans-European Suture Zone (Żelichowski, 1987; Narkiewicz *et al*., 1998, 2011, 2015; Narkiewicz, 2007; Narkiewicz and Narkiewicz, 2008; Krzywiec, 2009; Krzywiec *et al*., 2017a, b; Tomaszczyk and Jarosiński, 2017).

In the Lublin Basin, Bretonian (Early Carboniferous) faulting caused exhumation of up to 2–3 km of strata (Krzywiec, 2009; Krzywiec *et al*., 2017a). During the Tournaisian to early Viséan, an erosional and non-depositional regime predominated in the entire Lublin Basin, resulting in the removal of up to 1.5 km of Devonian strata and even partially the Lower Palaeozoic successions (Narkiewicz, 2007). In the Lublin Basin, the late Viséan sedimentary-tectonic cycle was preceded by the extrusion of laterally discontinuous, volcanic rocks of basaltic composition, locally up to 200 m thick (Grocholski and Ryka, 1995), that have yielded K-Ar ages of 348–338 Ma (Pańczyk and Nawrocki, 2015). During the late Viséan, a carbonate-clayey shelf sequence, 50 to 200 m thick, onlapped NE-wards the Bretonian unconformity (Skompski, 1998; Narkiewicz, 2007). The Viséan sequence continuously changed in the early Namurian into paralic-system cyclothems, comprising mostly siliciclastic shallow-marine to deltaic and fluvial facies, containing subordinate limestone and coal horizons (Porzycki and Zdanowski, 1995; Skompski, 1998; Waksmundzka, 1998, 2005, 2010). This succession attains a maximum thickness of 600 m near the SW margin of the Lublin Trough, particularly in its central and SE segment, whereas towards the NE it thins across the Kock Fault Zone and wedges out beyond it (Narkiewicz, 2007). During the Westphalian, the depocentre was in the NW part of the Lublin Basin and extended further NW-wards. The Namurian B to Westphalian C (D?) succession includes coal-bearing cyclothems, composed of alluvial clastic deposits with an upward-decreasing proportion of deltaic-marine facies. Its thickness decreases from up to 1,500 m in the axial NW part of the basin to ca. 600 m in SE part (Żelichowski, 1987; Porzycki and Zdanowski, 1995; Waksmundzka, 2010). Following deposition of shallow-marine-deltaic and continental coal-bearing sediments (Viséan to Westphalian D), latest Carboniferous Variscan compression significantly deformed the entire sedimentary cover and resulted in the development of the easternmost segment of the Variscan fold-and-thrust belt (Krzywiec *et al*., 2017a, b). A basal detachment of the Variscan thin-skinned frontal thrust belt was located at the base of the Silurian shales, hence the Neoproterozoic-Ordovician succession was not deformed (Krzywiec *et al*., 2017a, b).

Late Variscan (latest Carboniferous, Westphalian D–Stephanian) tectonic inversion led to extensive erosion and the formation of a regional unconformity (e.g., Lamarche *et al*., 2003; Narkiewicz, 2007; Narkiewicz *et al*., 2010), above which the Permian–Mesozoic succession of the Polish Basin was deposited (e.g., Kutek and Głazek, 1972; Dadlez *et al*., 1995; Kutek, 2001; Lamarche *et al*., 2003). Permian–Mesozoic thickness increases towards the west and SW. Finally, the Polish Basin was inverted in the Late Cretaceous–Palaeogene, but the area of EEC margin was not influenced by significant inversion-related tectonic movements (Krzywiec, 2002; Lamarche *et al*., 2003; Mazur *et al*., 2005; Scheck-Wenderoth *et al*., 2008; Krzywiec, 2009). The uppermost part of the sedimentary section is composed of varied, poorly consolidated Cainozoic deposits of very minor thickness.

PETROLEUM SYSTEMS AND SOURCE ROCKS

In the study area in the Polish part of the EEC area, petroleum system elements are related only to the Palaeozoic strata. In the Baltic Basin, middle Cambrian sandstones represent major reservoirs of conventional oil and gas deposits, which are exploited in the central offshore part of the Polish Baltic Basin, whereas in the Lublin Basin, both Devonian carbonates and sandstones in Carboniferous reservoirs are producing (Karnkowski, 1993, 2007; Helcel-Weil *et al*., 2007; Pletsch *et al*., 2010). In the Lublin Basin, hydrocarbon accumulations (mainly gas) are found in a northwest–southeast-trending zone of anticlinal structures along the basin axis. Structural, fault-related traps formed mainly during the latest Carboniferous. The main reservoirs are Namurian fluvial sandstones with porosities of 1–22%, and permeabilities of 1–400 mD, which are sealed by interdistributary, fine-grained sediments, prodelta shales and marine bands (Pletsch *et al*., 2010). In the Devonian carbonates and sandstones, several gas fields and one oil field were discovered (Pletsch *et al*., 2010). However, the petrophysical properties of the Palaeozoic rocks on the EEC vary significantly (e.g., Krakowska, 2017).

Excellent petroleum source rocks are widely known on the SW slope of the EEC (Pletsch *et al.,* 2010). Oil-prone, low-sulphur type-II kerogen occurs in all Lower Palaeozoic strata in the Polish part of the Baltic Basin and the Podlasie-Lublin Basins (Pletsch *et al*., 2010; Poprawa, 2010; Więcław *et al*., 2010; Kosakowski *et al*., 2016; Podhalańska *et al*., 2016). In Poland, in the Baltic Basin, the best source-rock parameters are documented in the upper Cambrian–Tremadocian Alum Shale Formation, which is represented by black shales with a high total organic carbon (TOC) content of up to ca. 20%. However, their thickness varies significantly (usually below 10 m) and their extent is very limited. The next section of organic-rich (1–3%) strata is the Upper Ordovician, mainly Caradocian shale (Sassino Formation), with its thickness increasing towards the west up to ca. 40 m. The Llandovery shales (including the Jantar Member) are the most important source-rock horizon in the Silurian section with thickness ranging between 20–70 m and a general tendency to increase westwards. The highest measured TOC content reaches 20%, while the average present-day TOC contents within the Llandovery shale usually equal 1–3%. Sedimentation of fine-grained material continued during the Wenlock, Ludlow and Pridoli; however, the proportion of mudstone, marl and even sandstone increased with time and is higher up-section. The thickness of the Wenlock section significantly varies laterally from less than 100 m in the eastern part of the Baltic Basin to more than 1,000 m in the western part. The average TOC content is within the range of ca. 1–2%. In the Polish part of the EEC, the recent burial depth of the Upper Ordovician – Lower Silurian shales increases from approximately 1,000 m in its eastern part to more than 4,500 m in its western part (Pletsch *et al*., 2010; Poprawa 2010; Więcław *et al*., 2010; Kosakowski *et al*., 2016; Podhalańska *et al*., 2016).

The thermal maturity of the Ediacaran-Mesozoic strata of the SW margin of the EEC was investigated so far by reflectance of organic particles (in the Ediacaran to Silurian strata) and vitrinite reflectance (R_o), Rock-Eval Tmax, conodont colour alteration index (CAI) and Thermal Alteration Index (Drygant, 1993; Kanev *et al*., 1994; Nikishin *et al*., 1997; Grotek, 1998, 1999, 2005, 2006, 2015, 2016; Grotek *et al*., 1998; Kosakowski *et al*., 1998, 1999, 2013, 2016; Botor *et al*., 2002; Zdanavièiûtë, 2005; Zdanavièiûtë and Lazauskiene, 2007; Skręt and Fabiańska, 2009; Poprawa, 2010; Więcław *et al*., 2010 Stempień-Sałek, 2011). However, determination of the thermal maturity of organic matter by means of a microscope technique for the Ediacaran and Lower Palaeozoic shales is difficult since these sediments do not contain true vitrinite, which did not exist prior to the Devonian (e.g., Taylor *et al*., 1998). Therefore, thermal maturity measurements are widely conducted on vitrinite-like organic particle (VLR_o), mainly zooclasts (e.g., graptolites), as well as on solid bitumen and alginate, which leads to greater uncertainty in assessments of thermal maturity for pre-Devonian strata. Petersen *et al*. (2013) performed reflectance measurements on zooclasts (graptolites, chitinozoans and vase-shaped microfossils) and other organic particles (vitrinite-like particles, porous/granular vitrinite-like particles, and solid bitumen) in the middle Cambrian - Upper Silurian shales of central and southern Sweden and Bornholm Island in the Baltic Sea (Denmark). The most abundant organic components in all shales were fragments of graptolites and vitrinite-like particles. The reflectance distribution of these two types of component is largely identical and it is suggested that the vitrinite-like

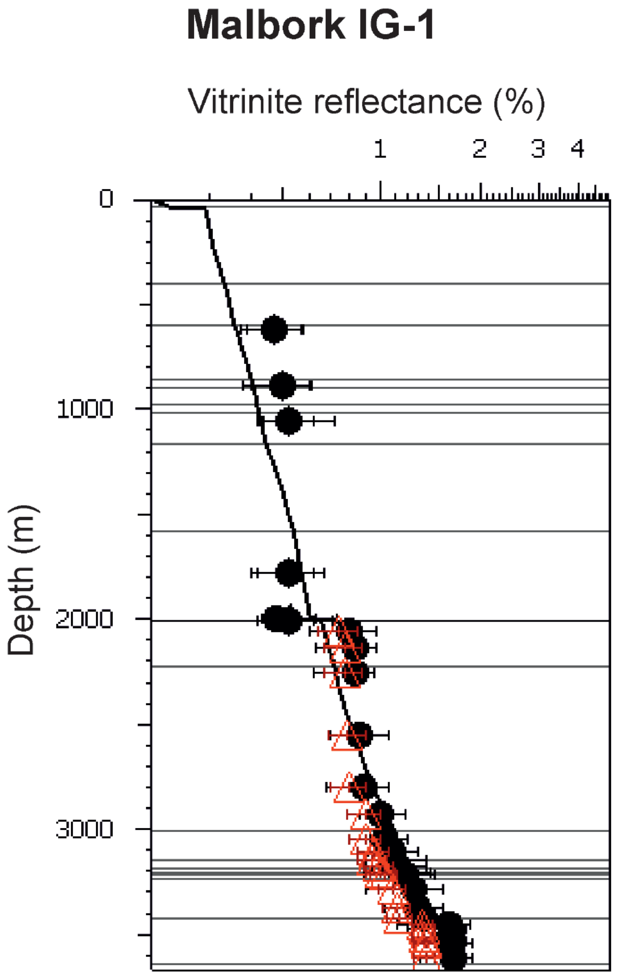

Fig. 3. Example of model calibration for the Malbork IG-1 well, using recalculated organic particle reflectance values for pre-Devonian strata (red triangle) applying the Petersen *et al.* (2013) approach. The required proper model calibration still is preserved in such a case. Therefore, in the thermal maturity ranges occurring the study area, the Petersen *et al.* (2013) approach does not change the results of burial and thermal modelling.

particles are fragments of graptolites without any recognizable morphology. A similar result was published for the Cambrian shales of northern Poland by Schleicher *et al.* (1998). The combination of measurements made on graptolites and vitrinite-like particles provided the reflectance population that was used to assess the thermal maturity. It was suggested that the relationship between graptolite reflectance and the equivalent vitrinite reflectance follows the correlation: $R_{eqv} = 0.73R_{(grap + vitr)low} + 0.16$ (Petersen *et al.*, 2013). This would imply that the reflectance of graptolites increases faster than the reflectance of vitrinite (Petersen *et al.*, 2013). In this paper, thermal maturity applied in model calibration was based on measurements on graptolites and vitrinite-like particles for the Ediacaran to Silurian shales, whereas measurements on true vitrinite were applied for the Devonian and younger strata (Drygant, 1993; Kanev *et al.*, 1994; Nehring-Lefeld *et al.*, 1997; Grotek, 1998, 1999; 2005, 2006, 2015, 2016; Grotek *et al.*, 1998; Kosakowski *et al.*, 1998, 1999, 2013, 2016; Swadowska and Sikorska, 1998; Botor *et al.*, 2002; Zdanavièiûtë, 2005; Zdanavièiûtë and Lazauskiene, 2007; Skręt and Fabiańska, 2009; Poprawa, 2010; Więcław *et al.*, 2010, Stempień-Sałek, 2011). No bitumen or alginate particles were used for model calibration. Because of the problems mentioned above, wider error bars were applied in model calibration. In the approach of Petersen *et al.* (2013), the difference between R_o and VLR_o became more noticeable above 1.30%R_o, which is equivalent to 1.56 VLR_o. Such values at the top of the Silurian occur only in a few wells along the TTZ. In the Permian–Mesozoic, the R_o values are very low, below 0.5% R_o, and therefore a maturity break is obvious in this case between the top of the Silurian and the overlying strata. Therefore, the present authors did not apply the Petersen *et al.* (2013) re-calculation, because in this case it is not source of significant error. Therefore, these findings do not change the results of the maturity modelling performed (Fig. 3). As well, the method of Petersen *et al.* (2013) was established in a single basin, so it should be checked and proved in other basins worldwide before receiving wider use.

The Ediacaran - Lower Palaeozoic strata of the SW margin of the EEC revealed a systematic zonation (NE to SW) in thermal maturity along the entire margin (Drygant, 1993; Kanev *et al.*, 1994; Nehring-Lefeld *et al.*, 1997; Kosakowski *et al.*, 1998, 1999; Swadowska and Sikorska, 1998; Grotek, 1999, 2006, 2016; Zdanavièiûtë, 2005; Zdanavièiûtë and Lazauskiene, 2007; Skręt and Fabiańska, 2009; Poprawa, 2010; Kosakowski *et al.*, 2013, 2016). In the Baltic Basin, the regional thermal maturity pattern is consistent with the parallel increase in vitrinite-like particles from ca. 0.5 to over 4.0% (Nehring-Lefeld *et al.*, 1997; Kosakowski *et al.*, 1998, 1999; Swadowska and Sikorska, 1998; Grotek, 1999, 2006, 2016; Zdanavièiûtë, 2005; Zdanavièiûtë and Lazauskiene, 2007; Skręt and Fabiańska, 2009; Poprawa 2010; Kosakowski *et al.*, 2016). In the central part of the Podlasie Basin, the thermal maturity is ca. 0.9–1.1% R_o, in the western part reaching 1.3% R_o. In the eastern part of the Lublin Basin, the thermal maturity changes from east to west from 0.6–0.7% R_o to ca. 1.5–2.0% R_o (Grotek, 2005, 2016). The highest thermal maturity is in the Łopiennik IG-1 well (2.7–3.4% R_o). In the Biłgoraj-Narol Zone (SW part of Lublin Basin along the TTZ), despite the minor depth of occurrence of the Lower Palaeozoic, the thermal maturity is above 2.0% R_o (Grotek, 2005; Poprawa 2010). The interior of the EEC has yielded CAI values of 1–1.5 (for Ordovician–Devonian rocks), indicative of palaeotemperatures between ca. 50 and 90 °C. Toward the SW, the CAI values (for the Ordovician) gradually increase and reach level 5 (i.e. over 300 °C) in the TTZ (Drygant, 1993; Kanev *et al.*, 1994; Nehring-Lefeld *et al.*, 1997). Toward the SE, the Lower Palaeozoic strata of the Podlasie Basin and the Lublin Basin are covered by the Devonian and Carboniferous strata that show variable thermal maturity (Botor *et al.*, 2002; Poprawa and Pacześna, 2002; Grotek, 2005). 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). In the Devonian, a thin source-rock horizon containing type-II kerogen occurs, having low TOC values usually below 1% (Pletsch *et al.*, 2010;

Radkovets *et al*., 2017). The Carboniferous source rocks are dominated by dispersed organic matter occurring within the entire Viséan to Westphalian section. However, coal seams (eight of which are locally up to 3.5 m thick) occur also in the Upper Carboniferous successions. The Lower Carboniferous strata have an average TOC content of 1.8% and the organic matter is mixed type-II/-III, whereas the Upper Carboniferous organic matter is terrestrial for the most part. The Namurian shales have similar average TOC contents (2.0%) and the Westphalian shales have an average TOC content of 1.5%. The thermal maturity of dispersed organic matter in the Carboniferous strata ranges from ca. 0.4 to 1.2% of R_o values. However, the Upper Carboniferous coals show a relatively low thermal maturity (c. 0.7–0.8% R_o) with minor quantities of methane. (Botor *et al*., 2002; Pletsch *et al*., 2010). The Permian–Mesozoic strata along the entire SW margin of the EEC in general show relatively low thermal maturity below 0.5% R_o (Grotek *et al*., 1998; Grotek 1999, 2005, 2006, 2016; Poprawa *et al*., 2010).

RESULTS AND DISCUSSION

Thermochronology

Hansen (1995) was the first to perform a thermochronological study in the western part of the EEC area. On the basis of zircon and apatite fission track data from the Silurian strata of Bornholm Island, she concluded that uplift/erosion of ca. 3 km occurred prior to 260 Ma (in the Late Palaeozoic) and it was followed by cooling to the present-day (Hansen, 1995). The maximum temperatures attained during burial of the Silurian strata were ca. 130–190 °C and were closer to 190 °C; the maximum temperatures occurred in the Carboniferous, ca. 330 Ma ago in the Early Carboniferous (Hansen, 1995). Moreover, the combined FT and (U-Th)/He patterns in Sweden indicate the total annealing of fission tracks in southern and west-central Sweden and partial helium retention plus partial annealing of fission-tracks farther east. Such an extensive thermal event is best explained by heating beneath an Upper Palaeozoic foreland basin cover, thinning towards the east and progressively redeposited across SE Scandinavia (Hansen, 1995; Larson *et al*., 1999; Cederbom *et al*., 2000; Huigen and Andriessen, 2004).

In Poland, the reset of ZHe ages from Palaeozoic samples, sensitive in the range ca. 150–200 °C, show values from Early Carboniferous (345 Ma) to Late Permian (255 Ma), strongly suggesting a cooling event (or events), related to the Late Palaeozoic stage of development of the crust on the SW slope of the EEC (Botor *et al*., 2017b, c). These ZHe ages from the Lower Palaeozoic strata are successively younger from NW (in the Baltic Basin) to SE (in the Lublin Basin) along the TTZ. AFT data from Proterozoic to Carboniferous samples record a t-T history in a lower temperature range (ca. 60–120 °C) than that of the ZHe system and therefore the AFT ages are younger than the ZHe ages. These AFT data show mainly slow post-Variscan exhumation from the Permian to the Mesozoic. The best time-temperature curves, calculated by iterative inverse thermal modelling, gave very uniform and distinct results (Botor *et al*., 2017b, c). It can be inferred from this modelling that in the Baltic Basin, the maximum heating of the Palaeozoic sequences occurred in the Early Carboniferous, whereas in the Podlasie-Lublin Basin in Late Carboniferous, or even in earliest Permian in the SE corner of the Lublin Basin. All of the combined ZHe and AFT data indicate that late to post-Variscan cooling of the Palaeozoic strata from the maximum temperatures is shown to have been a major feature of the SW slope of the EEC in Poland. This cooling probably followed a heating event, related to burial and/or higher heat flow, mainly in the Devonian–Carboniferous. This is very similar to the results from the Palaeozoic strata of the Holy Cross Mts. (Botor *et al*., 2018). The increase of thermal maturity of the Palaeozoic strata from the NE to the SW of the EEC (towards the TTZ) corresponds very well with these thermochronological data (Nehring-Lefeld *et al*., 1997; Grotek, 1998, 1999, 2005, 2006, 2015, 2016; Grotek *et al*., 1998; Kosakowski *et al*., 1998, 1999, 2010, 2016; Swadowska and Sikorska, 1998; Botor *et al*., 2002; Skręt and Fabiańska, 2009; Pletsch *et al*., 2010; Poprawa, 2010; Więcław *et al*., 2010; Wróbel and Kosakowski, 2010). The Palaeozoic rocks in the NE part of the EEC (between the Gołdap IG-1 and Tyniewicze IG-1 wells) did not experience temperatures above ca. 100–150 °C and the ZHe ages are not reset or are not fully reset. However, towards the SW, the thermochronological data have shown an increase in maximum palaeotemperature above ca. 150–200 °C and the ZHe ages are reset.

