Annales Societatis Geologorum Poloniae (2020), vol. 90: 99–123 doi: https://doi.org/10.14241/asgp.2020.16

BURIAL AND THERMAL HISTORY OF THE UPPER SILESIAN COAL BASIN (POLAND) CONSTRAINED BY MATURITY MODELLING – IMPLICATIONS FOR COALIFICATION AND NATURAL GAS GENERATION

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Botor, D., 2020. Burial and thermal history of the Upper Silesian Coal Basin (Poland) constrained by maturity modelling – implications for coalification and natural gas generation. *Annales Societatis Geologorum Poloniae*, 90: 99–123.

Abstract: Maturity modelling was carried out using basin and petroleum system modelling (BPSM) software in the lithologic sections of 17 wells of the Upper Silesian Coal Basin (Poland). The best fit between calculated and measured vitrinite reflectance (VR), porosity and density data was obtained by applying a thickness of eroded sedimentary overburden from 1700 m in the east to 4500 m in the west and relatively low to moderate heat flow values during the maximum late Carboniferous burial. These heat flow values were in the range 50–71 mW/m^2, most likely owing to rapid deposition of molasse sediment that led to a downward deflection of the isotherms. The upper Carboniferous strata were heated to temperatures in the range c. 90–170 °C, which is in accordance with the moderate to high levels of thermal maturity of these rocks (c. 0.6–1.7%VR). The coal rank pattern was reached before the Variscan tectonic inversion at the transition between the Carboniferous and the Permian (c. 300 Ma). This coalification level was not overprinted by any later thermal processes. The coalification resulted in the generation of natural gases. The upper Carboniferous strata are characterized by early to late phases of hydrocarbon generation. The kerogen transformation ratio (c. 5–75%TR) values vary across the basin. Most coals generated significant amounts of hydrocarbons, which reached over 80 mg of methane per gram of total organic carbon. Although most hydrocarbons generated most likely were lost during the intense post-Variscan exhumation, the hydrocarbon potential of the basin is still substantial.