On the basis of clay minerals and K-Ar dating in the western Baltic Basin, Środoń and Clauer (2001) showed that vertical changes in the illite-smectite ratio indicate that the maximum palaeotemperatures were reached on the craton after the beginning of the Devonian and before the Permian. The illite K-Ar ages from bentonites indicate that the maximum palaeotemperatures were reached ca. 370–390 Ma. In SE part of the EEC margin (in the Podolia area, western Ukraine), illite K-Ar dating of Silurian ash horizons and shales has given ages from 390 to 312 Ma (Środoń *et al*., 2013) that were interpreted as the effect of exhumation of the Carboniferous cover (Środoń *et al*., 2013). It is also supported by an increase of coal rank towards the SE (in the Lublin and the Lviv Basin) (Porzycki and Zdanowski, 1995; Botor *et al*., 2002). All these data represent a range of ages very close to those measured for bentonites from the Pomeranian sector of the EEC (382–294 Ma, Środoń *et al*., 2009). Środoń *et al*. (2009, 2013) interpreted these data as being indicative of deep burial in the Devonian and Carboniferous. A recent study of clay minerals (in shales and bentonites) and illite K-Ar (in bentonites) along the SW margin of the EEC from Pomerania to the Lublin area (Kowalska *et al*., 2017) also gave broadly similar conclusions, documenting a mainly Carboniferous diagenetic overprint of Palaeozoic samples. However, these new illite K-Ar ages clearly show an Early Carboniferous age for the maximum temperature occurrence in the Baltic Basin and Late Carboniferous across the Podlasie-Lublin Basin, except for the SE part of the Lublin basin, where the K-Ar ages are Early Permian (Kowalska *et al*., 2017). Also, Kozłowska (2011) documented Permian K-Ar age in illites from Carboniferous sandstones in the SE part of the Lublin Basin. Far from the SW margin of the EEC, the diagenetic overprint is low, as has been shown by Anczkiewicz *et al.* (2018) on the basis of AFT data from Belarus, Lithuania, and Ukraine. Additionally, weathered crystalline rocks in SW Scandinavia were recently investigated by illite K-Ar dating of saprolitic material contained in these rocks that constrain original basement exposure in the Late Triassic (221–206 Ma) by deep erosion (Fredin *et al.*, 2017). This implies that most Palaeozoic strata were removed by erosion before the Late Triassic.

The above thermochronological results might lead to the conclusion that the NE part of the EEC (the area between the Gołdap IG-1 and Tyniewicze IG-1 wells) in Poland was mildly heated. These results confirm previous suggestions (based on the thermal maturity of the kerogen) that the NE area of the EEC in Poland was least heated in the Phanerozoic, while the maximum temperatures were significantly higher in the SW part of the EEC (along the TTZ), with the maximum temperature occurring mainly in the Late Palaeozoic. This heating pattern certainly determined the development of hydrocarbon generation processes (Kosakowski *et al.*, 1998, 1999; Botor *et al.*, 2002, 2017d; Karnkowski, 2003a, b; Kosakowski *et al.*, 2010; Poprawa *et al.*, 2010; Botor, 2016). From the point of view of the analysis of hydrocarbon generation processes, it has been clearly demonstrated that these processes were already taking place in the Palaeozoic and could not be resumed in the Mesozoic and Cainozoic, owing to the lower temperatures then predominant in the strata.

Burial and thermal history

In order to test the possible influence of re-calculated VLR_o in pre-Devonian strata *vs*. R_o on development of thermal maturation of organic matter (Petersen *et al.*, 2013), maturity modelling was performed initially in several wells including the Malbork IG-1 well (Fig. 3). Re-calculated VLR_o values into R_o scale using the Petersen *et al.* (2013) approach generally show slightly lower range values (Fig. 3). However, calculated by the EASY%R_o (Sweeney and Burnham, 1990) method, the thermal maturity curve is still in the range of measured values and also does not extend the standard deviation (see error bars in Fig. 3). Therefore, the maturity modelling results are very similar to those obtained using not-recalculated R_o data by the Petersen *et al.* (2013) approach. It is noteworthy also that most of the R_o data set used in modelling is in the relatively low range of R_o (below 1.5%R_o). Therefore, the authors decided not to re-calculate the pre-Devonian R_o data set using the Petersen *et al.* (2013) approach. However, it should be emphasized that particularly above the range of ca. 2.0%R_o the difference between R_o and VLR_o calculated by the Petersen *et al.* (2013) approach seems to be more pronounced.

Burial and thermal history modelling (maturity modelling) was performed in over 60 wells across the study area (Fig. 1). Here, results are presented for 8 wells as a representative for various areas of the study: the Pasłęk IG-1, Gdańsk IG-1, Kościerzyna IG-1, and Słupsk IG-1 wells in the Baltic Basin (Figs 4–7); the Okuniew IG-1 and Bodzanów IG-1 wells, representing the Podlasie Basin and Polik-Bodzanów Zone (Figs 8–9), as well as the Parczew IG-10 and Łopiennik IG-1 wells in the Lublin Basin (Figs 10–11). However, all data from over 60 wells, were used for calculation of regional maps showing the total burial history of the Lower Palaeozoic throughout the entire geological history of the area (Figs 12–19).

The modern thermal regime was calibrated using the temperatures measured in the boreholes. The heat flow values obtained are comparable to the published values (e.g., Majorowicz, 1975, 1978; Majorowicz *et al.*, 1984; Plewa, 1991, 1994; Karwasiecka, 2008; Szewczyk and Gientka, 2009). The models of palaeothermal evolution were calibrated with vitrinite reflectance (R_o) and vitrinite-like reflectance (VLR_o) in the Ediacaran–Silurian strata as well as T_{max} values from Rock-Eval analysis. Modern temperature data can be used to calibrate the thermal reconstruction of the youngest period of geological history. In cases where tectonic inversion and then cooling of rock formations occurred, as was the case in the study area, modern temperature data have very limited application for model calibration in relation to organic matter maturity trends developed for older geological periods. These limits occur because the maturity of organic matter is controlled mainly by conditions during deep burial, not by the parameters of the youngest period in geological development. The burial history was reconstructed using an established, conceptual model that reflects the geological evolution from the Ediacaran up to today, given briefly above. After the calibration of the model, the sensitivity to changes in the most important input parameters was tested and the time changes of the main calculated parameters were examined. Attention was focused on the history of temperatures and that of the maturity of organic matter. Temperature and maturity increase in sediments, if the heat flow at the base of the sediment column does not drop greatly with time. The maximum temperature for the Lower Palaeozoic deposits occurs usually during the maximum burial: in the Early Carboniferous in the Baltic Basin and the Late Carboniferous in the Lublin Basin. The calculated thermal maturity increased until the strata reached the maximum temperature. The temperatures occurring later were too low to allow a further significant increase in thermal maturity of the organic matter. As a result, changes in modern heat flow do not have a significant impact on the assessment of palaeo-heat-flow in the past. It is noteworthy that uncertainty in the estimation of maximum burial is related to the quality of the data (mainly R_o) and can be improved further in future research, mainly because of the lack of measurements in some borehole profiles, which is underscored in the later discussion.

Baltic Basin

The quality of measurement data and /or their distribution in the profiles of individual boreholes often makes it impossible to obtain unique results of modelling. In some cases, the R_o profiles are very complex (e.g., in the Kościerzyna IG-1 and Słupsk IG-1 wells). Considering the limitations of the applied modelling methodology, a number of variants were tested, such as an early Cambrian syn-rift increase in heat flow (Kosakowski *et al.*, 1999), an increase of heat flow during the maximum burial at the end of the Variscan stage (Majorowicz *et al.*, 1984; Kosakowski *et al.*, 1998; Karn-

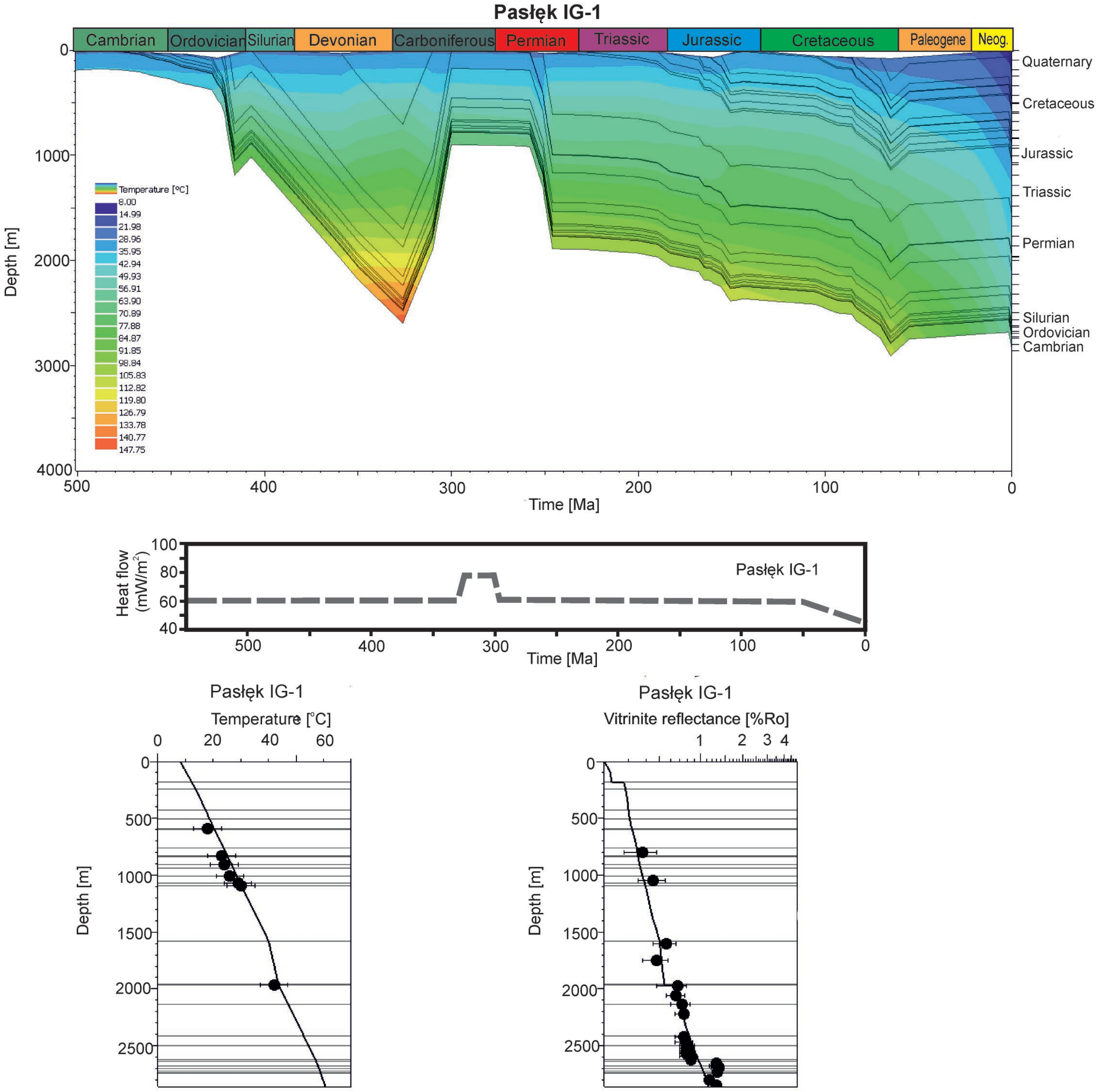

Fig. 4. Burial and thermal history model for the Pasłęk IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

kowski, 2003a, b; Poprawa and Grotek, 2005; Poprawa *et al.*, 2010) and the late Mesozoic thermal event model (Poprawa and Grotek, 2005; Poprawa 2007b; Poprawa *et al.*, 2010). The early Cambrian syn-rift model of thermal flux growth (Kosakowski *et al.*, 1999) in the Baltic Basin, which then decreased to contemporary values, results directly from the tectonic model of the basin (Poprawa *et al.*, 1999). However, owing to later significant burial, this model cannot be unambiguously determined by means of 1-D modelling, as was already emphasized by Poprawa *et al.* (2010). On the other hand, presumably R_o profiles of many wells in the Baltic Sea section (offshore) may be explained by the assuming a constant heat flow equal to the present value (Poprawa *et al.*, 2010). Such a model assumes a significant amount of eroded Palaeozoic overburden, in the order of 1,400–3,000 m necessary for correct calibration (Poprawa *et al.*, 2010). However, in the onshore part (between the Żarnowiec IG-1 and Łeba-8 wells), it is necessary to assume about 3,000 m of erosion of the uppermost Silurian to the Lower Carboniferous section. Thermal maturity data in the Mesozoic part of the profile presented by Poprawa *et al.* (2010) do not allow a unique reconstruction of thermal history. Poprawa *et al.* (2010) argue that this is an unacceptable amount of erosion and proposed a model with an elevated heat flux, which according to their assumptions occurred during Late Cretaceous time. However, the lack of high values of R_o in the Mesozoic section of profiles of the Żarnowiec IG-1 and Łeba-8 wells does not confirm this hypothesis. There also are no other factors that could indicate a thermal event in the Cretaceous, e.g. hydrothermal veins, mineralization, etc. In

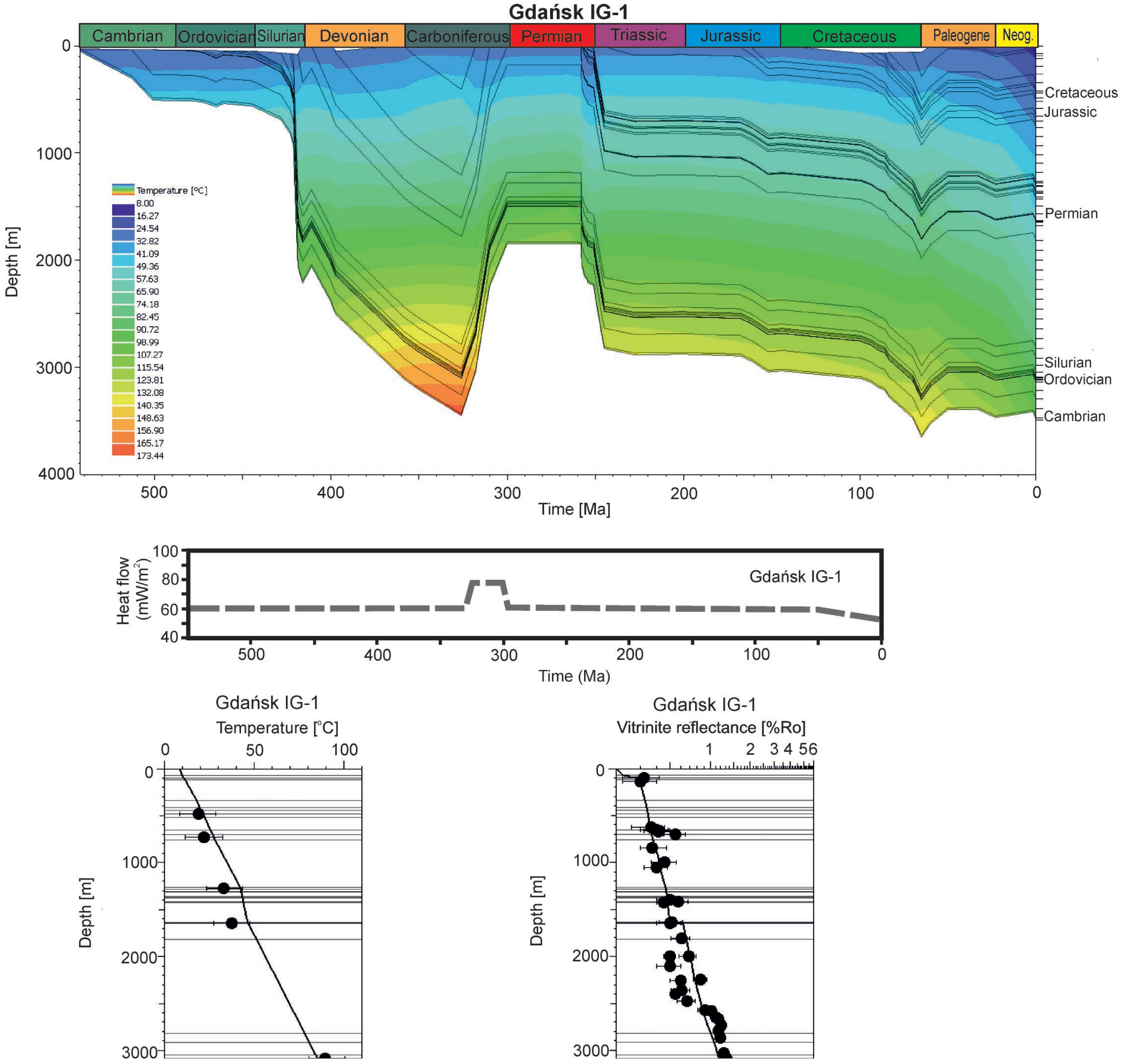

Fig. 5. Burial and thermal history model for the Gdańsk IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

turn, Karnkowski (2003b) proposed a model of a relatively low heat flow in the Mesozoic, equal to the contemporary one in the Baltic Basin, which is supported by the work of Poprawa and Andriessen (2006), documenting a cool thermal regime in Cretaceous based on apatite fission track data in the Middle Polish Trough. In many boreholes in the Baltic Basin, sub-vertical R_o profiles are observed, which indicates the influence of hydrothermal solutions on thermal maturity (Poprawa and Grotek, 2005; Poprawa *et al.*, 2010).

In addition, in the western part of the basin, lowering of the R_o value is observed in part of the Lower Palaeozoic profile (mainly in the Silurian), which indicates the possible impact of palaeo-overpressure development (Poprawa and Grotek, 2005; Poprawa *et al.*, 2010; Botor, 2016), although it is commonly believed today that overpressure does not occur in the study area. Poprawa and Grotek (2005) assumed that the development of these overpressures was associated with a very high rate of deposition of the Upper Silurian sediments, exceeding 1,000 m/Ma. Therefore, the growth of the Variscan thermal flux could be conditioned by both regional lithospheric processes and thermal solutions (Poprawa and Grotek, 2005).