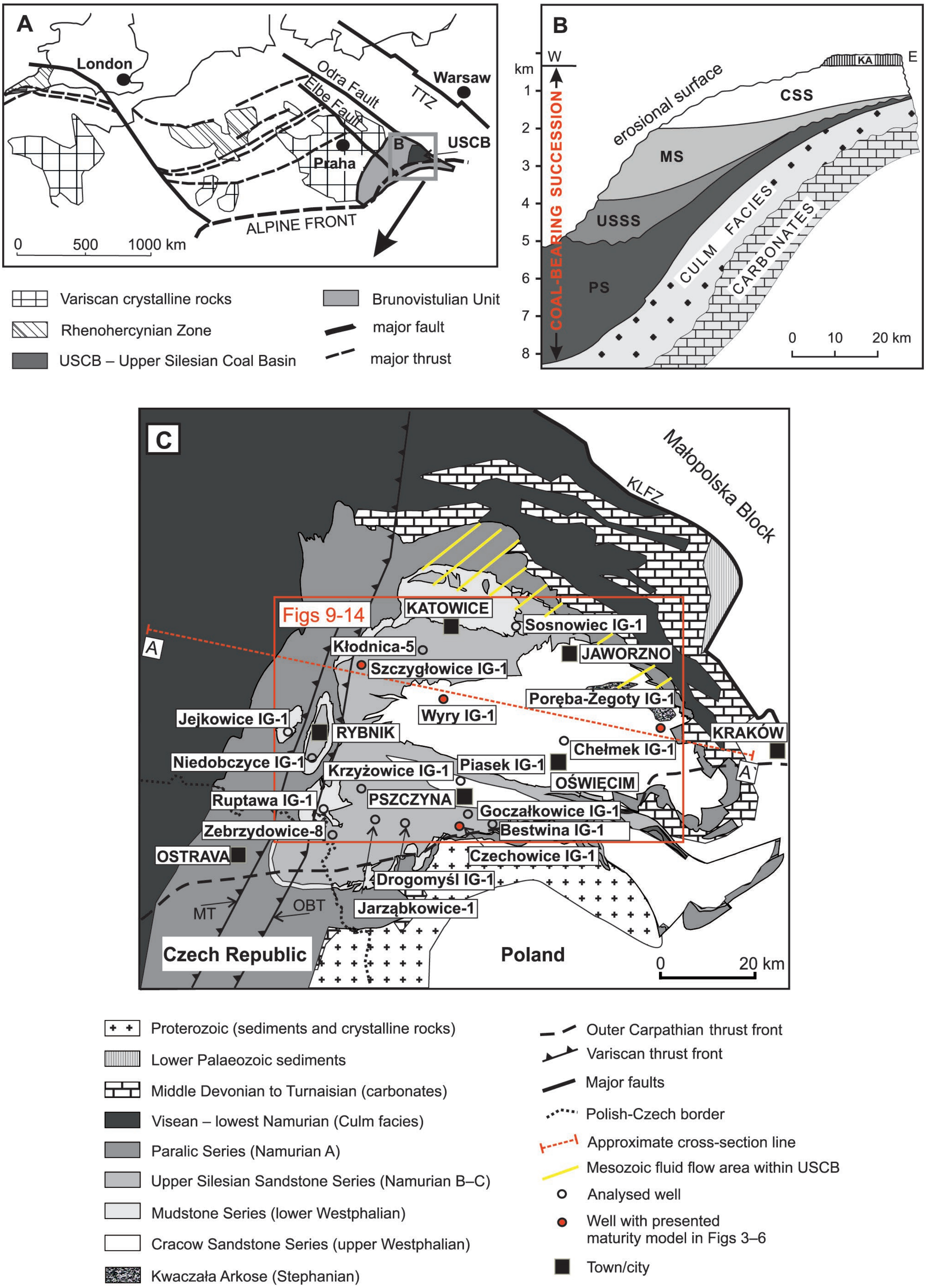
Key words: Maturity modelling, vitrinite reflectance, hydrocarbon generation, methane, Variscides, Carboniferous.

Manuscript received 24 May 2020, accepted 1 October 2020.

INTRODUCTION

Coal deposits are associated with the occurrence of natural gas containing variable amounts of hydrocarbons (mainly methane) and also carbon dioxide and nitrogen (e.g., Rice, 1993; Moore, 2012). Although the methane is partially microbial in origin (e.g., Rice, 1993; Kotarba and Pluta, 2009), most methane resources are generated during coalification (thermogenic gas); some of these resources subsequently were adsorbed by the coal and/or expelled into associated siliciclastic strata (e.g., Moore, 2012). The coalification (thermal maturation) of coals causes the inner structure of organic matter to change. Furthermore, coalification was not only associated with structural changes but also with chemical changes (defunctionalization, aromatization, condensation), which were partly responsible for gas generation (e.g., Teichmüller and Teichmüller, 1979; Rice, 1993; Hantschel and Kauerauf, 2009; Moore, 2012). All these changes are mainly related to heating in a sedimentary basin (e.g., Hantschel and Kauerauf, 2009).

The Upper Silesian Coal Basin (USCB, Fig. 1) is one of the largest coal basins in Europe. The area of the USCB is more than 7000 km^2; more than two-thirds of the basin is in southern Poland, whereas the small SW part is in the NE Czech Republic (Kotas, 1994, 1995; Sivek *et al.*, 2003). The USCB is an area of high potential for coal-bed methane (CBM) exploration, in which recoverable resources are estimated at 97 billion m^3. This is comparable to conventional recoverable resources of 117 billion m^3 in all the basins of Poland (Szuflicki *et al.*, 2018). Geochemical investigations of CBM provided evidence of the co-occurrence of thermogenic and microbial gas both in the Polish (Kotarba,