In the Baltic Basin, the quality of measurement data regarding thermal maturity makes it impossible in most cases to obtain an unambiguous thermal history model and several variants are possible. Therefore, thermochronological data (Botor *et al.*, 2017c, 2018), and illite K-Ar dating (Kowalska *et al.*, 2017) are particularly important, which allows at least narrowing down the possible geological scenarios of thermal evolution. Illite K-Ar dating of Lower Palaeozoic bentonites showed that the maximum palaeotemperatures in these formations occurred from the Devonian (ca. 360–390 Ma) in the most western part of the Baltic Basin to the Early Carboniferous (320–330 Ma) in its middle

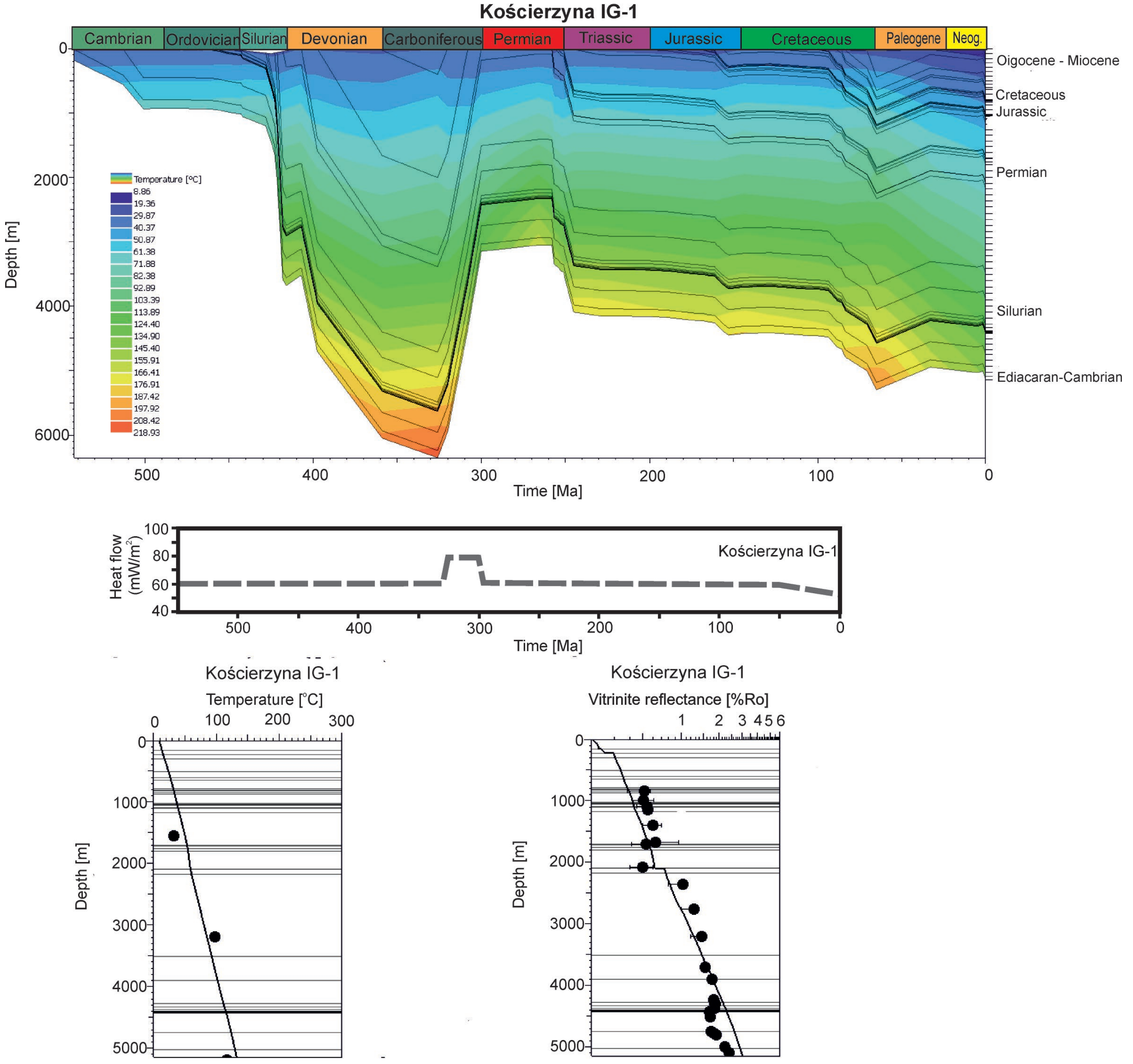

Fig. 6. Burial and thermal history model for the Kościerzyna IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

part (Środoń and Clauer, 2001; Środoń *et al.*, 2009; Kowalska *et al.*, 2017). This conclusion is confirmed by zircon helium dating and AFT data (Botor *et al.*, 2017c), as well as AFT analyses from Bornholm Island (Hansen, 1995), which all together pointed to an Early Carboniferous maximum temperature. Thus, palaeotemperatures in the Lower Palaeozoic rocks in the area of boreholes, from the O-2 well to the Kościerzyna IG-1 well increased in the Devonian to the Early Carboniferous. In contrast, to the west of the zone mentioned above, a significant temperature rise was possible at the end of the Silurian (e.g., Kosakowski *et al.*, 1998; Poprawa and Grotek, 2005; Botor, 2016). In turn, in the eastern part of the Baltic Basin (e.g., in the Gołdap IG-1 well area), no significant anomaly (above c. 60–80 °C) was found in the thermochronological data (Botor *et al.*, 2017c). The above dating results were used indirectly in thermal maturity modelling, because they allow selection and testing of the most appropriate thermal history model. From the thermochronological data, it can be seen that the maximum palaeotemperatures in the Lower Palaeozoic strata occurred in the Late Palaeozoic, as was suggested earlier (Majorowicz *et al.*, 1984, Kosakowski *et al.*, 1998, 1999; Karnkowski, 2003b; Poprawa and Grotek, 2005; Poprawa *et al.*, 2010) for one of the possible scenarios for the thermal evolution of the Baltic Basin. In the boreholes analysed in this study, the correct calibration of thermal models was obtained assuming a maximum burial of the Lower Palaeozoic sediments in the Early Carboniferous, which is determined by assuming a significant amount of erosion in the range of 1,800 m to 3,000 m (Fig. 4–7), with the elevated (compared to the present-day) heat flow (in the Carboniferous) values, which increased towards west from c. 60 to 80 mW/m^2. The values

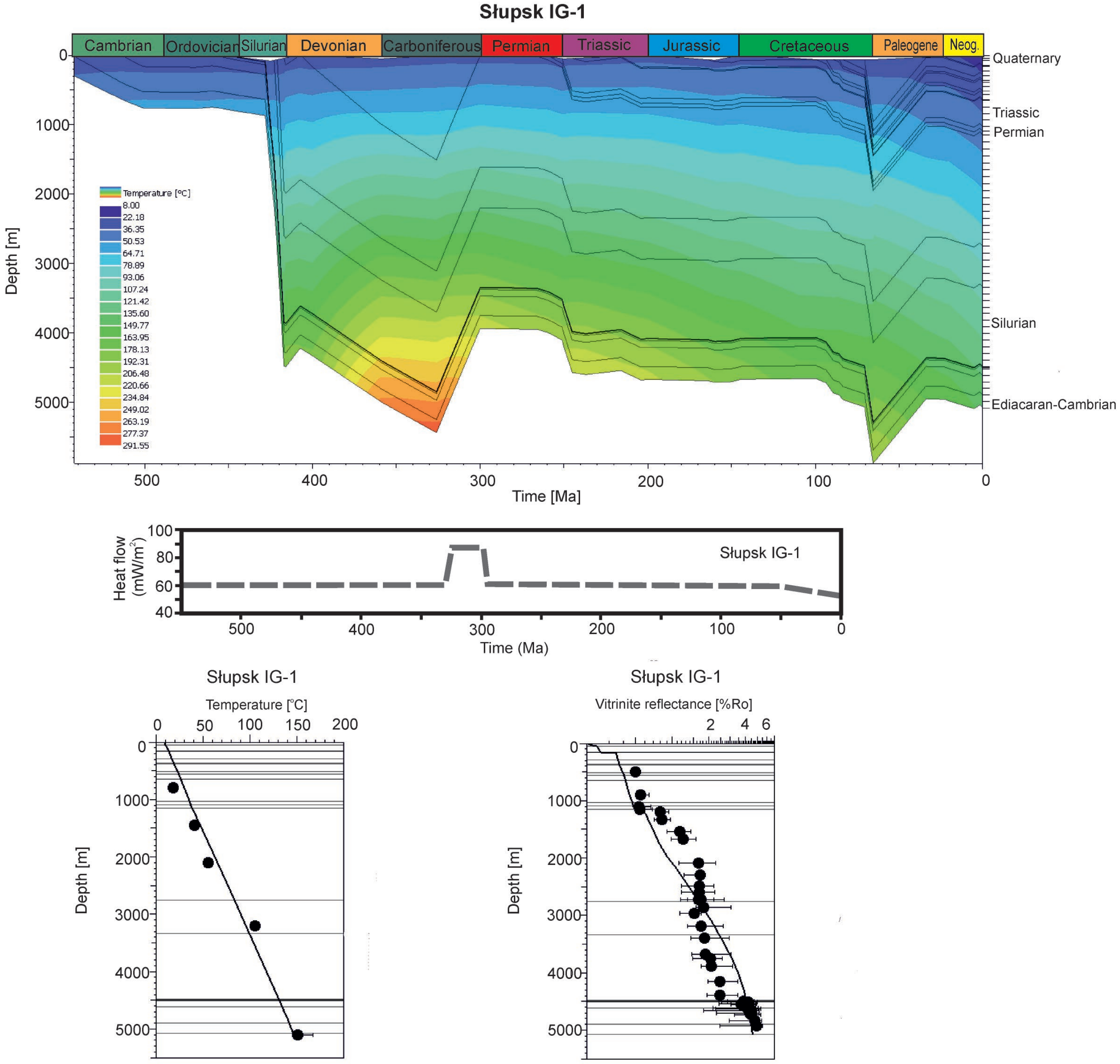

Fig. 7. Burial and thermal history model for the Słupsk IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

of the thermal flux decreased gradually to the present-day values. However, the relatively poorly controlled factor in these models is the thermal conductivity of rocks, the value of which was adopted on the basis of the library values for the PetroMod software, taking into account the averaging of particular lithological types. More precise modelling results could have been obtained if the thermal conductivity in the individual wells had been measured. To some extent, it is also possible to obtain the correct calibration by reducing the amount of erosion and slightly increasing the heat flow value in the Carboniferous. However, further discussion of this issue would require better quality of measurement data, i.e. a larger number of measured samples in profiles and verification of thermal maturity measurements and this is best done by various methods, not only by vitrinite reflectance. Additionally, the lack of higher terrestrial plants (that are the source of vitrinite) in the Early Palaeozoic distorts slightly the measured values, particularly above the range of ca. 1.5–2.0%R_o (Petersen *et al.*, 2013).

The maximum palaeotemperatures increase in a westerly direction and at the bottom of the profiles analysed (Cambrian and / or Ediacaran) range from about 140 °C (Pasłęk IG-1) to over 250 °C (Słupsk IG-1; Figs 4–7). In the eastern part of the Baltic Basin, the maximum temperatures were significantly below 100 °C. The Caradocian and Lower Silurian strata analysed respectively have reached temperatures: from about 120 °C (in the Pasłęk IG-1 well) to over 250 °C in the case of the Słupsk IG-1 well (Figs 4–7). Although the causes of high temperatures in the Variscan stage in part may be debatable (e.g., heat flow or the amount of exhumation/erosion), it is not questionable that the maximum palaeotemperatures in the Lower Palaeozoic rocks

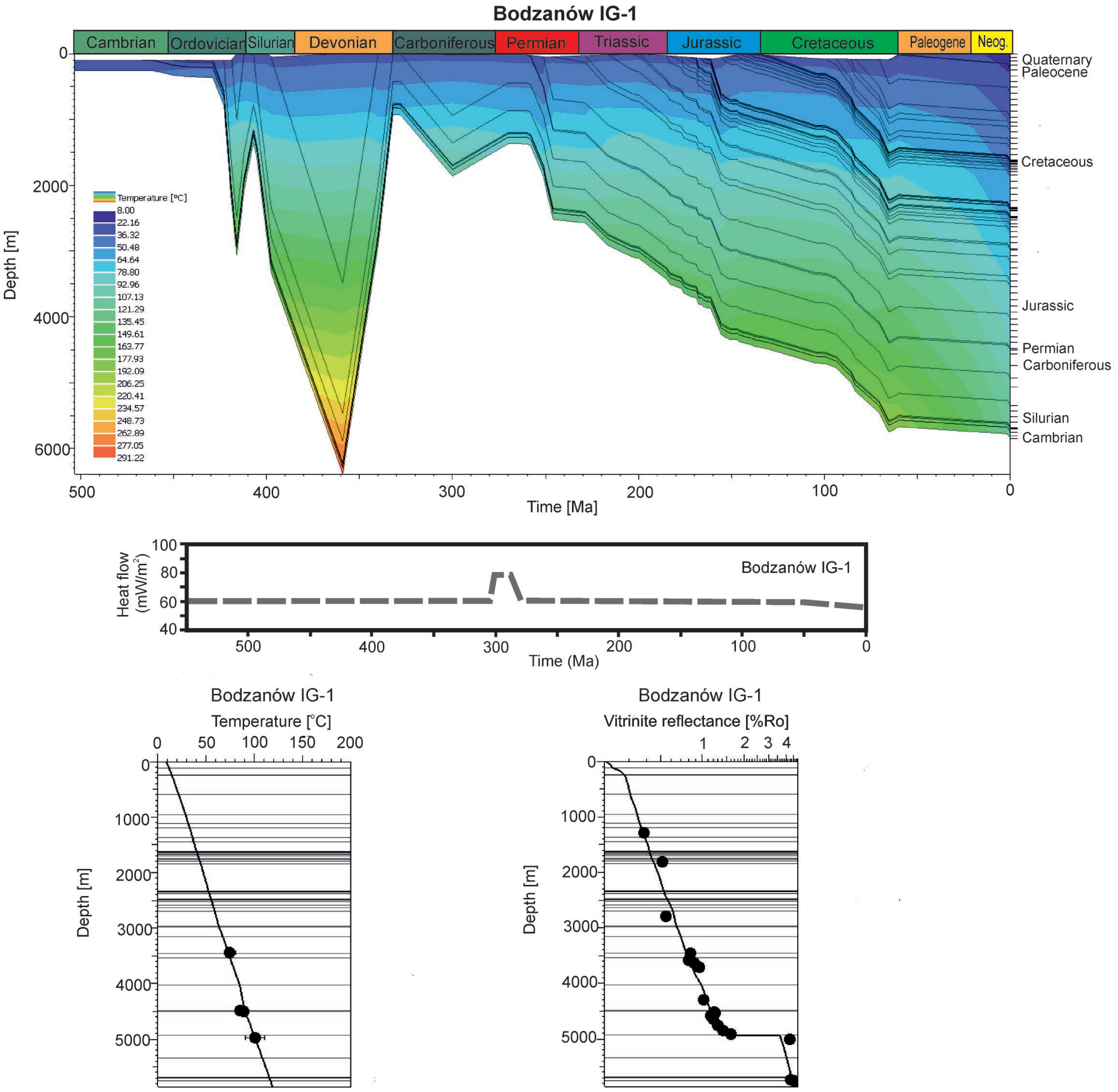

Fig. 8. Burial and thermal history model for the Bodzanów IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

of the study area occurred only then (Early Carboniferous) and not later (in the Mesozoic or Cainozoic). In summary, in the Baltic Basin, maturity modelling has shown that an increase of temperature and burial was continuous from the Late Silurian to the early mid-Carboniferous. Closer to the TTZ, the Late Silurian burial was more significant, whereas towards the east, burial in the Devonian and Early Carboniferous was more important.

Podlasie-Lublin Basin

In the Podlasie-Lublin region, the quality of measured thermal maturity data and/or their distribution in the profile of individual wells also often makes it impossible to obtain unequivocal modelling results, especially in the absence of measurements from the Mesozoic part of individual borehole profiles. Nevertheless, several models of thermal evolution have been published so far. The first attempt was made by Majorowicz *et al.* (1983, 1984), indicating an increased geothermal gradient / heat flow in the Carboniferous, which gradually decreased until today. Later works by Botor *et al.* (2002), Botor and Littke (2003) and Karnkowski (2003a) also emphasized the higher-than-modern conductive heat flow, connecting it mainly to the period of maximum burial of Palaeozoic strata. Poprawa and Żywiecki (2005) proposed an explanation for the thermal maturity pattern of the Lower Palaeozoic, Devonian and Carboniferous sediments with reference to the migration of hydrothermal fluids. The thermal effect of these overlapped the consequences of maximum burial in the Carboniferous.

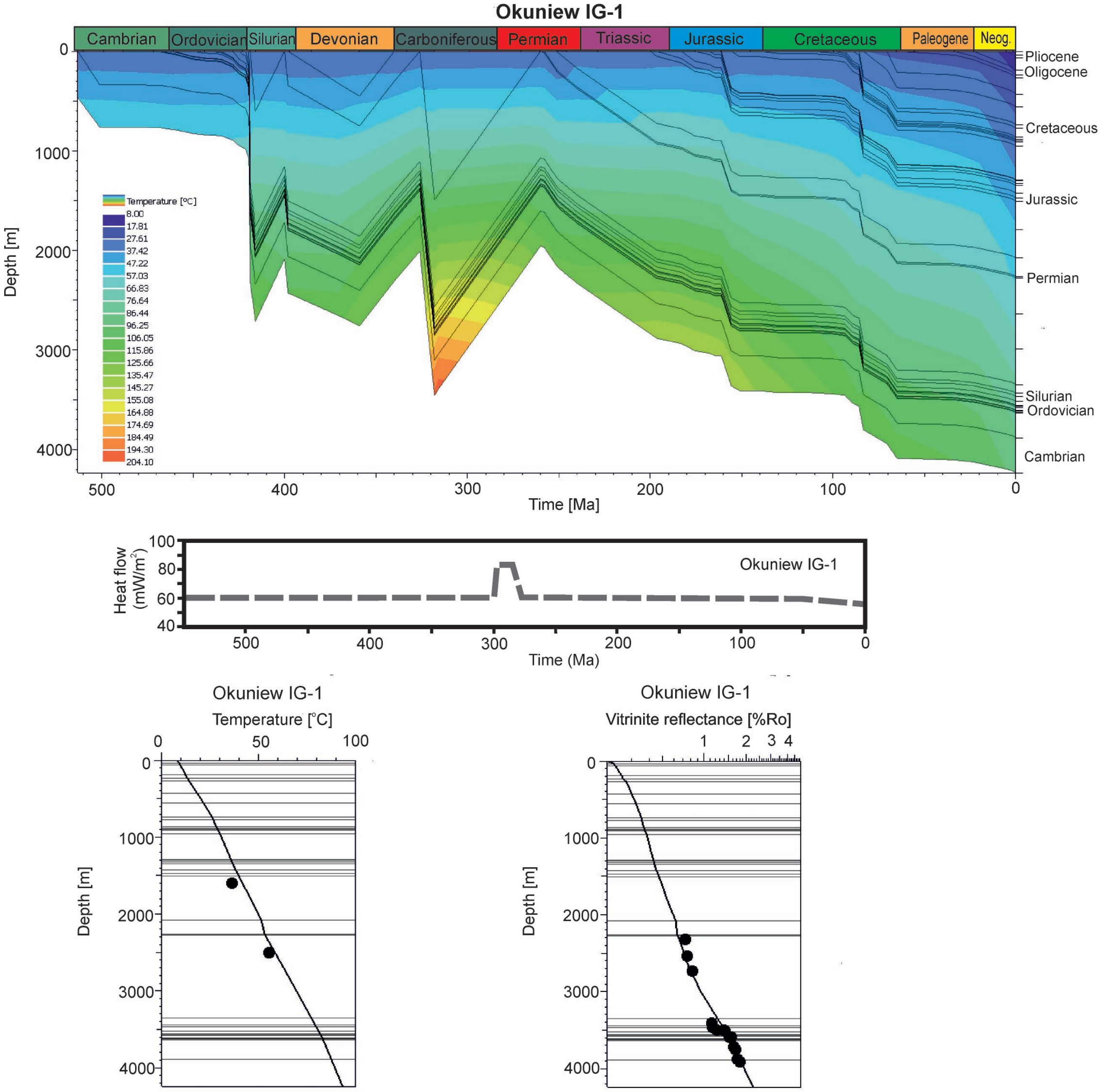

Fig. 9. Burial and thermal history model for the Okuniew IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

In their opinion, migration itself may have appeared in the Late Devonian to the Carboniferous and / or Jurassic. In turn, Poprawa (2008b) proposed that the thermal maturity of organic matter contained in the Palaeozoic deposits in the Łopiennik IG-1 borehole was achieved in the Cretaceous and / or the Palaeocene, as a result of the additional supply of thermal energy to the Upper Cretaceous strata, although without providing any evidence to support this hypothesis. As a potential mechanism for supplying additional thermal energy to the Upper Cretaceous deposits, the assumed migration of these hot solutions was indicated. The time of occurrence of such thermal solutions was proposed as earlier in the Jurassic (Poprawa and Żywiecki, 2005). However, there is no evidence to support the existence of such solutions in the post-Variscan period as in the Baltic Basin.

The calculated burial curves for the Podlasie-Lublin Basin and the Polik-Bodzanów Zone show very rapid subsidence in the Palaeozoic, reaching in most cases about 90% of the total subsidence (Figs 8–9). In most of the Lublin area, the maximum burial of Palaeozoic sediments occurred at the end of the Carboniferous (Figs 10–11), which already was demonstrated in relation to the Lublin Trough (Botor *et al.*, 2002) and the entire Lublin Basin area (Karnkowski, 2003a). Thus, the Lower Palaeozoic deposits also probably reached the currently measured degree of thermal maturity, owing to the achievement of maximum palaeotemperatures. Only in the NW part of the Lublin Trough (the area around the Warka IG-1 and Izdebno IG-1 wells) the maximum palaeotemperature and degree of maturity were attained in the Late Cretaceous (Botor *et al.*, 2002), or in the Jurassic in area

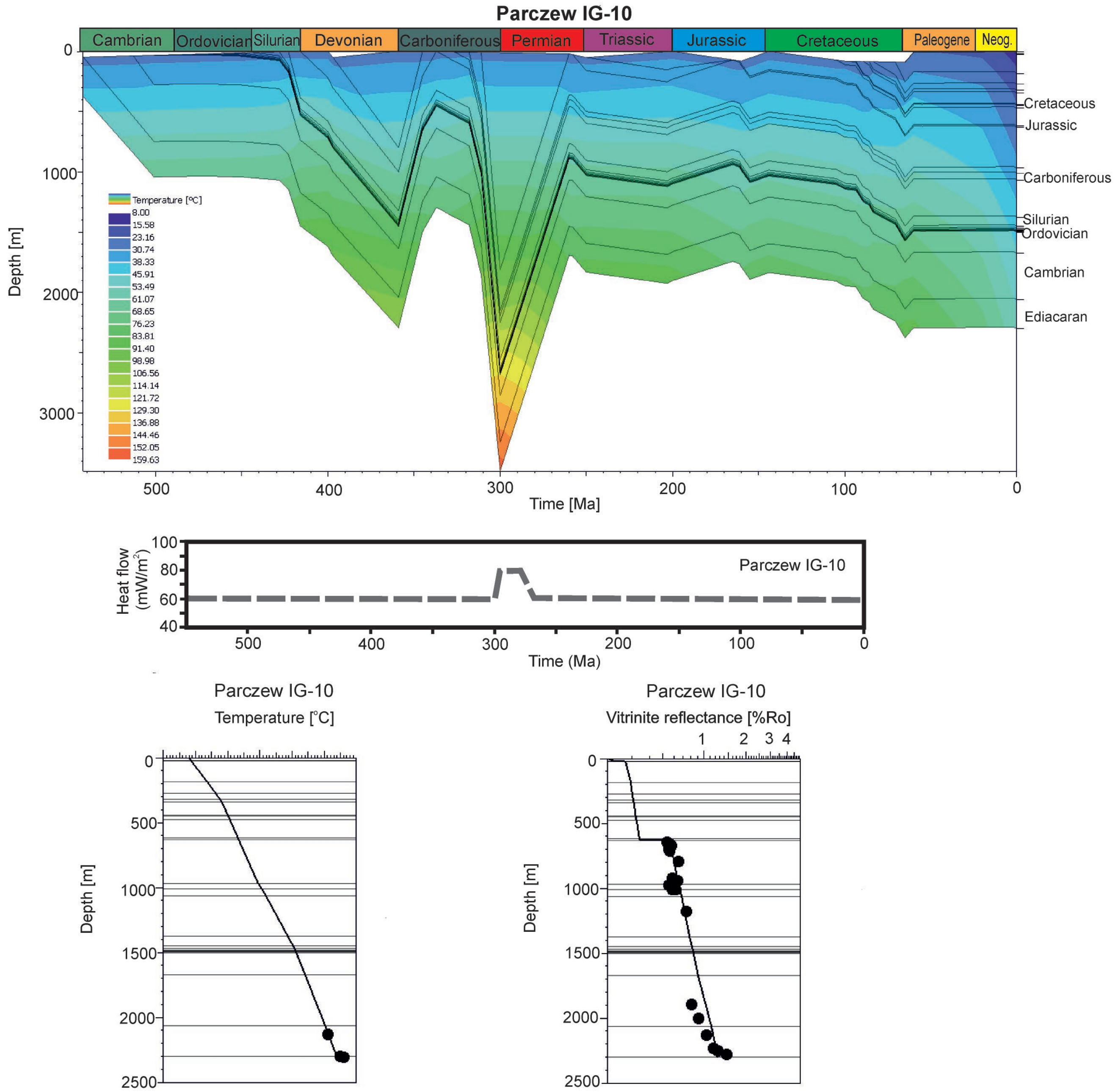

Fig. 10. Burial and thermal history model for the Parczew IG-10 well including calibration. Based on Botor *et al.* (2017c), modified.

of the Nadarzyn IG-1 to Maciejowice IG-1 wells (Kozłowska and Poprawa, 2004). On the other hand, there are a few boreholes in the Polik-Bodzanów Zone that would enable detailed reconstructions of the thermal history. In the Polik IG-1 borehole, the coalification jump in the R_o profile clearly documents the Variscan age of maturation of the Lower Palaeozoic strata (see also Poprawa, 2010), which is confirmed by the results of thermochronological research (Botor *et al.*, 2017b, c; Kowalska *et al.*, 2017). In the Bodzanów IG-1 profile, the maturity jump occurs between the Silurian and the Carboniferous, which indicates pre-Carboniferous coalification (Fig. 8). Because the Bodzanów IG-1 borehole is located close to the TTZ, for example, like Słupsk IG-1 well in the Baltic area, it cannot be ruled out that substantial maturation of the Lower Palaeozoic organic matter already had occurred at the end of Silurian, especially since in other wells in the western part of the Podlasie region it also was reached at the end of the Silurian (see Okuniew IG-1, Fig. 9).

In the geological development of the Podlasie-Lublin area, several intensive exhumation/erosion processes happened between the Late Carboniferous and the Permian, and/or the Triassic and/or the Middle Jurassic as well as in the Early Cretaceous and Cainozoic (e.g., Narkiewicz, 2007). The main unconformity separates the Palaeozoic and Mesozoic strata and represents the effect of the late Variscan tectonic inversion. It was probably of fundamental importance for the evolution of the thermal maturity of organic matter. In the Lublin area, the extent of post-Variscan, mainly Late Carboniferous sediment erosion increases from the north towards the south, from ca. 50 m to ca. 3500 m in the

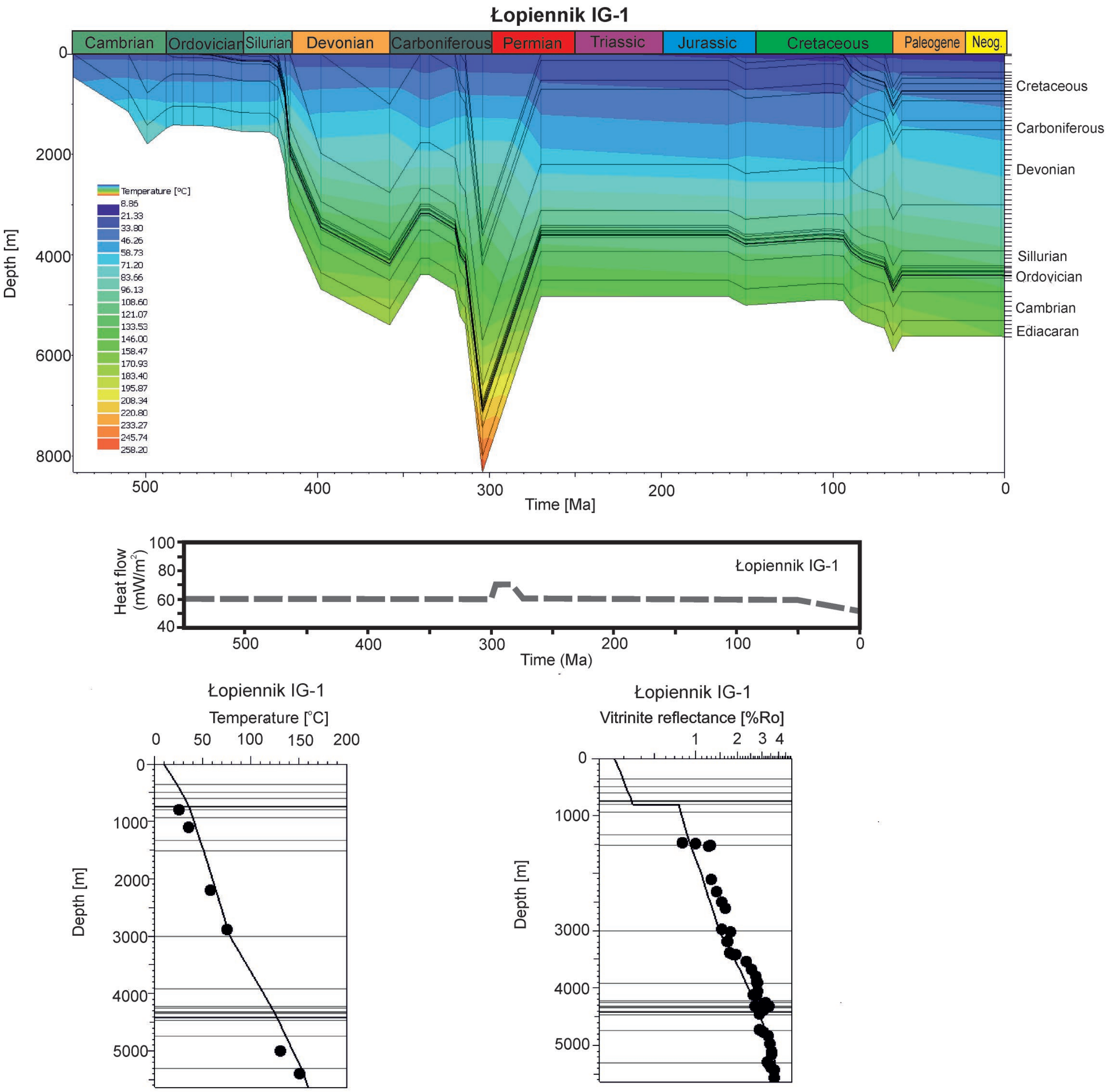

Fig. 11. Burial and thermal history model for the Łopiennik IG-1 well including calibration. Based on Botor *et al.* (2017c), modified.

area of the Łopiennik IG-1 well (Figs 10–11, see also Botor *et al*., 2002; Karnkowski, 2003a). The size of the eroded overburden suggests that in particular Carboniferous sedimentation could have reached a much greater extent than is seen at the present day. This range probably could have been larger than known palaeogeographic reconstructions.

The Lublin Basin was characterized by increased Carboniferous heat flow, which was possible owing to the significant development of basaltic volcanism (Grocholski and Ryka, 1995) dated to the Early Carboniferous: 348–338 Ma (Pańczyk and Nawrocki, 2015). The current thermal heat flow in the Lublin region is from ca. 40 to 70 mW/m^2 (e. g. Karwasiecka, 2008; Szewczyk and Gientka, 2009). In the Lublin area, the heat flow in the Carboniferous Period probably ranged from ca. 62 to 95 mW/m^2. However, in the NW part of the area (between the Maciejowice IG-1 and Izdebno IG-1 wells), it was the smallest ca. 62–72 mW/m^2, while in the SE part (around the Terebin IG-5 well) and in the central part (between the Lublin IG-1 and Świdnik IG-1 wells) was much higher, in the order of 83–95 mW/m^2 (Botor *et al*., 2002; Botor, 2007). Even higher values were proposed by Karnkowski (2003a); however, it is difficult to verify them, owing to the lack of calibration data in his work. Regional differences in thermal flux values can be explained by tectonic extension processes in latest Devonian or Early Carboniferous (Narkiewicz *et al*., 1997, 2007; Krzywiec, 2009). The probable increased heat flow was preserved only in the Permian (Kozłowska, 2011) or at the end of the Carboniferous (Karnkowski, 2003a).

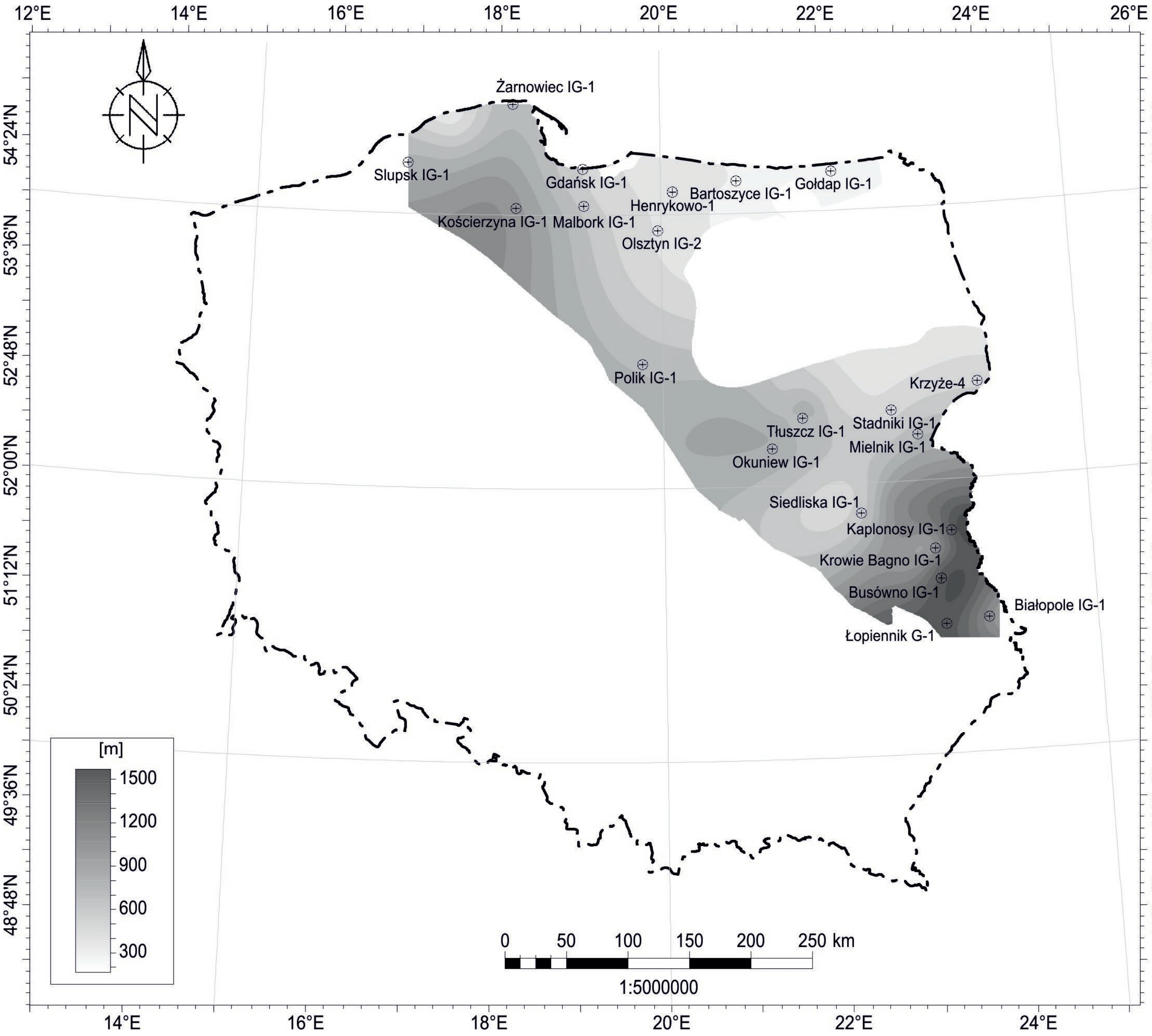

Fig. 12. Total burial depth of sedimentary sequence in Ediacaran-Cambrian time (in m). Based on Botor *et al.* (2017c), modified.

The degree of thermal maturity of the upper Viséan strata varies from ca. 0.6% (between the Wilga IG-1 and Warka IG-1 wells) to 1.2% R_o (between the Tyszowce IG-2 and Terebin IG-5 wells). The lowest values are found in the NW part of the Lublin area, while the highest values are in the SE part and at the SW edge of the Lublin Trough. The Namurian and Westphalian strata show a similar distribution of the degree of coalification, although the values are lower than those found in the Viséan strata (Grotek *et al.*, 1998; Botor *et al.*, 2002; Grotek, 2005). However, the Jurassic and Cretaceous strata have R_o values at a level of ca. 0.4–0.5% (e.g., Botor, 1997; Botor *et al.*, 2002), showing a coalification jump between the Carboniferous and Mesozoic overburden in the greater part of the Lublin area. In the Biłgoraj-Narol Zone, the thermal maturity of the Lower Palaeozoic deposits expressed on the vitrinite reflectance scale is high (Poprawa and Żywiecki, 2005; Grotek, 2015). In the Potok IG-1 well, it is 1.2 to 1.3% R_o (in Pridoli strata only), in the Dyle IG-1 well from 1.8 to 2.1% R_o (in upper Cambrian–Ordovician strata), in the Narol IG-1 borehole from 1.6 to 1.9% R_o (in upper Cambrian–Pridoli strata), in the Narol PIG-2 borehole from 1.3 to 2.4% R_o (in middle Cambrian–Ludlow strata), and slightly further to the east, in the LK-1 borehole from ca. 2.0 to 2.5% R_o (in Ludlow–Caradocian strata). The abrupt increase in the degree of the organic maturity between the Mesozoic overburden and the Lower Palaeozoic strata is also noteworthy. For example, values of 0.55–0.57% R_o were measured in the Jurassic of the Potok IG-1 borehole, while in the Silurian section (only 200 m lower) 1.2% R_o was measured. In the Cretaceous in the Narol IG-1 well the value 0.65% R_o was measured, and at the top of the Silurian 1.6% R_o (Poprawa and Żywiecki, 2005). Similar jumps in the degree of coalification of organic matter between the Palaeozoic and Mesozoic sections also were recorded in other boreholes to the SE in the Lublin Basin (Botor, 1999, 2007; Botor *et al.*, 2002; Wróbel *et al.*, 2008). Although the number of measurements in individual borehole profiles is not very large in many cases, it is ma-

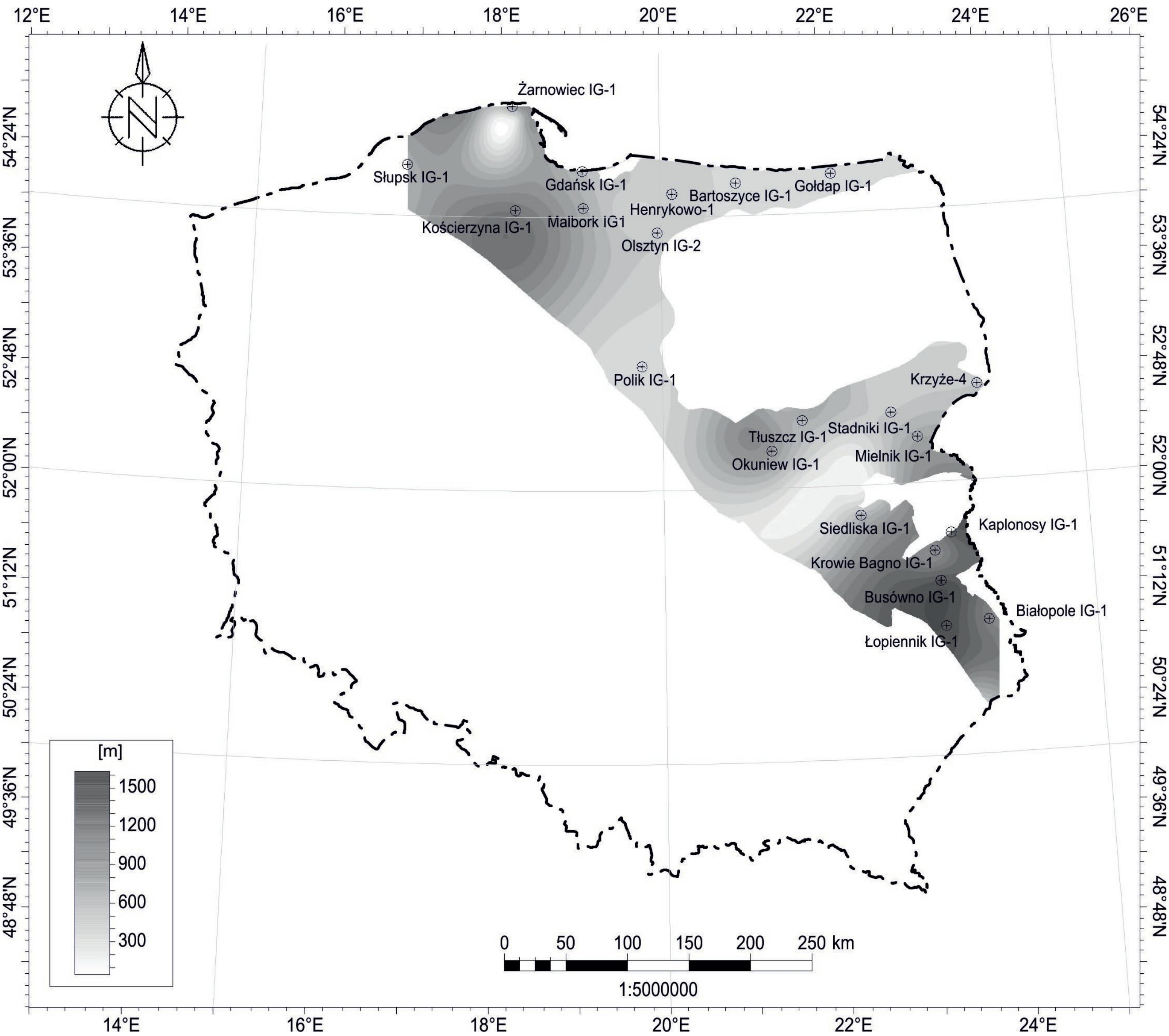

Fig. 13. Total burial depth of sedimentary sequence in the Ordovician Period (in m). Based on Botor *et al.* (2017c), modified.

terial sufficient to unequivocally reflect the different conditions for maturation of organic matter in the Palaeozoic Era in relation to the Mesozoic. The high thermal maturity of organic matter attained in the Palaeozoic evidences the effects of a thermal field characterized by a much higher heat flux than that of the Mesozoic. This conclusion also is clearly confirmed by the results of helium zircon dating, by apatite fission track analyses (Botor *et al.*, 2017b, c, 2018) and by the K-Ar ages of illite (Kozłowska, 2011; Kowalska *et al.*, 2017).