A
London
Warsaw
Odra Fault
Elbe Fault
TTZ
B
USCB
Praha
ALPINE FRONT
0 500 1000 km
Variscan crystalline rocks
Rhenohercynian Zone
USCB – Upper Silesian Coal Basin
Brunovistulian Unit
major fault
major thrust
B
W
E
KA
km
1
2
3
4
5
6
7
8
erosional surface
CSS
MS
USSS
PS
COAL-BEARING SUCCESSION
CULM FACIES
CARBONATES
0 10 20 km
C
Małopolska Block
KLFZ
Figs 9-14
KATOWICE
Sosnowiec IG-1
Kłodnica-5
JAWORZNO
Szczygłowice IG-1
Poręba-Żegoty IG-1
Wyry IG-1
Jejkowice IG-1
RYBNIK
KRAKÓW
Chełmek IG-1
Niedobczyce IG-1
Krzyżowice IG-1
Piasek IG-1
OŚWIĘCIM
Ruptawa IG-1
PSZCZYNA
Goczałkowice IG-1
Zebrzydowice-8
Bestwina IG-1
OSTRAVA
Czechowice IG-1
Drogomyśl IG-1
Jarząbkowice-1
MT
OBT
A
A'
Czech Republic
Poland
0 20 km
Proterozoic (sediments and crystalline rocks)
Lower Palaeozoic sediments
Middle Devonian to Turnaisian (carbonates)
Visean – lowest Namurian (Culm facies)
Paralic Series (Namurian A)
Upper Silesian Sandstone Series (Namurian B–C)
Mudstone Series (lower Westphalian)
Cracow Sandstone Series (upper Westphalian)
Kwaczała Arkose (Stephanian)
Outer Carpathian thrust front
Variscan thrust front
Major faults
Polish-Czech border
Approximate cross-section line
Mesozoic fluid flow area within USCB
Analysed well
Well with presented maturity model in Figs 3–6
Town/city

2001; Kotarba and Pluta, 2009) and in the Czech parts of the USCB (Weniger *et al.,* 2012a, b), showing a complex relationship between gas composition and the coal rank of associated coal seams as well as complex relationships between gas composition and stratigraphy and depth (Kotas, 1994; Kędzior, 2009, 2015; Weniger *et al.,* 2012a, b; Sechman *et al.,* 2019, 2020a, b). Unconventional natural gas, including CBM, is a possible energy resource that is undeveloped in Poland. Knowledge of the origin, migration pathways and accumulation of natural gases is useful in the evaluation of gas reserves. In the USCB, there is also a possible occurrence of natural gas in low-permeability sandstone or siltstone in addition to gas trapped in the coal seams. This basin-centred gas system (Law, 2002) might have developed in the deeper part of the basin (Poprawa and Kiersnowski, 2010; Poprawa, 2018). In this type of system, the gas would be generated from coals, and a "permeability jail" would be the sealing mechanism (Cluff and Byrnes, 2010). This idea remains unconfirmed owing to the low number of boreholes that reach more than 2,500 m depth in the USCB (Poprawa, 2018). In the deeper, western part of the USCB, the bottom of the coal-bearing strata is buried to a depth of c. 5,000 m. Additionally, sandstone interbedded with coal and mudstone loses porosity and permeability with increasing depth, and deeper than c. 2,500 m it can be assumed to be a tight rock (Law and Spencer, 1993). Therefore, it was suggested by Poprawa (2018) that a section in the USCB, at least a few hundred metres thick, might be saturated with dry gas. However, the time of gas generation (Carboniferous *versus* Mesozoic–Cenozoic) is uncertain as well, owing to the lack of porosity/permeability data for the rocks at depths of c. 2,500–5,000 m in the majority of the USCB.