In the Podlasie-Lublin region, the calculated maximum temperatures at the bottom of the modelled sedimentary sequences increase in a southerly direction, reaching over 250 °C in the Łopiennik IG-1 borehole, while in the Caradocian and the Lower Silurian rocks, they are lower (up to 150 °C in the Łopiennik IG-1 well; Fig. 11). In turn, in the Bodzanów IG-1 borehole, the calculated maximum temperatures at the bottom of the Palaeozoic strata are approx. 280–290 °C (Fig. 8). These high temperatures were caused by elevated heat flow as well as significant burial in the Variscan orogeny. High palaeogradients (above 40 °C/km) are characteristic for the southern part of the Lublin region, while smaller values (20–30 °C/km) were obtained in the northern part (Majorowicz *et al.*, 1983, 1984). Such high values of palaeogradients also reflect high values of heat flow (Botor *et al.*, 2002). The geothermal palaeogradient in the Lublin region was much higher than the geothermal gradient currently registered (Plewa, 1994; Karwasiecka, 2008; Szewczyk and Gientka, 2009). This resulted in a higher degree of maturity of organic matter than would have resulted from considerations of maximum burial with the assumption of modern temperatures (Majorowicz *et al.*, 1983, 1984). It follows that the heat flow had to be higher in the past. This can be explained by the Variscan overheating that affected the areas discussed, and its effects, including volcanism in the Carboniferous (Grocholski and Ryka, 1995; Pańczyk and Nawrocki, 2015). The existence of magmatic activity was associated with the elevated asthenosphere

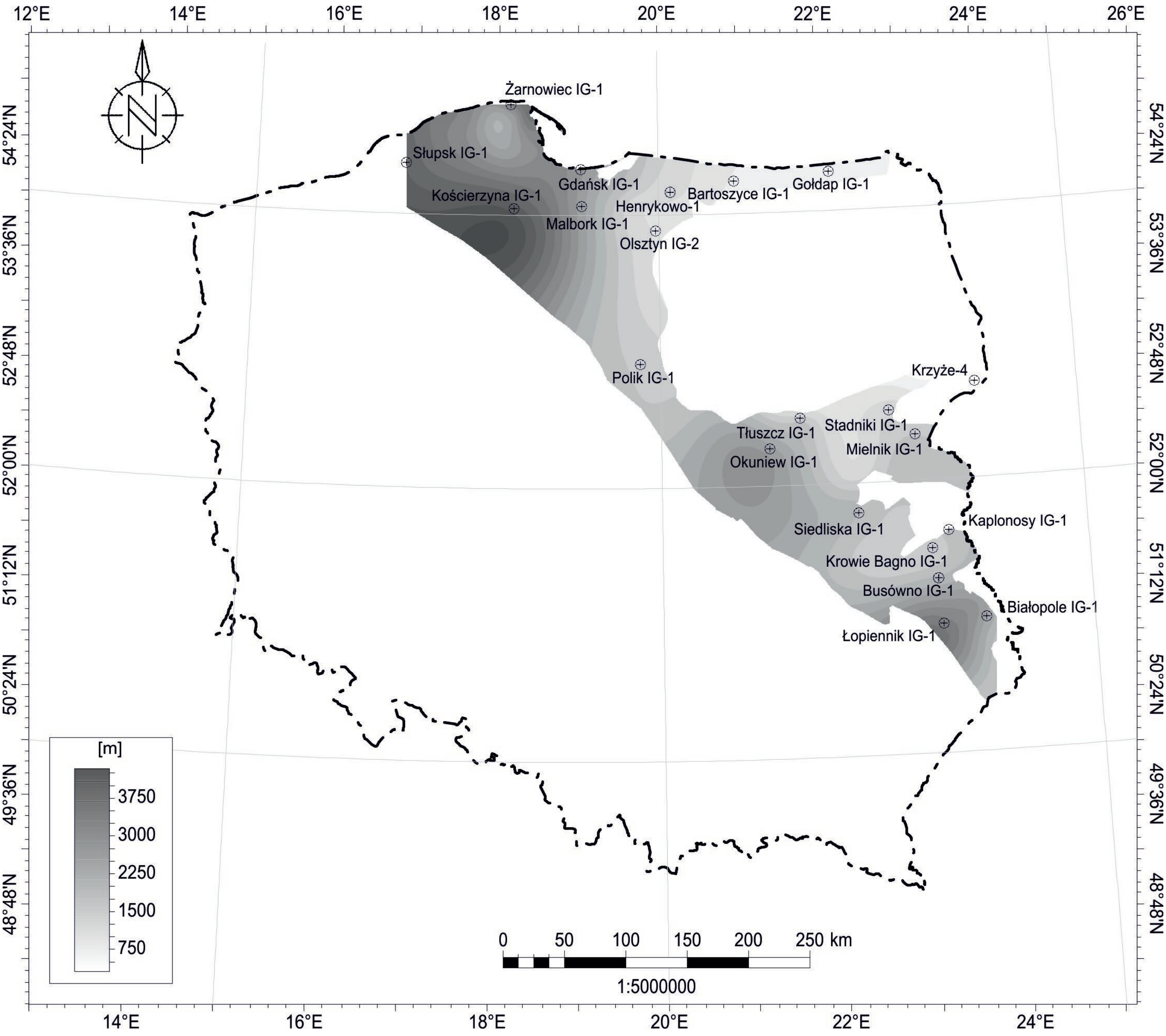

Fig. 14. Total burial depth of sedimentary sequence in the Silurian Period (in m). Based on Botor *et al.* (2017e), modified.

and thus with the influence of regionally elevated heat flux (Majorowicz, 1978). The operation of these elevated and anomalous, thermal conditions could have been long-lasting, if they were associated with very deep heat sources in the crust (Majorowicz *et al*., 1983, 1984).

Maturity modelling based on vertical R_o profiles has shown that in the Lublin area, thermal evolution was related to burial in the Devonian to Late Carboniferous, but with the most prominent increase in Late Carboniferous. This is similar to the results of previous modelling, done in the last decades (Botor *et al*., 2002; Botor and Littke, 2003; Karnkowski, 2003a; Poprawa and Grotek, 2005; Kosakowski *et al*., 2013; Botor, 2018). However, in recent years, Poprawa (2007b, c, 2008b, 2011b) has suggested that maximum temperature was connected with maximum burial in the Late Cretaceous with additional heating within the Upper Cretaceous section during the time of its deposition and/or in the Paleocene in both the Baltic and Podlasie-Lublin basins. However, no evidence was given to support this hypothesis. Poprawa and Grotek (2005) also emphasize the possible influence of fluid flow as a means of heat transport in the Lublin Basin, which requires further investigations.

Regional variability of sedimentary burial on the SW slopes of the EEC

This regional analysis is based on data from more than sixty wells (Fig. 1). The spatial distribution of these wells is not uniform in the Polish part of the EEC. This is due to the location of the wells in the most perspective parts from the point of view of geological and especially exploratory work in the last decades. Nevertheless, the distribution of these boreholes makes it possible to assess the subsidence/burial history across the EEC area. Showing the variability from NE parts (between the Gołdap IG-1 and Krzyże-4 wells) to the SW edge of the EEC (between the Słupsk IG-1, Kościerzyna IG-1, Bodzanów IG-1, Łopiennik IG-1 and Narol IG-1 wells). The results of 1-D maturity modelling are pre-

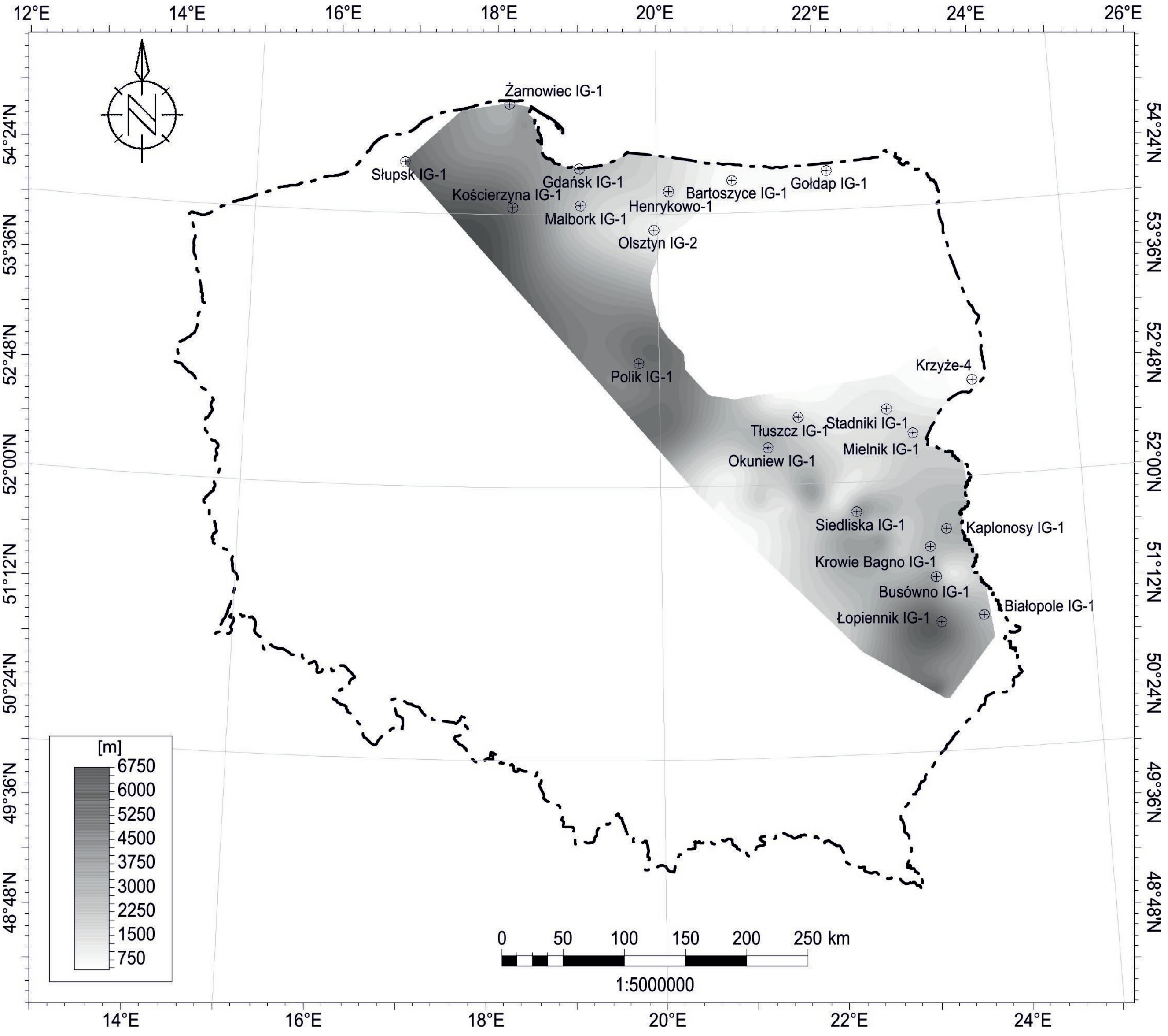

Fig. 15. Total burial depth of sedimentary sequence in the Devonian Period (in m). Based on Botor *et al.* (2017c), modified.

sented in the form of maps of the spatial distribution of the total burial of sedimentary sequence on the SW slope of the EEC (Figs 12–19). This approach was motivated by the goal of assessment of hydrocarbon generation in the Lower Palaeozoic deposits studied, which is presented in a complementary paper (Botor *et al.*, 2019). Previous analyses of subsidence did not include exhumation/erosion and therefore were limited only to those parts of the geological record that are documented in lithostratigraphic profiles (e.g., Poprawa *et al.*, 1999; Poprawa and Pacześna, 2002). This allows assessment of the tectonic evolution of the sedimentary basins, although it is insufficient for the reconstruction of hydrocarbon generation processes. In most cases, in the study area, the thermal maturity of organic matter is higher than that resulting from the subsidence associated only with the presently existing rock record. Therefore, when analysing petroleum-generation processes, it is necessary to take into account the effects exhumation/erosion. The data were compiled for the following phases of geological development of the EEC slope, showing the potential variability of hydrocarbon generation due to tectonic processes: the Ediacaran–middle Cambrian (1) phase, the late Cambrian phase through the Ordovician to the beginning of Silurian (2), the Silurian phase (3), Devonian (4), Carboniferous (5), Permian to Early Triassic (6) phase, Middle Triassic–Jurassic phase (7) and the last Cretaceous phase (8). Owing to the lack of significant subsidence, a Cainozoic phase was not distinguished.

Ediacaran–middle Cambrian phase

This phase includes the earliest documented development of subsidence on the SW slope of the EEC. The total burial depth for the Ediacaran–Cambrian phase is calculated at the end of this phase (before the late Cambrian stratigraphic gap) and is shown in Fig. 12. In the Baltic Basin, the depth of burial of the sedimentary sequence increases from NE to SW (towards the TTZ), from below 250 m (in the vicinity of the Gołdap IG-1 well) to over 900 m near the Kościer-

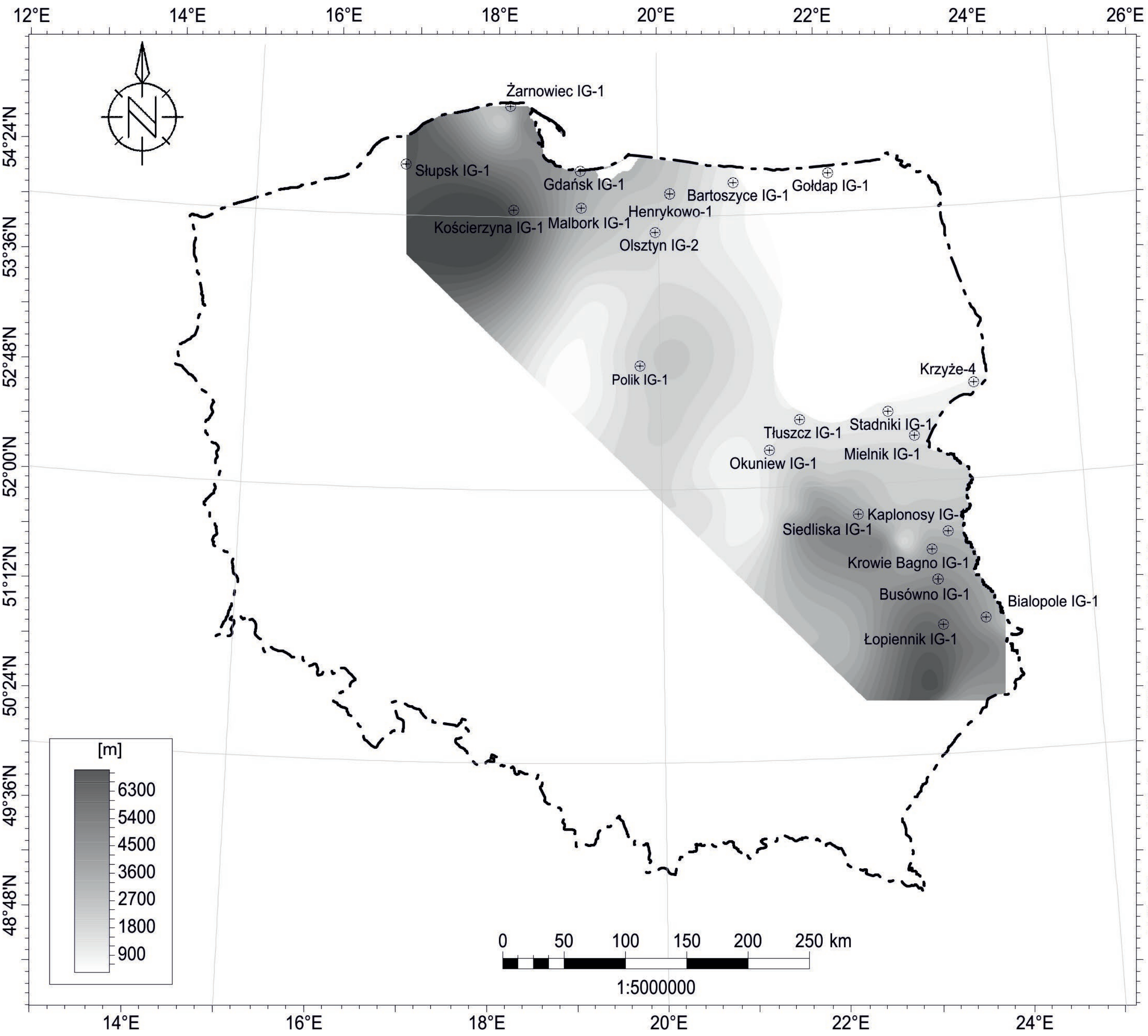

Fig. 16. Total burial depth of sedimentary sequence in the Carboniferous Period (in m). Based on Botor *et al.* (2017c), modified.

zyna IG-1 well. In the Podlasie Basin, the regional trend mentioned above (NE–SW) is similar. The values increase from 450 m at the Krzyże-4 borehole to over 750 m at the Okuniew IG-1 borehole. The lack of reliable data for the area between the Bodzanów IG-1 and Polik IG-1 wells is due to the very great depth of the rocks analysed. The burial was also great in the Lublin Basin, especially in the area between the Łopiennik IG-1 and Busówno IG-1 wells (up to 1,400 m; Fig. 12).

Late Cambrian through the Ordovician to the beginning of Silurian phase

In general, this phase is characterized by a much lower burial rate, compared to the Ediacaran to middle Cambrian phases (Fig. 13). The total burial depth of the sedimentary sequence at the end of this phase is only slightly greater than that obtained in the earlier phases. In the Baltic Basin, the burial depths increase from below 400 m (around the Gołdap IG-1 well) towards SW, reaching over 1,100 m in the vicinity of the Kościerzyna IG-1 well. In the Podlasie Basin, the regional trend (NE–SW) is similar. Values increase from about 500 m at the Krzyże-4 borehole to a value over 800 m, west of the Okuniew IG-1 borehole. The burial was the greatest in the Lublin Basin, especially between the Busówno IG-1 and Łopiennik IG-1 wells (up to around 1,500 m; Fig. 13).