In order to assess the thermal maturity of the organic matter and hence, its maximum temperatures, many parameters can be used. The most commonly applied is mean random vitrinite reflectance (VR); its widespread use is based on the broad temperature range, in which it is applicable (e.g., Teichmüller and Teichmüller, 1979; Mukhopadhyay, 1992; Suarez-Ruiz *et al.,* 2012; Ferreiro *et al.,* 2016). VR, together with the measured temperature in a borehole, is the most frequently used calibration parameter to validate burial history models (e.g., Waples *et al.,* 1992a, b; Sachsenhofer *et al.*, 2002). Modelling algorithms can be used to evaluate the maturation and hydrocarbon generation history of a source rock as well as hydrocarbon expulsion and migration (e.g., Hantschel and Kauerauf, 2009). In this study, one-dimensional (1-D) maturity modelling was performed in borehole sections to constrain the burial and thermal history of the basin and assess its effect on coalification and gas generation in the USCB, which eventually leads to establishing the timing of hydrocarbon generation in a more precise way.

GEOLOGICAL SETTING

The USCB is situated at the eastern margin of the Bohemian Massif, and it represents the eastern part of the Moravo-Silesian Palaeozoic Basin (Figs 1, 2). The USCB occupies the NE corner of the Brunovistulicum Block – the Neoproterozoic crystalline basement, which was consolidated during the Cadomian orogenic cycle (Buła *et al.,* 1997, 2015; Finger *et al.,* 2000; Buła and Żaba, 2005; Narkiewicz, 2007). The western part of Brunovistulicum extends beneath the Moravian-Silesian fold-and-thrust belt that developed as a result of interaction between the Brunovistulian Block and Variscan terranes of the Bohemian Massif (e.g., Schulmann and Gayer, 2000; Buła and Żaba, 2005; Kalvoda *et al.*, 2008; Chopin *et al.*, 2012; Janousek *et al.*, 2014). The thrusting of the Moravian-Silesian fold-and-thrust belt took place during the late phases of Variscan convergence in the late Carboniferous (Schulmann and Gayer, 2000; Bábek *et al.*, 2006; Kalvoda *et al.,* 2008). The Viséan to earliest Namurian sedimentary sequence of the Moravian-Silesian fold-and-thrust belt is overlain by Namurian to Westphalian coal-bearing sediments of the USCB (Figs 2, 3), which represent the final depositional phase of the Moravo-Silesian Palaeozoic Basin (Buła and Żaba, 2005; Kędzior *et al.,* 2007; Kalvoda *et al.,* 2008).

The USCB was developed as a foreland basin, located in front of the Moravian-Silesian fold-and-thrust belt. The thickness of deposited sediments probably reached c. 8,500 m but was decreased by exhumation after the latest Carboniferous tectonic inversion (Kotas, 1994, 1995). The preserved thickness of coal-bearing strata is c. 1,500–2,000 m in the eastern part of the USCB and increases westward to over 4,500 m (Figs 2, 3). The USCB forms a broad synclinorium, which is differentiated in deformation style. In the western part, along both main overthrusts, i.e., the Orlová-Boguszowice and Michálkovice thrusts, there is a narrow zone of east-vergent folds, which delimits the Variscan front of the Moravian-Silesian fold-and-thrust belt (Figs 1, 2). However, most of the USCB has mainly been affected by fault tectonics (Kotas, 1994, 1995; Buła *et al.,* 1997).

The sedimentary overburden of the USCB usually does not exceed a few hundred metres. Upper Carboniferous sediments are overlain by thin (below 200 m) and varied Lower Permian rocks, which are largely restricted to the narrow zone along the NE margin of the USCB (Siedlecka, 1964). The sequence consists of continental red beds, mainly conglomerates, carbonates and tuffs. In the NE part of the USCB, the Carboniferous rocks are overlain discordantly by 100–200 m of Triassic strata (Jureczka and Kotas, 1995). Jurassic strata (below a few tens of metres thick) occur only in a very restricted area in the NE margin of the USCB

Fig. 1. Geological setting of the Upper Silesian Coal Basin. **A.** Tectonostratigraphic zones of the European Variscides (modified after Kalvoda *et al.,* 2008) with the study area highlighted by the grey lines. TTZ – Teisseyre-Tornquist Zone, USCB – Upper Silesian Coal Basin. **B.** A schematic lithostratigraphic section through the Upper Silesian Coal Basin (after Kotas, 1995). CSS – Cracow Sandstone Series, KA – Kwaczała Arkose, MS – Mudstone Series, PS – Paralic Series, USSS – Upper Silesian Sandstone Series. **C.** Simplified location map of the Upper Silesian Coal Basin without strata younger than Carboniferous and with locations of the wells analysed (after Kotas, 1995; Buła *et al.,* 1997; Buła and Żaba, 2005; Kędzior *et al.,* 2007). KLFZ – Kraków - Lubliniec Fault Zone, MT – Michálkovice Thrust, OBT – Orlová - Boguszowice Thrust.

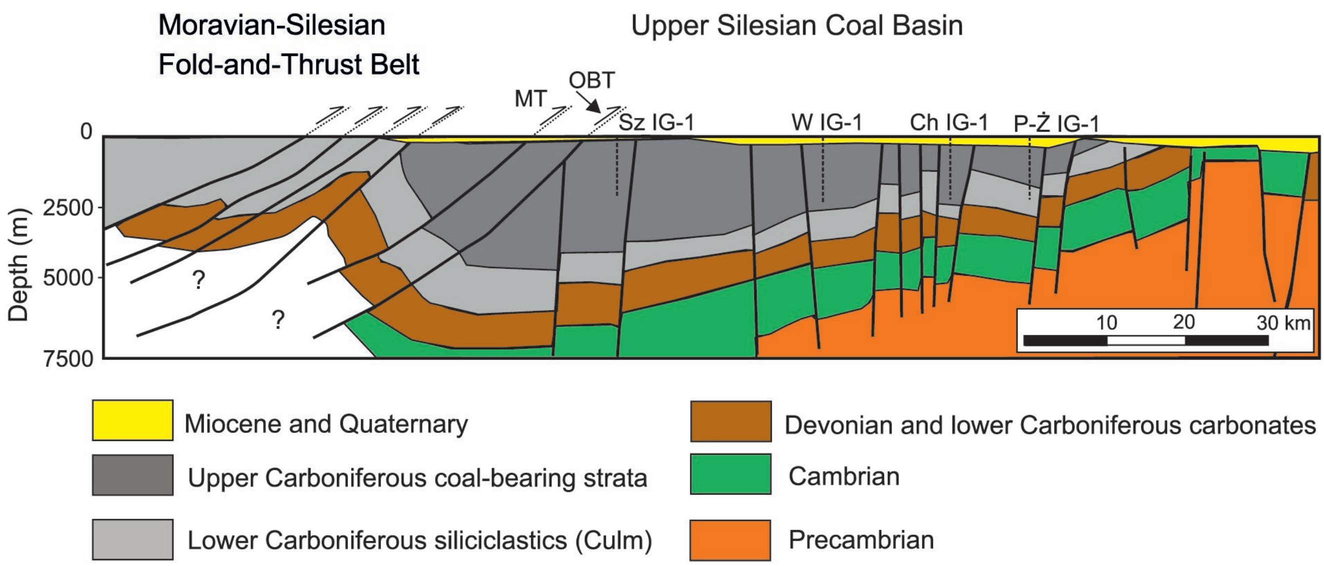


Fig. 2. Simplified crosssection of the study area (modified after Buła *et al.,* 2008). Sz IG-1 – Szczygłowice IG-1, W IG-1 – Wyry IG-1, Ch IG-1 – Chełmek IG-1, P-Ż IG-1 – Poręba-Żegoty IG-1, OBT – Orlová-Boguszowice Thrust, MT – Michálkovice Thrust.

(Jureczka and Kotas, 1995; Kotas, 1995). Cretaceous sediments do not exist and most likely were not deposited in the USCB (e.g., Marcinowski, 1989). The major part of the USCB makes up the basement of the Carpathian Foredeep, infilled by marine Miocene sediments. In the southernmost part, Western Carpathians nappes are overthrust onto Miocene deposits. The total thickness of the Miocene strata is from 0 to 400 m in the USCB (Kotas, 1994, 1995; Jureczka and Kotas, 1995).