Silurian phase

The total burial depth of the sedimentary sequence calculated for the end of the Silurian is shown in Figure 14. In the Baltic Basin, the values increase from NE to SW, from about 600 m (in the vicinity of the Gołdap IG-1 well) to over 3,000 m in the area between the Kościerzyna IG-1 and Słupsk IG-1 wells. In the Podlasie Basin, the regional trend is similar. The values increase from the NE (about 400–500 m) to over 2,000 m in the vicinity of the Okuniew IG-1 borehole. In the area between the Bodzanów IG-1 and Polik IG-1 wells, the burial reached ca. 1,600 m. In the Lublin Ba-

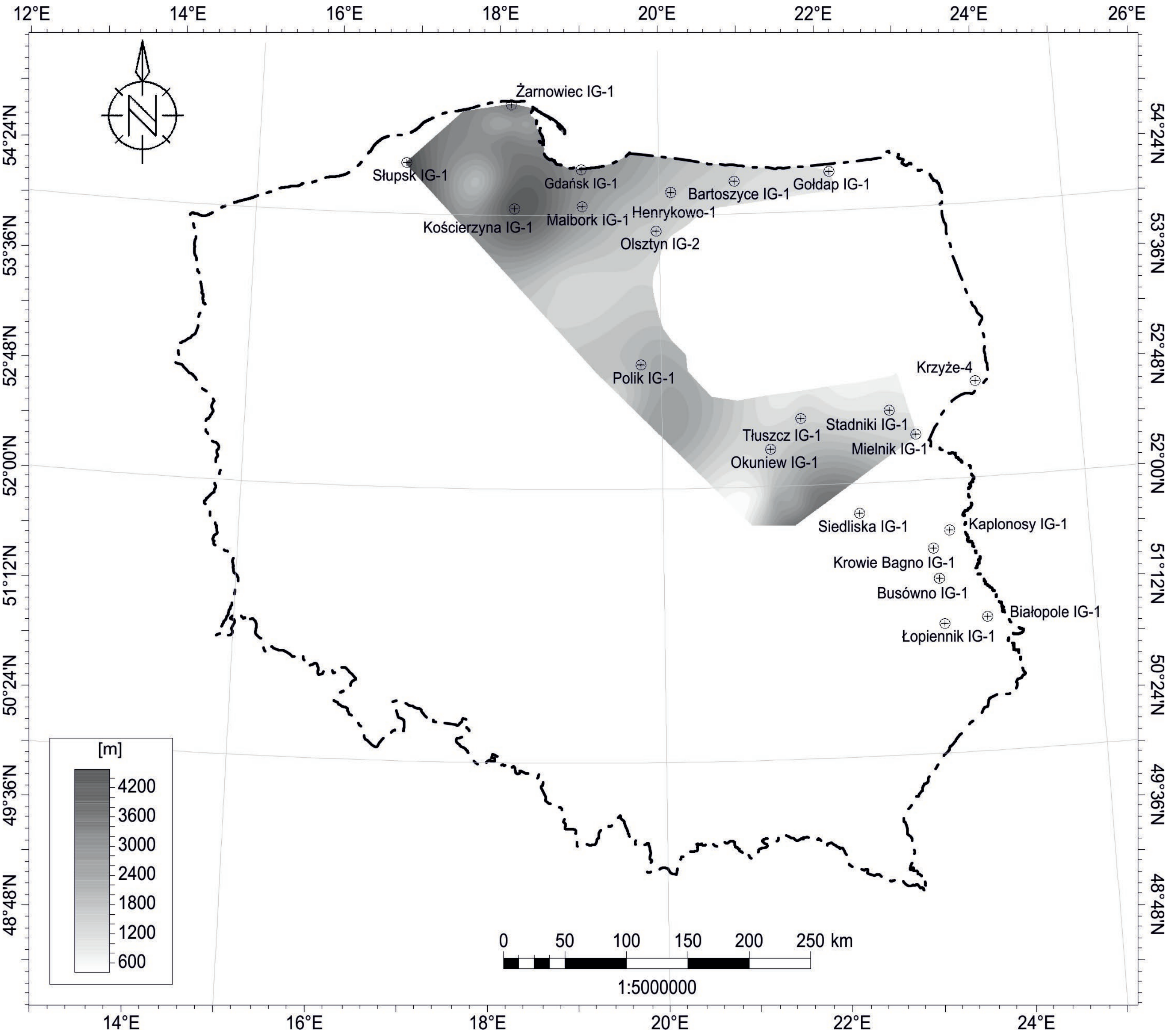

Fig. 17. Total burial depth of sedimentary sequence in Permian to Early Triassic time (in m). Based on Botor *et al.* (2017c), modified.

sin the burial increases from ca. 1,000–1,200 m in the area between the Stadniki IG-1 and Mielnik IG-1 wells to over 2,500 m at the Łopiennik IG-1 well (Fig. 14).

Devonian phase

The total burial depth of the sedimentary sequence at the end of the Devonian is shown in Figure 15. In the Baltic Basin, the burial values increase from NE to SW, from about 600–700 m (at the Gołdap IG-1 well) to over 4–5 km in the area between the Kościerzyna IG-1 and Słupsk IG-1 wells. In the Podlasie Basin, the regional trend is similar. The values increase from the NE (from about 500 m) to over 2,000 m at the Okuniew IG-1 borehole. In the area between the Bodzanów IG-1 and Polik IG-1 wells, the total burial reached approximately 4,000–5,000 m. In the Lublin Basin, it increases from approx. 1,200–1,400 m in the area between the Stadniki IG-1 and Mielnik IG-1 wells up to 4,000–5,000 m in the southern part, especially in the area between the Łopiennik IG-1 and Narol IG-2 wells (Fig. 15).

Carboniferous phase

The extent of Carboniferous sedimentation was smaller than during the earlier phases of development. The total burial depth of the sedimentary sequence at the end of the Carboniferous is shown in Fig. 16. In the Baltic Basin, the burial depths increase from NE to SW, from about 1,000 m to over 5–6 km in the area between the Kościerzyna IG-1 and Słupsk IG-1 wells. In the Podlasie Basin, the regional trend (NE–SW) is similar. Values increase from approx. 1,000 m in the area between the Stadniki IG-1 and Tłuszcz IG-1 boreholes, to a value of over 3,000 m in the area between the Maciejowice IG-1 and Izdebno IG-1 boreholes. In the Lublin basin, the total burial depth increases from approximately 1,000–1,500 m in the area between the Stadniki IG-1 and Mielnik IG-1 wells up to over 3,000 m in the SW part. Especially in the area between the Łopiennik IG-1 and Busówno IG-1 wells, there is a positive anomaly of the burial depth, which reaches the Narol IG-1 well (up to approx. 4,000–5,000 m; Fig. 16).

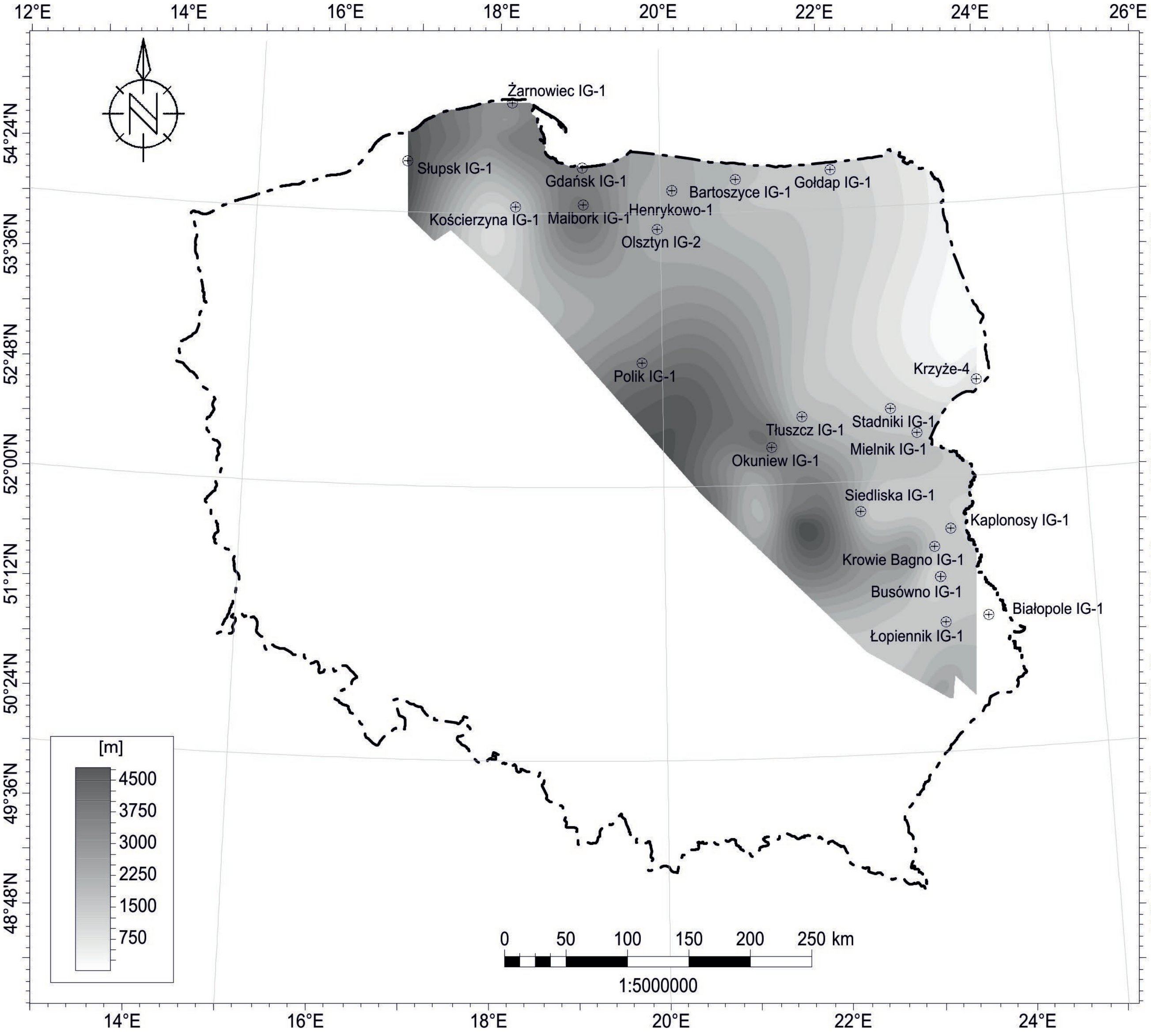

Fig. 18. Total burial depth of sedimentary sequence in Middle Triassic–Jurassic time (in m). Based on Botor *et al.* (2017c), modified.

Permian to Early Triassic phase

The total burial depth of the sedimentary sequence at the end of the Permian–Early Triassic is shown in Figure 17. In the NE part of the EEC, the burial depth reaches over 1,000 m (in the area between the Gołdap IG-1 and Stadniki IG-1 wells). The total burial increases towards the SW up to over 4,000 m in the area between the Kościerzyna IG-1 and Słupsk IG-1 boreholes and up to over 3,000 m in the area between the Maciejowice IG-1 and Izdebno IG-1 wells. In the southern part of the Lublin Basin, sediments of this age do not occur and probably it was a period of non-deposition and erosion of the older sediments (Fig. 17).

Middle Triassic–Jurassic phase

The total burial depth of the sedimentary sequence at the end of the Middle Triassic–Jurassic is shown in Figure 18. In the NE part of the EEC, the burial depth was around 600–800 m (between the Krzyże-4 and Gołdap IG-1 wells). The total burial increases towards the SW to over 4,000 m in the area between the Słupsk IG-1 and Bodzanów IG-1 wells (Fig. 18).

Cretaceous phase

The minimum values below 800 m burial occur in the NE region of the EEC (between wells Gołdap IG-1 and Krzyże-4). The burial depth of sedimentary sequences is increasing towards SW, reaching over 5,000 m along the TTZ (between the Słupsk IG-1, Kościerzyna IG-1, Bodzanów IG-1 and Łopiennik IG-1 wells; Fig. 19).

Summary of burial history

Ediacaran–Lower Palaeozoic phase

The geological development in this phase commenced with an event of relatively rapid tectonic subsidence in the latest Ediacaran, which was followed by a systematically decreasing rate of subsidence during the Cambrian and Ordovician, clearly visible close to TTZ. Towards the east and

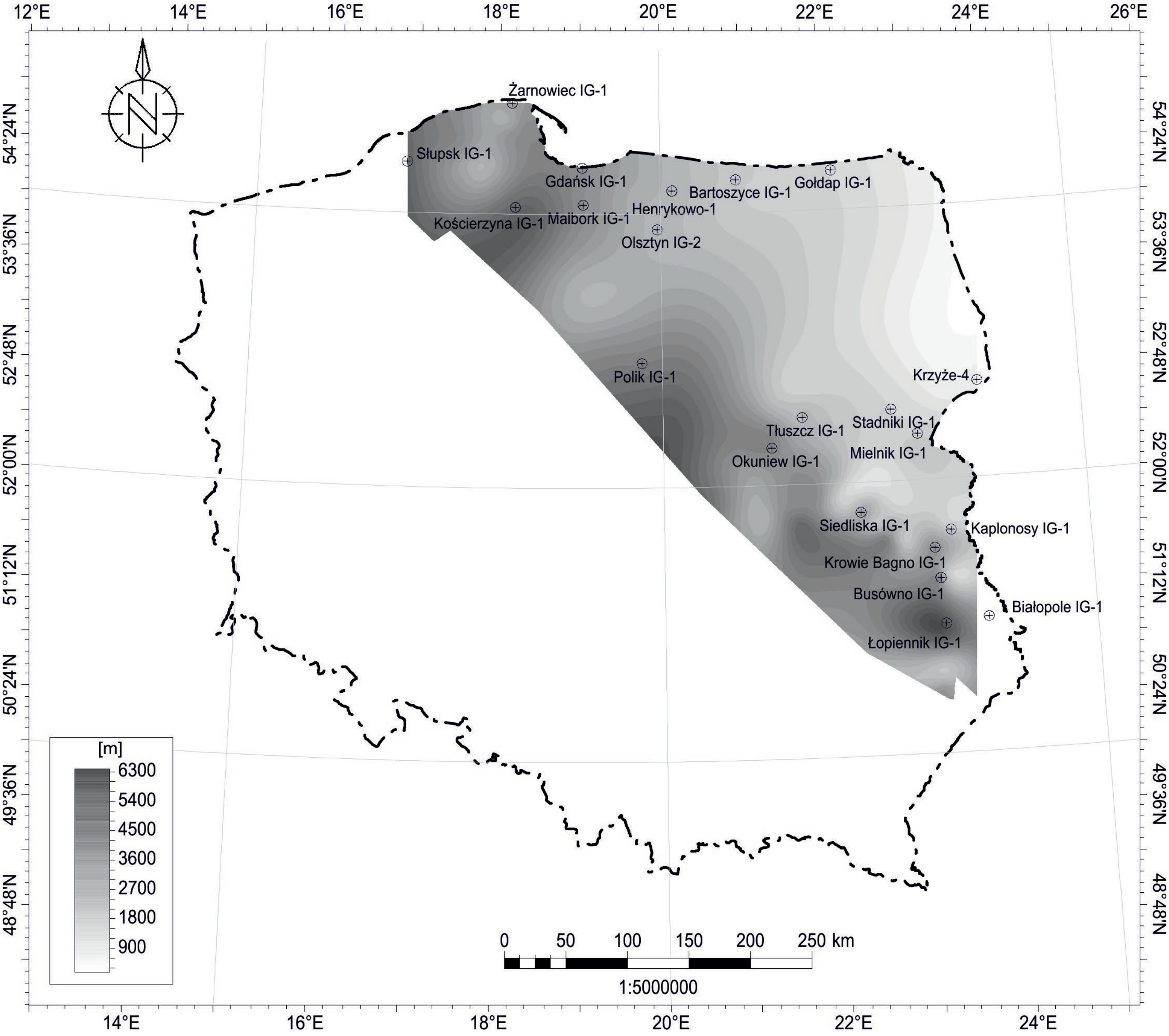

Fig. 19. Total burial depth of sedimentary sequence in the Cretaceous Period (in m). Based on Botor *et al.* (2017c), modified.

NE, i.e. away from the EEC margin, the pattern of subsidence rate decreases in time throughout the Ediacaran, Cambrian and Ordovician and is less prominent owing to the lesser thickness of the Ediacaran–Ordovician section. In the Silurian, particularly from the Wenlock, a significant change in subsidence pattern compared to the Ediacaran–Ordovician is observed across the whole SW margin of the EEC. Subsidence began to increase in rate systematically from the Wenlock to the end of Silurian time, creating subsidence curves with convex shapes that are typical of foreland basin development (Poprawa *et al.*, 1999, 2017, 2018; Stypa *et al.*, 2017). A high subsidence rate is common, particularly in the SW and western parts of the EEC slope.

Devonian to Carboniferous phase

The phase of Devonian–Carboniferous subsidence determined in the area of the Baltic Basin has been documented in the Podlasie-Lublin area (Żelichowski, 1987; Narkiewicz *et al.*, 1998, 2011, 2015; Narkiewicz, 2007; Narkiewicz and Narkiewicz, 2008; Krzywiec, 2009; Krzywiec *et al.*, 2017a, b; Stypa *et al.*, 2017). In the Lublin area and in part the Podlasie area, Devonian–Carboniferous deposits, belonging to the Variscan orogen (Krzywiec *et al.*, 2017a, b), rest on Lower Palaeozoic deposits. The location near the edge of the craton (TTZ) determined the development of subsidence and sedimentation of Devonian–Carboniferous sediments in the dynamically changing field of stress, transferred from the Variscan orogen as well as from the interior of the EEC. The Early Devonian to the Middle Devonian shows a gradual decrease in the rate of subsidence. The subsidence rate of this phase decreases towards the north (Maciejowice IG-1) and to the NE of the axis of the depocentre of the Mazowsze-Lublin Trough. The second phase consists mainly of the Late Devonian and is characterized by a rapid acceleration in the rate of subsidence in the Frasnian and a reduction during the Fammenian (Narkiewicz *et al.*, 1998; Narkiewicz, 2003, 2007). The next phase is related to the episode of uplift and erosion in the Early Carboniferous.

The interpreted amounts of this erosion probably could amount to between 200 and 2,000 m (Żelichowski, 1987). The next phase is characterized by an increase in the rate of subsidence in the late Viséan to Westphalian, with a local episode of reduction of the subsidence rate in the middle part of the Namurian. Then, at the turn of the Late Carboniferous to Early Permian, tectonic inversion and significant erosion of Carboniferous and sometimes Devonian deposits occurred in the Asturian (?) phase (Narkiewicz *et al*., 1998; Botor *et al*., 2002; Narkiewicz, 2003, 2007; Narkiewicz *et al*., 2011). On the basis of seismic research, the development of Variscan tectonics in the Lublin area recently was postulated (Krzywiec *et al*., 2017a, b), suggesting erosion of a significant thickness of the overburden, mainly Carboniferous in age.

Permian–Cainozoic

From the Permian, the SW zones of the slope of the EEC analyzed, both Baltic and Podlasie-Lublin, were located on the marginal part of the Permian–Mesozoic basin of Central Poland. The Permian and Mesozoic formations in the Middle Polish Basin rest on the age-related links of the Palaeozoic, the genesis of which is connected with the development of rift processes in the Permian (Dadlez *et al*., 1995; Poprawa, 1997; Karnkowski, 1999; Kutek, 2001). The deposition of the Permian sediments occurred during a period of relatively rapid subsidence, continuing through the Late Permian and Early Triassic (Dadlez *et al*., 1995; Poprawa, 1997; Poprawa, 2007a, 2008a, 2011a; Poprawa *et al*., 2010). This event is correlated with the tectonic phase, commonly observed in the Middle Polish Basin and interpreted as the syn-rift phase (Dadlez *et al*., 1995). Then, for most of the Triassic, Jurassic and Early Cretaceous, tectonic subsidence related to the rift phase of thermal subsidence was maintained (Dadlez *et al*., 1995; Poprawa, 1997; Karnkowski, 1999; Kutek, 2001). It affects to a small extent the changes in subsidence of the Lower Palaeozoic deposits. In the Late Cretaceous, in the study area, as well as in the other zones of the Polish Basin, a process of tectonic reactivation took place, expressing the accelerated subsidence in a compressive tectonic regime (Dadlez *et al*., 1995; Krzywiec, 2002). Taking into account the evolution of the Polish basin at this time, it can be assumed that this process took place in a tectonic regime of compression (Dadlez *et al*., 1995; Krzywiec, 2002) and at the end of the Cretaceous underwent tectonic inversion (Dadlez *et al*., 1995; Krzywiec, 2002; Resak *et al*., 2008, 2009). The Cainozoic deposits, owing to the very minor thickness and variability of distribution in the study area, do not significantly affect the curves of subsidence of the Lower Palaeozoic sediments (Poprawa, 2007a, 2008a, 2011a; Poprawa *et al*., 2010). The development of the Permian–Mesozoic subsidence in the study area should be considered relatively insignificant among the subsidence processes affecting the Lower Palaeozoic sediments.

CONCLUSIONS

The results of thermochronological research and maturity modelling showed that the Ordovician and Silurian strata occurring on the SW margin of the EEC already reached a maximum palaeotemperature in the Palaeozoic, mainly during the Devonian–Carboniferous. The increase in temperature was highest in the Devonian Period in the greater part of the study area. In Mesozoic and Cainozoic times, the Ordovician and Silurian strata generally were subjected to cooling or to a very small increase in temperature, lower than that attained during the Palaeozoic. The maximum burial of the Ediacaran–Lower Palaeozoic strata was during the Early Carboniferous in the Baltic Basin and in the Late Carboniferous in the Lublin area. In the Baltic Basin, the maximum palaeotemperatures occurred in the Late Devonian and Early Carboniferous and in the Podlasie-Lublin region at the turn of the Late Carboniferous and Early Permian. The least unambiguous are the results in the Polik-Bodzanów Zone, where the maximum temperatures could have occurred either at the end of the Silurian, in the Devonian (Bodzanów IG-1) or in the Late Carboniferous (Polik IG-1). Only in the Mazovian area between the Nadarzyn IG-1 and Maciejowice IG-1 wells, the maximum burial and maximum temperatures could have occurred in the late Mesozoic. Thus, the main period of maturation of organic matter and hydrocarbon generation in the Ordovician and Silurian source rocks was the Late Palaeozoic (mainly Devonian to Late Carboniferous), while in the westernmost zone along the TTZ the temperature rise at the end of the Silurian was significant. In the Lublin region, the results of the thermal maturity modelling are consistent with the interpretation proposed by Antonowicz *et al*. (2003) and Krzywiec *et al*. (2017a, b). This concept suggests the existence of large Variscan shifts in the Lublin and Radom-Kraśnik areas as well as the existence of a significant, exhumed overburden, especially of Carboniferous age. Consequently, the extent of the Carboniferous sediments could have been much greater than previously thought (e.g., Narkiewicz *et al*., 1998; Narkiewicz, 2007).

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REFERENCES

Anczkiewicz, A. A., Środoń, J. & Paszkowski, M., 2018. Thermal history of the western part of the East European Craton. In: *Thermo 2018: 16th International Conference on Thermochronology, 16-21.09.2018, Palais Salfeldt - Quedlinburg (Germany). Conference Book of Abstracts.* University of Bremen, Bremen, Germany, p. 4.

Antonowicz, L., Hooper, R. & Iwanowska, E., 2003. Lublin Syncline as a result of thin-skinned Variscan deformation (SE Poland). *Przegląd Geologiczny*, 51: 344–350. [In Polish, with English summary.]

Botor, D., 1997. *Petroleum Generation in the Lower and Upper Paleozoic Strata of the Lublin Basin Constrained by 2-D* *modelling and Organic Geochemistry and Petrology*. Archive of the Forschungszentrum, Jülich, Germany, 64 pp.

Botor, D., 1999. *Procesy generowania i ekspulsji węglowodorów w utworach karbonu Rowu Lubelskiego*. Unpublished PhD. Dissertation, *AGH University of Science and Technology, Kraków*, 143 pp. [In Polish.]

Botor, D., 2007. Thermal history of the Carboniferous strata in the Lublin Trough (Lublin Coal Basin) constrained by a numerical maturity modelling approach. *Górnictwo i Geologia*, 2: 5–16. [In Polish, with English abstract.]

Botor, D., 2014. Timing of coalification of the Upper Carboniferous sediments in the Upper Silesia Coal Basin (SW Poland) on the basis of by apatite fission track and helium dating. *Gospodarka Surowcami Mineralnymi*, 30: 85–104. [In Polish, with English abstract.]

Botor, D., 2016. Hydrocarbon generation in the Upper Cambrian–Lower Silurian source rocks of the Baltic Basin (Poland): implications for shale gas exploration. In: *16th International Scientific GeoConference SGEM, Vienna, Austria*. *Book 1, Oil and Gas section*. International Multidisciplinary Scientific GeoConferences, Sofia, Bulgaria. pp. 127–134.

Botor, D., 2018. Tectono-thermal evolution of the lower Paleozoic petroleum source rocks in the southern Lublin Trough, implications for shale gas exploration from maturity modelling. *E3S Web of Conferences 35*, 02002, EDP Sciences, Paris, France, doi.org/10.1051/e3sconf/20183502002.

Botor, D. & Anczkiewicz, A. A., 2010. Zastosowanie metody trakowej i helowej do rekonstrukcji termicznej basenów sedymentacyjnych. *Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój*, 49: 133–149. [In Polish.]

Botor, D., & Anczkiewicz, A. A., 2015. Thermal history of the Sabero Coalfield (Southern Cantabrian Zone, NW Spain) as revealed by apatite fission-track analyses from tonstein horizons: implications for timing of coalification. *International Journal of Earth Sciences,* 104: 1779–1793.

Botor, D., Anczkiewicz A. A., Dunkl, I., Golonka, J., Paszkowski, M. & Mazur, S., 2018. Tectonothermal history of the Holy Cross Mountains (Poland) in light of low-temperature thermochronology. *Terra Nova*, 30: 270–278.

Botor, D., Dunkl, I., Anczkiewicz, A. A. & Mazur S., 2017a. Post-Variscan thermal history of the Moravo-Silesian lower Carboniferous Culm Basin (NE Czech Republic – SW Poland). *Tectonophysics,* 712–713: 643–662.

Botor, D., Golonka, J., Anczkiewicz, A. A. & Dunkl, I., 2017b. Ewolucja paleotermiczna przedpola platformy wschodnioeuropejskiej (Góry Świętokrzyskie) na tle badań termochronologicznych utworów dolnopaleozoicznych. 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. 381–392. [In Polish.]

Botor, D., Golonka, J., Anczkiewicz, A. A., Dunkl, I., Papiernik, B., Zając, J. & Guzy, P., 2017c. Historia pogrążania utworów dolnopaleozoicznych i ich ewolucja paleotermiczna w obszarze platformy wschodnioeuropejskiej na tle badań termochronologicznych. 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. 393–422. [In Polish.]

Botor, D., Golonka, J., Papiernik, B., Zając, J. & Guzy, P., 2017d. Generowanie i ekspulsja węglowodorów w utworach dolnopaleozoicznych w obszarze SW skłonu wschodnioeuropejskiej platformy prekambryjskiej w NE Polsce: implikacje dla poszukiwań złóż niekonwencjonalnych. 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. 423–451. [In Polish.]

Botor, D., Golonka, J., Zając, J., Papiernik, B. & Guzy, P., 2019. Petroleum generation and expulsion in the Lower Paleozoic petroleum source rocks in the SW margin of the East European Craton (Poland). *Annales Societatis Geologorum Poloniae,* 89: 153–174.

Botor, D. & Kosakowski, P., 2000. Application of numerical maturity modelling to reconstruction of paleotemperature and petroleum. *Przegląd Geologiczny*, 48: 154–162. [In Polish, with English abstract.]

Botor, D., Kotarba, M. & Kosakowski, P., 2002. Petroleum generation in the Carboniferous strata of the Lublin Trough (Eastern Poland): an integrated geochemical and numerical modelling approach. *Organic Geochemistry*, 33: 461–476.

Botor, D. & Littke, R., 2003. 2-D numerical modelling by Petromod software of the burial and thermal history of the coal-bearing Lublin Carboniferous Basin. In: Lipiarski, I. (ed.), *Proceedings of the International Conference – Geology of Coal-bearing Basins, Kraków, 20–21.04.2004*. Wydawnictwo Akademii Górniczo- Hutniczej, Kraków, pp. 42–46.

Botor, D., Toboła, T. & Jelonek, I., 2017e. Thermal history of the lower Carboniferous Culm Basin in the Nízký Jeseník Mts. (NE Bohemian Massif, Czech Republic and Poland). *Annales Societatis Geologorum Poloniae,* 87: 13–40.

Burzewski, W., Kotarba, M., Kosakowski, P., Botor, D. & Słupczyński, K., 1998. Petroleum generation and expulsion modelling in the Upper Paleozoic strata of the Radom-Lublin and Pomeranian areas. In: Narkiewicz, M. (ed.), *Analiza basenów sedymentacyjnych Niżu Polskiego. Prace Państwowego Instytutu Geologicznego*, 165: 273–284.

Cederbom, C., Larson, S. Å., Tullborg, E. L. & Stiberg, J. P., 2000. Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden. *Tectonophysics,* 316: 153–167.

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,* 252: 179–195.

Drygant, D., 1993. Conodont colour as indicator of the geological processes (Volyn-Podolia). *Paleontologiceskij Zbirnyk*, 29: 35–137. [In Ukrainian.]

Fredin, O., Viola, G., Zwingmann H., Sørlie, R., Brönner, M., Lie, J. E., Grandal, E. M., Müller, A., Margreth, A., Vogt, C. & Knies, J., 2017. The inheritance of a Mesozoic landscape in western Scandinavia. *Nature Communications* 8, Article 14879, doi: 10.1038/ncomms14879.

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 węglowodorów*. Wydawnictwo Arka, Cieszyn, Poland, 504 pp. [In Polish.]

Golonka, J., Krzywiec, P., Pietsch, K., Barmuta, J., Bębenek, S., Botor, D., Porębski, S. J., Papiernik, B., Barmuta, M., Michna, M., Buniak, A. & Mikołajewski, Z., 2017. Paleozoic Evolution of the Eastern European Platform in Poland and Shale Gas Potential. *AAPG Datapages/Search and Discovery Article #90291, AAPG Annual Convention, Houston, USA, April 2–5, 2017*. http://www.searchanddiscovery.com/abstracts/html/2017/90291ace/abstracts/2611996.html [02.04. 2017].

Górecki, W. (ed.), Szczepański, A., Sadurski, A., Hajto, M., Papiernik, B., Kuźniak, T., Kozdra, T., Soboń, J., Szewczyk, J., Sokołowski, A., Strzetelski, W., Haładus, A., Kania, J., Kurzydłowski, K., Gonet, A., Capik, M., Śliwa, T., Ney, R., Kępińska, B., Bujakowski, W., Rajchel, L., Banaś, J., Solarski, W., Mazurkiewicz, B., Pawlikowski, M., Nagy, S., Szamałek, K., Feldman-Olszewska, A., Wagner, R., Kozłowski, T., Malenta, Z., Sapińska-Śliwa, A., Sowiżdżał, A., Kotyza, J., Leszczyński, K. P. & Gancarz, M., 2006a. *Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands*. Wydawnictwo AGH, Kraków, 484 pp.

Górecki, W. (ed.), Szczepański, A., Sadurski, A., Hajto, M., Papiernik, B., Szewczyk, J., Sokołowski, A., Strzetelski, W., Haładus, A., Kania, J., Rajchel, L., Feldman-Olszewska, A., Wagner, R., Leszczyński, K. P. & Sowiżdżał A., 2006b. *Atlas of Geothermal Resources of Paleozoic Formations in the Polish Lowlands*. Wydawnictwo AGH, Kraków, 240 pp.

Grocholski, A. & Ryka, W., 1995. Carboniferous magmatism in Poland. In: Zdanowski, Z. & Żakowa, H. (eds), *The Carboniferous in Poland. Prace Państwowego Instytutu Geologicznego*, 148: 181–189.

Grotek, I., 1998. Thermal maturity of organic matter in the Zechstein deposits of the Polish Lowlands area. In: Narkiewicz, M. (ed.), *Analiza basenów sedymentacyjnych Niżu Polskiego. Prace Państwowego Instytutu Geologicznego*, 165: 255–260. [In Polish, with English summary.]

Grotek, I., 1999. Origin and thermal maturity of the organic matter in the Lower Paleozoic rocks of the Pomerania Caledonides and their foreland (N Poland). *Geological Quarterly*, 43: 297–312.

Grotek, I., 2005. Alteration of the coalification degree of the organic matter dispersed in the Carboniferous sediments along border of the East-European Craton in Poland. *Biuletyn Państwowego Instytutu Geologicznego*, 413: 5–80. [In Polish, with English abstract.]

Grotek, I., 2006. Thermal maturity of organic matter from the sedimentary cover deposits from Pomeranian part of the TESZ, Baltic Basin and adjacent area. In: Matyja, H. & Poprawa, P. (eds), *Ewolucja facjalna, tektoniczna i termiczna pomorskiego segmentu szwu transeuropejskiego oraz obszarów przyległych*. *Prace Państwowego Instytutu Geologicznego*, 186: 253–270. [In Polish, with English summary.]

Grotek, I., 2015. Charakterystyka petrograficzna oraz dojrzałość termiczna materii organicznej rozproszonej w utworach kambru–syluru. In: Pacześna, J. & Sobień, K. (eds), *Narol IG 1, Narol PIG 2***.** *Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego***,** 143: 160–167. [In Polish.]

Grotek, I., 2016. A petrologic study and thermal maturity of organic matter from the Cambrian, Ordovician and Silurian deposits in the Baltic and Podlasie-Lublin areas. *Przegląd Geologiczny*, 64: 1000–1004. [In Polish, with English abstract.]

Grotek, I., Matyja, H. & Skompski, S., 1998. Thermal maturity of organic matter in the Carboniferous deposits of the Radom-Lublin and Pomerania areas. In: Narkiewicz, M. (ed.), *Analiza basenów sedymentacyjnych Niżu Polskiego. Prace Państwowego Instytutu Geologiczneg*o, 165: 245–254. [In Polish, with English summary]

Guterch, A. & Grad, M., 2006. Lithospheric structure of the TESZ in Poland based on modern seismic experiments. *Geological Quarterly*, 50: 23–32.

Hansen, K., 1995. Fennoscandian Borderzone thermal and tectonic history of a tufaceous sandstone and granite from fission track analysis, Bornholm, Denmark. *Tectonophysics*, 244: 153–160.

Hantschel, T. & Kauerauf A., 2009. *Fundamentals of Basin and Petroleum Systems Modeling*. Springer, Heidelberg, 436 pp.

Helcel-Weil, M., Dzięgielowski, J., Florek, R., Maksym, A. & Słyś, M., 2007. The Lublin Basin: petroleum exploration results and their importance for future prospects. *Biuletyn Państwowego Instytutu Geologicznego*, 411: 51–62. [In Polish, with English summary.]

Hunt, J. M., 1996. *Petroleum Geochemistry and Geology*. W. H. Freeman and Company, New York, 604 pp.

Huigen, Y. & Andriessen, P. A. M., 2004. Thermal effects of Caledonian foreland basin formation, based on fission track analyses applied on basement rocks in central Sweden. *Physics and Chemistry of Earth*, 29: 683–694.

Kanev, S., Margulis, L., Bojesen-Koefoed, J. A., Weil, W. A., Merta, H. & Zdanaviciute, O., 1994. Oils and hydrocarbon source rocks of the Baltic syneclise. *Oil and Gas Journal*, 92: 69–73.

Karnkowski, P., 1993. *Złoża gazu ziemnego i ropy naftowej w Polsce, Tom 1. Niż Polski.* Wydawnictwo GEOS, Kraków, 326 pp. [In Polish.]

Karnkowski, P. H., 1999. Origin and evolution of the Polish Rotliegend basin. *Polish Geological Institute Special Papers,* 3: 1–93.

Karnkowski, P. H., 2003a. Carboniferous time in the evolution of the Lublin Basin as the main hydrocarbon formation stage in the Lublin area – results of the geological modelling (PetroMod). *Przegląd Geologiczny*, 51: 783–790. [In Polish, with English abstract.]

Karnkowski, P. H., 2003b. Modelling of hydrocarbon generating conditions within Lower Palaeozoic strata in the western part of the Baltic Basin. *Przegląd Geologiczny*, 51: 756–763. [In Polish, with English abstract.]

Karnkowski, P. H., 2007. Petroleum provinces in Poland. *Przegląd Geologiczny*, 55: 1061–1067.

Karwasiecka, M., 2008. Porównanie środowiska geotermicznego w obrębie basenów węglonośnych Lubelskiego i Górnośląskiego Zagłębia Węglowego. *Kwartalnik AGH – Geologia*, 34: 335–357. [In Polish.]

Klimuszko, E., 2002. Silurian sediments from SE Poland as a potential source rocks for Devonian oils. *Biuletyn Państwowego Instytutu Geologicznego,* 402: 75–100. [In Polish, with English summary.]

Kosakowski, P., Kotarba, M. J., Piestrzyński, A., Shogenova, A. & Więcław, D., 2016 Petroleum source rock evaluation of the Alum and Dictyonema Shales (Upper Cambrian–Lower Ordovician) in the Baltic Basin and Podlasie Depression (eastern Poland). *International Journal of Earth Sciences,* 106: 743–761.

Kosakowski, P., Poprawa, P. & Botor, D., 1998. Historia subsydencji i procesów generowania węglowodorów w utworach starszego paleozoiku syneklizy perybałtyckiej. In: Matyasik, I. (ed.), *III Sympozjum badania geochemiczne i petrofizyczne w poszukiwaniach naftowych. Ustroń 20–22.09.1998*. Wydawnictwo Instytutu Górnictwa Nafty i Gazu, Kraków, pp. 133–140. [In Polish.]

Kosakowski, P., Poprawa, P., Kotarba, M. J. & Botor, D., 1999. Modelling of thermal history and hydrocarbon generation of the western part of the Baltic region. *EAGE 61st Conference, Helsinki, June 7–11, 1999. Extended Abstracts Book*, 2, p. 565.

Kosakowski, P., Wróbel, M. & Krzywiec, P., 2013. Modelling hydrocarbon generation in the Paleozoic and Mesozoic successions in SE Poland and West Ukraine. *Journal of Petroleum Geology*, 36: 139–161.

Kosakowski, P., Wróbel, M. & Poprawa, P., 2010. Hydrocarbon generation and expulsion modelling of the lower Paleozoic source rocks in the Polish part of the Baltic region. *Geological Quarterly*, 54: 241–256.

Kowalska, S., Wójtowicz, A, Hałas, S., Wemmer, K., Mikołajewski, Z. & Buniak, A., 2017. Odtworzenie historii paleotermicznej skał paleozoicznych na podstawie badania skał ilastych ze strefy krawędziowej platformy wschodnioeuropejskiej metodą K-Ar. 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. 452–471. [In Polish.]

Kozłowska, A., 2011. Clay minerals in the Carboniferous sandstones of the southeastern part of the Lublin basin as paleotemperature indicators of diagenesis. *Biuletyn Państwowego Instytutu Geologicznego*, 444: 99–112.

Kozłowska, A. & Poprawa, P., 2004. Diagenesis of the Carboniferous clastic sediments of the Mazowsze region and the northern Lublin region related to their burial and thermal history. *Przegląd Geologiczny*, 52: 491–500. [In Polish, with English abstract.]

Krakowska, P. I., 2017. Digital rock models of Precambrian and Paleozoic tight formations from Poland. *Geological Quarterly*, 61: 896–907.

Krzemiński, L. & Poprawa, P., 2006. Geochemistry of the Ordovician and Silurian clastic sediments of the Koszalin-Chojnice Zone and the western Baltic Basin. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 123–142. [In Polish, with English abstract.]

Krzywiec, P., 2002. Mid-Polish Trough inversion - seismic examples, main mechanisms and its relationship to the Alpine-Carpathian collision. In: Berotti, G., Schulmann, K. & Cloetingh, S. (eds), *Continental Collision and the Tectonosedimentary Evolution of Forelands*, *European Geosciences Union Stephan Mueller Special Publication Series*, pp. 151–165.

Krzywiec, P., 2009. Devonian–Cretaceous repeated subsidence and uplift along the Teisseyre-Tornquist zone in SE Poland - Insight from seismic data interpretation. *Tectonophysics*, 475: 142–159.

Krzywiec, P., Gągała, Ł., Mazur, S., Słonka, Ł., Kufrasa, M., Malinowski, M., Pietsch, K. & Golonka, J., 2017a. Variscan deformation along the Teisseyre-Tornquist Zone in SE Poland: Thick-skinned structural inheritance or thin-skinned thrusting? *Tectonophysics*, 718: 83–91.

Krzywiec, P., Malinowski, M., Lis, P., Buffenmyer, V. & Lewandowski, M., 2014. Lower Paleozoic basins developed above the East European Craton in Poland: New insight from regional high-effort seismic reflection data. *SPE/EAGE European Unconventional Resources Conference and Exhibition, Vienna (extended abstract), Book of Abstracts*, SPE-167739-MS. The European Association of Geoscientists and Engineers, Houten, The Netherlands, p. 143.

Krzywiec, P., Mazur, S., Gągała, Ł., Kufrasa, M., Lewandowski, M., Malinowski, M. & Buffenmyer, V., 2017b. Late Carboniferous thin-skinned compressional deformation above the SW edge of the East European Craton as revealed by reflection seismic and potential fields data – correlations with the Variscides and the Appalachians, In: Law, R., Thigpen, R., Stowell, H. & Merschat, A. (eds), *Linkages and Feedbacks in Orogenic Processes*. Geological Society of America Publishing House, New York, pp. 353–372.

Krzywiec, P., Poprawa, P., Mikołajczak, M., Mazur, S. & Malinowski, M., 2018. Deeply concealed half-graben at the SW margin of the East European Craton (SE Poland) -Evidence for Neoproterozoic rifting prior to the break-up of Rodinia. *Journal of Palaeogeography,* 7: 88–97.

Kutek, J., 2001. The Polish Permo–Mesozoic Rift Basin. *Mémoires du Muséum National d'Histoire Naturelle*, 186: 213–236.

Kutek, J. & Głazek, J., 1972. The Holy Cross area, central Poland, in the Alpine cycle. *Acta Geologica Polonica*, 22: 603–651.

Lamarche, J., Scheck, M. & Lewerenz, B., 2003. Heterogeneous tectonic inversion of the Mid-Polish Trough related to crustal architecture, sedimentary patterns and structural inheritance. *Tectonophysics*, 373: 75–92.

Larson, S. Å., Tullborg, E. L. Cederbom, C. & Stiberg, J. P., 1999. Sveconorwegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochronology. *Terra Nova*, 11: 210–215.

Lassen, A., Thybo, H. & Berthelsen, A., 2001. Reflection seismic evidence for Caledonian deformed sediments above Sveconorwegian basement in the SW Baltic Sea. *Tectonics*, 20: 268–276.

Lazauskiene, J., Stephenson, R. Šliaupa, S. & van Wees, J. D., 2002. 3-D flexural modelling of the Silurian Baltic Basin. *Tectonophysics*, 346: 115–135.

Majorowicz, J., 1975. Heat flow in the Polish Lowlands. *Acta Geophysica Polonica*, 23: 259–275.

Majorowicz, J., 1978. Mantle heat flow and geotherms for major tectonic units in Central Europe. *Pure & Applied Geophysics*, 117: 107–124.

Majorowicz, J., Marek, S. & Znosko, J., 1983. The paleogeothermics of central and south-eastern Polish Lowlands and its influence on generation and preservation of hydrocarbon. *Kwartalnik Geologiczny*, 27: 1–24. [In Polish, with English summary.]

Majorowicz, J., Marek, S. & Znosko, J., 1984. Paleogeothermal gradients by vitrinite reflectance data and their relation to the present geothermal gradient patterns of the Polish Lowlands. *Tectonophysics*, 103: 141–156.

Maletz, J., Baie, H., Katzung, G. & Niedźwiedź, A., 1997. A Lower Paleozoic (Ordovician–Silurian) foreland basin at the SW rim of Baltica. *Terra Nostra*, 11: 81–84.

Marek, S. & Pajchlowa, M. (eds), 1997. Epicontinental Permian and Mesozoic in Poland. *Prace Państwowego Instytutu Geologicznego*, 153: 1–284 [In Polish, with English summary.]

Matyasik, I., 1998. Geochemical characteristics of the Carboniferous source rocks in selected borehole profiles of the Radom-Lublin and Pomeranian areas. In: Narkiewicz, M. (ed.), *Prace Państwowego Instytutu Geologicznego*, 165: 215–226. [In Polish, with English summary.]

Matyja, H., 2006. Stratigraphy and facies development of Devonian and Carboniferous deposits in the Pomeranian Basin and in the western part of the Baltic Basin and palaeogeography of the northern TESZ during Late Palaeozoic times. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 79–122. [In Polish, with English summary.]

Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Buffenmyer, V. & Lewandowski, M., 2015. Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica? *Tectonics*, 34: 2465–2477.

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.

Mazur, S., Scheck-Wenderoth, M. & Krzywiec, P., 2005. Different modes of the Late Cretaceous–Early Tertiary inversion in the North German and Polish basins. *International Journal of Earth Sciences*, 94: 782–798.

McCann, T., 1998. Lower Paleozoic evolution of the northeast German Basin/Baltica borderland. *Geological Magazine*, 135: 129–142.

Meissner, R., Sadowiak, P. & Thomas, S. A., 1994. Avalonia, the third partner in the Caledonian collisions: Evidence from deep seismic data. *Geologische Rundschau*, 83: 186–96.

Modliński, Z. (ed.), 2010. *Atlas paleogeologiczny podpermskiego paleozoiku kratonu wschodnioeuropejskiego w Polsce i na obszarach sąsiednich*. Państwowy Instytut Geologiczny, Warszawa, 36 maps. [In Polish.]

Narkiewicz, M., 2003. Tectonic controls of the Lublin Graben (Late Devonian–Carboniferous). *Przegląd Geologiczny*, 51: 771–776. [In Polish, with English summary.]

Narkiewicz, M., 2007, Development and inversion of Devonian and Carboniferous basins in the eastern part of the Variscan foreland (Poland). *Geological Quarterly*, 51: 231–256.

Narkiewicz, M., Grad, M., Guterch, A. & Janik, T., 2011. Crustal seismic velocity structure of southern Poland: preserved memory of a pre-Devonian terrane accretion at the East European Platform margin. *Geological Magazine*, 148: 191–210.

Narkiewicz, M., Jarosiński, P., Krzywiec, P. & Waksmundzka, M., 2007. Regional controls on the Lublin Basin development and inversion in the Devonian and Carboniferous *Biuletyn Państwowego Instytutu Geologicznego*, 422: 19–34. [In Polish, with English summary.]

Narkiewicz, M., Maksym, A., Malinowski, M., Grad, M., Guterch, A., Petecki, Z., Probulski, J., Janik, T., Majdański, M., Środa, P., Czuba, W., Gaczyński, E. & Jankowski, L., 2015. Transcurrent nature of the Teisseyre-Tornquist Zone in Central Europe – results of the POLCRUST-01 deep reflection seismic profile. *International Journal of Earth Sciences*, 104: 775–796.

Narkiewicz, M. & Narkiewicz, K., 2008. The mid-Frasnian subsidence pulse in the Lublin Basin (SE Poland) sedimentary record, conodont biostratigraphy and regional significance. *Acta Geologica Polonica*, 58: 287–301.

Narkiewicz, M., Poprawa, P., Lipiec, M., Matyja, H. & Miłaczewski, L., 1998. Paleogeographic and tectonic setting and the Devonian–Carboniferous subsidence development of the Pomerania and Radom-Lublin areas (TESZ, Poland). In: Narkiewicz, M. (ed.), *Prace Państwowego Instytutu Geologicznego*, 165: 31–46. [In Polish, with English summary.]

Narkiewicz, M., Resak, M., Littke, R., & Marynowski, L. 2010. New constraints on the Middle Palaeozoic to Cenozoic burial and thermal history of the Holy Cross Mts. (central Poland): results of numerical modeling. *Geologica Acta*, 8: 189–205.

Nawrocki, J. & Poprawa, P., 2006. Development of Trans-European Suture Zone in Poland: from Ediacaran rifting to Early Palaeozoic accretion. *Geological Quarterly*, 50: 59–76.

Nehring-Lefeld, M., Modliński, Z. & Swadowska, E., 1997. Thermal evolution of the Ordovician in the western margin of the East-European Platform: CAI and R_o data. *Geological Quarterly*, 41: 129–137.

Nikishin, A. M., Ziegler, P. A., Stephenson, R. A., Cloethingh, S. A. P. L., Furne, A. V., Fokin, P. A., Ershov, A. V., Bolotov, S. N., Korotaev, M. V., Alekseev, A. S., Gorbachev, V. I., Shipilov, E. V., Lankreijer, A., Bembinova, E. Yu. & Shalimov, I. V., 1996. Late Permian to Triassic history of the East European Craton: dynamics of sedimentary basin evolution. *Tectonophysics*, 268: 23–63.

Oliver, G. J. H., Corfu, F. & Krogh, T. E., 1993. U-Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *Journal of the Geological Society, London*, 150: 355–369.

Pacześna, J., 2006. Evolution of Late Neoproterozoic–Early Cambrian rift depocenters and facies in the Lublin-Podlasie sedimentary basin. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 9–38. [In Polish, with English summary.]

Pańczyk, M. & Nawrocki, J., 2015. Tournaisian 40Ar/39Ar age for alkaline basalts from the Lublin Basin (SE Poland). *Geological Quarterly*, 59: 473–478.

Petersen, H. I, Schovsbo, N. H. & Nielsen, A. T., 2013. Reflectance measurements of zooclasts and solid bitumen in Lower Paleozoic shales, southern Scandinavia: Correlation to vitrinite reflectance. *International Journal of Coal Geology*, 114: 1–18.

Pletsch, T., Appel, J., Botor, D., Clayton, C. J., Duin, E. J. T., Faber, E., Górecki, W., Kombrink, H., Kosakowski, P., Kuper, G., Kus, J., Lutz, R., Mathiesen, A., Ostertag, C., Papiernik, B. & Van Bergen, F., 2010. Petroleum generation and migration. In: Doornenbal, J. C. & Stevenson, A. G. (eds), *Petroleum Geological Atlas of the Southern Permian, Basin Area.* EAGE Publications, Houten, Holland, pp. 225–253.

Plewa, M., 1991. Strumień cieplny na obszarze Polski. *Zeszyty Naukowe AGH*, 1373: 141–151. [In Polish.]

Plewa, S., 1994. *Rozkład parametrów geotermalnych na obszarze Polski*. Wydawnictwo CPPGSMiE PAN, Kraków, 170 pp. [In Polish.]

Podhalańska, T. & Modliński, Z., 2006. Stratigraphy and facies characteristics of the Ordovician and Silurian deposits of the Koszalin-Chojnice Zone; similarities and differences to the western margin of the East European Craton and Rügen area. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 39–78. [In Polish, with English summary.]

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., Pacześna, 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 abstract.]

Poprawa, P., 1997. Late Permian to Tertiary dynamics of the Polish Trough. *Terra Nostra*, 97: 104–109.

Poprawa, P., 2006a. Neoproterozoic break-up of the supercontinent Rodinia/Pannotia recorded by development of sedimentary basin at the western slope of Baltica. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 165–188. [In Polish, with English summary.]

Poprawa, P., 2006b. Development of the Caledonian collision zone along the western margin of Baltica and its relation to the foreland basin. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 189–214. [In Polish, with English summary.]

Poprawa, P., 2007a. Analiza subsydencji tektonicznej. In: Modliński, Z. (ed.), *Słupsk IG-1. Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 116: 109–112. [In Polish.]

Poprawa, P., 2007b. Analiza historii termicznej, warunków pogrzebania oraz historii generowania i ekspulsji węglowodorów. In: Modliński, Z. (ed.), *Słupsk IG-1. Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 116: 106–108. [In Polish.]

Poprawa, P., 2007c. Analiza subsydencji oraz historii termicznej. In: Modliński, Z. (ed.), *Busówno IG-1. Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 118: 148–151. [In Polish.]

Poprawa, P., 2008a. Analiza subsydencji tektonicznej oraz tempa depozycji. In: Pacześna, J. (ed.), Łopiennik IG-1. *Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 123: 194–196. [In Polish].

Poprawa, P., 2008b. Modelowanie historii termicznej oraz warunków pogrzebania. In: Pacześna, J. (ed.), Łopiennik IG-1. *Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 123: 196–200. [In Polish.]

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., 2011a. Analiza susbydencji tektonicznej oraz tempa depozycji. In: Pacześna, J., (ed.), *Parczew IG-10. Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 130: 147–149. [In Polish].

Poprawa, P., 2011b. Rekonstrukcja historii termicznej oraz warunków pogrzebania. In: Pacześna, J. (ed.), *Parczew IG-10. Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego*, 130: 149–152. [In Polish].

Poprawa, P., 2017. Neoproterozoiczno–dolnopaleozoiczny rozwój basenów osadowych na zachodnim skłonie kratonu wschodnioeuropejskiego oraz przyległej części strefy szwu transeuropejskiego. 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. 12–28. [In Polish.]

Poprawa, P. & Andriessen, P., 2006. Apatite fission track thermochronology of the northern and central part of the Polish Basin – preliminary results. In: Poprawa, P. & Matyja, H. (eds), *Prace Państwowego Instytutu Geologicznego*, 186: 289–299. [In Polish, with English summary.]

Poprawa, P. & Grotek, I., 2005. Revealing palaeo-heat flow and paleooverpressures in the Baltic Basin from thermal maturity modelling. *Mineralogical Society of Poland, Special Papers*, 26: 235–238.

Poprawa, P., Kosakowski, P. & Wróbel, M., 2010. Burial and thermal history of the Polish part of the Baltic region. *Geological Quarterly*, 54: 131–142.

Poprawa, P. & Pacześna, J., 2002. Rift development in Late Neoproterozoic–Early Paleozoic in the Lublin-Podlasie part of the East European Craton slope – subsidence analysis and facies record. *Przegląd Geologiczny*, 50: 49–61. [In Polish, with English abstract.]

Poprawa, P., Radkovets, N. & Rauball, J., 2018. Ediacaran–Paleozoic subsidence history of the Volyn-Podillya-Moldavia basin (Western and SW Ukraine, Moldavia, NE Romania). *Geological Quarterly*, 62: 459–486.

Poprawa, P., Šliaupa, S., Stephenson, R. A. & Lazauskiene, J., 1999. Late Vendian–Early Palaeozoic tectonic evolution of the Baltic Basin: regional implications from subsidence analysis. *Tectonophysics*, 314: 219–239.

Poprawa, P. & Żywiecki, M. 2005. Heat transfer during development of the Lublin Basin: maturity modelling and fluid inclusion analysis. *Mineralogical Society of Poland, Special Papers*, 26: 241–250.

Porzycki, J. & Zdanowski, Z., 1995. Lithostratigraphy and sedimentologic-paleogeographic development of the Lublin Carboniferous Basin. In: Zdanowski, Z. & Żakowa, H. (eds), *The Carboniferous in Poland*, *Prace Państwowego Instytutu Geologicznego,* 148: 102–109.

Reiners, P. W. & Ehlers, T. A. (eds), 2005. *Low-Temperature Thermochronology: Techniques, Interpretations, Applications*. *Reviews in Mineralogy and Geochemistry*, 58, 622 pp. Mineralogical Society of America, Chantilly, USA.

Radkovets, N. Y., Kotarba, M. & Wójcik, K., 2017. Source rock geochemistry, petrography of reservoir horizons and origin of natural gas in the Devonian of the Lublin and Lviv basins (SE Poland and western Ukraine). *Geological Quarterly*, 61: 569–589.

Resak, M., Glasmacher, U., Narkiewicz, M. & Littke, R., 2009. Maturity modelling integrated with apatite fission-track dating: Implications for the thermal history of the Mid-Polish Trough (Poland). *Marine and Petroleum Geology*, 27: 108–115.

Resak, M., Narkiewicz, M. & Littke, R., 2008. New basin modelling results from the Polish part of the Central European Basin system (Pomerania): implications for the Late Cretaceous–

Early Paleogene structural inversion. *International Journal of Earth Sciences*, 97: 955–972.

Scheck-Wenderoth, M., Krzywiec, P., Zülke, R., Maystrenko, Y. & Frizheim, N., 2008. Permian to Cretaceous tectonics. In: McCann, T. (ed.), *The Geology of Central Europe*. Geological Society of London, London, pp. 999–1030.

Schleicher, M., Köster, J., Kulke, H. & Weil, W., 1998. Reservoir and source-rock characterization of the early Palaeozoic interval in the Peribaltic Syneclise, northern Poland. *Journal of Petroleum Geology,* 21: 33–56.

Skompski, S., 1998. Regional and global chronostratigraphic correlation levels in the late Viséan to Westphalian sequence stratigraphy of the Carboniferous in the Lublin Basin (SE Poland). *Geological Quarterly*, 42: 121–130.

Skręt, U. & Fabiańska, M., 2009. Geochemical characteristics of organic matter in the Lower Palaeozoic rocks of the Peribaltic Syneclise (Poland). *Geochemical Journal*, 43: 343–369.

Stempień-Sałek, M., 2011. Palynomorph assemblages from the Upper Ordovician in northern and central Poland. *Annales Societatis Geologorum Poloniae*, 81: 21–61.

Stypa, A., Krzywiec, P., Kufrasa, M. & Słonka, Ł., 2017. Analiza krzywych subsydencji tektonicznej na obszarze basenu lubelskiego. 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. 372–380. [In Polish.]

Šliaupa, S., Poprawa, P., Lazauskiene, J. & Stephenson, R. A., 1997. The Palaeozoic subsidence history of the Baltic Syneclise in Poland and Lithuania. *Geophysical Journal*, 19: 137–139.

Šliaupa, S., Fokin, P., Lazauskiene, J. & Stephenson, R. A., 2006. The Vendian–Early Paleozoic sedimentary basins of the East European Craton, In: Gee, D. G. & Stephenson, R. A. (eds), *European Lithosphere Dynamics, Geological Society of London, Memoirs*, 32: 449–462.

Środoń, J. & Clauer, N., 2001. Diagenetic history of Lower Paleozoic sediments in Pomerania (northern Poland) traced across the Teisseyre-Tornquist tectonic zone using mixed-layer illite-smectite. *Clay Minerals*, 36: 15–27.

Środoń, J., Clauer, N., Huff, W., Dudek, T. & Banaś, M., 2009. K-Ar dating of the Lower Palaeozoic K-bentonites from the Baltic Basin and the Baltic Shield: implications for the role of temperature and time in the illitization of smectite. *Clay Minerals*, 44: 361–387.

Środoń, J., Paszkowski, M., Drygant, D., Anczkiewicz, A. & Banaś, M., 2013. Thermal history of Lower Paleozoic Rocks on the Peri-Tornquist Margin of the East European Craton (Podolia, Ukraine) inferred from combined XRD, K-Ar, and AFT data. *Clays and Clay Minerals*, 61: 107–132.

Swadowska, E. & Sikorska, M., 1998. Burial history of the Cambrian strata constrained by vitrinite-like macerals in Polish part of the East European Platform. *Przegląd Geologiczny*, 46: 699–706. [In Polish, with English summary.]

Sweeney, J. J. & Burnham, A. K., 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *AAPG Bulletin,* 74: 1559–1570.

Szewczyk, J. & Gientka, D., 2009. Terrestrial heat flow density in Poland: a new approach. *Geological Quarterly*, 53: 125–140.

Tanner, B. & Meissner, R., 1996. Caledonian deformation upon southwest Baltica and its tectonic implications: alternatives and consequences. *Tectonics*, 15: 803–812.

Tomaszczyk, M. & Jarosiński, M., 2017. The Kock Fault Zone as an indicator of tectonic stress regime changes at the margin of the East European Craton (Poland). *Geological Quarterly*, 61: 234–244.

Torsvik, T. H., Olesen, O., Ryan, P. D. & Trench, A., 1990. On the paleogeography of Baltica during the Paleozoic: new palaeomagnetic data from the Scandinavian Caledonides. *Geophysical Journal International*, 103: 261–79.

Torsvik, T. H., Smethurst, M. A., Meert, J. G., Van Der Voo, R., McKerrow, W. S., Brasier, M. D., Sturt, B. A. & Walderhaug, H. J., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic – A tale of Baltica and Laurentia. *Earth Science Reviews*, 40: 229–58.

Torsvik, T. H., Trench, A., Svensson, I. & Walderhaug, H. J., 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain – major revision of the apparent polar wander path for eastern Avalonia. *Geophysical Journal International*, 113: 651–68.

Taylor, G. H., Teichmüller, M., Davis, A., Diessel, C. F. K., Littke, R. & Robert, P., 1998. *Organic Petrology*. Gebrüder Borntraeger, Berlin, 626 pp.

Waksmundzka, M. I., 1998. Depositional architecture of the Carboniferous Lublin Basin. In: Narkiewicz, M. (ed.), Sedimentary basin analysis of the Polish Lowlands. *Prace Państwowego Instytutu Geologicznego,* 165: 89–100. [In Polish, with English summary.]

Waksmundzka, M. I. 2005. *Ewolucja facjalna i analiza sekwencji w paralicznych utworach karbonu z północno–zachodniej i centralnej Lubelszczyzny*. Unpublished Ph.D. thesis. Państwowy Instytut Geologiczny, Warszawa, 197 pp. [In Polish.]

Waksmundzka, M. I., 2010. Sequence stratigraphy of Carboniferous paralic deposits in the Lublin Basin (SE Poland). *Acta Geologica Polonica*, 60: 557–597.

Więcław, D., Kotarba, M. J., Kosakowski, P., Kowalski, A. & Grotek, I., 2010. Habitat and hydrocarbon potential of the Lower Palaeozoic source rocks of the Polish part of the Baltic region. *Geological Quarterly*, 54: 159–182.

Wróbel, M., Kotarba, M. & Kosakowski, P., 2008. Jedno- i dwuwymiarowe modelowania numeryczne procesów generowania, ekspulsji i migracji węglowodorów w utworach karbonu południowo-wschodniej części rowu lubelskiego. *Geologia - Kwartalnik Akademii Górniczo-Hutniczej w Krakowie*, 34: 171–193. [In Polish.]

Wróbel, M. & Kosakowski, P., 2010. 2-D modelling of petroleum processes of the lower Paleozoic strata in the Polish part of the Baltic region. *Geological Quarterly*, 54: 257–266.

Zdanavièiûtë, O., 2005. Perspectives of oil field exploration in Middle Cambrian sandstones of Western Lithuania. *Geologija,* 51: 10–18.

Zdanavièiûtë, O. & Lazauskiene, J. 2007. The petroleum potential of the Silurian succession in Lithuania. *Journal of Petroleum Geology*, 30: 325–337.

Żelichowski, A.M., 1987. Development of Carboniferous of the SW margin of the East-European Platform in Poland. *Przegląd Geologiczny*, 35: 230–237. [In Polish, with English abstract.]