The NE boundary of the USCB runs a few kilometres west of the narrow Kraków-Lubliniec Fault Zone that separates the Brunovistulicum and Małopolska blocks (Oberc, 1993; Buła *et al.,* 1997, 2015; Żaba, 1999; Narkiewicz, 2007). The Kraków-Lubliniec Fault Zone contains igneous intrusive rocks that developed during two major Variscan phases. The older magmatism is related to extensional faults in the basement of the Moravo-Silesian foreland. The younger, latest Carboniferous to early Permian, more intense magmatic activity is related to the final stages of the tectonic inversion of the USCB; however, it is known only along the eastern border of USCB and on the Małopolska Block (Harańczyk, 1979; Buła *et al.,* 1997; Słaby *et al.*, 2010; Mikulski *et al.*, 2019). Igneous rocks that occur along the Kraków-Lubliniec Fault Zone are the products of bimodal magmatism, associated either with crustal thickening (Słaby *et al.*, 2010) or with the dextral wrench regime and fault activity in the Trans European Suture Zone (Żelaźniewicz *et al.*, 2016). A more comprehensive discussion of the regional geology of the study area can be found in Kotas (1994, 1995), Buła *et al.* (1997, 2008, 2015), Buła and Żaba (2005), Kędzior *et al.* (2007) and Narkiewicz (2007).

Coals in the USCB

In the USCB, the upper Carboniferous sedimentary sequence contains more than 250 bituminous (hard) coal seams, occurring mostly at depths of between c. 200 m and 1,600 m, and dispersed organic matter in mudstone/siltstone. Both were excellent and mature source rocks for gas hydrocarbons, such as methane (Kotas, 1994; Kotarba, 2001; Kotarba *et al.,* 2002; Kędzior, 2009, 2011, 2015, 2019; Hemza *et al.*, 2009; Weniger *et al.*, 2012a, b; Kędzior *et al.,* 2013). The seam thickness reaches c. 30 m, but usually ranges from 0.5 m to 15 m. The cumulative coal resources are c. 48 billion tons (PGI, 2020).

In the USCB, coal rank is highly variable, ranging almost from subbituminous coal through high- to low-volatile bituminous coal to low-volatile steam coal and locally occurring anthracite (e.g., Kotas *et al.,* 1983; Gabzdyl and Probierz, 1987; Probierz, 1989; Jurczak-Drabek, 1996, 2000; Sivek *et al.,* 2003, 2010; Jureczka *et al.,* 2005; Komorek *et al.,* 2010). USCB coals are petrographically variable, but with the predominance of the vitrinite group over other maceral groups. The amount of vitrinite increases westwards from c. 40% to 80%. The inertinite group amounts to 10–50% and it increases northwards and eastwards. Liptinite group macerals rarely exceed 15% (e.g., Jurczak-Drabek, 1996, 2000; Kędzior, 2009). There is also vertical change in the maceral composition in particular coal seams (Jurczak-Drabek, 1996, 2000; van Bergen *et al.*, 2006; Kędzior, 2009). In these vitrinite-dominated coals, the main natural gas product of coalification is methane (e.g., Kotarba, 2001). More comprehensive information about the chemical and physical parameters of coal seams was summarized by Kotas *et al.* (1983), Jurczak-Drabek (1996), Sivek *et al.* (2003), Jureczka *et al.* (2005) and Martinec *et al.* (2005).

The USCB is characterized by a diversity of CBM occurrences and a complex pattern of methane content in coal seams (Kędzior, 2009, 2015, 2019). The gas content of coal-bearing sequences in the Czech part of the USCB mostly ranges between 2 and 10 m^3/t coal and shows an overall decline with increasing depth (Hemza *et al.,* 2009). In the Polish part of the USCB, methane content in the coal seams ranges between 0.01 and 1 m^3/t coal in the shallower strata and up to 20 m^3/t coal at greater depths (Kędzior, 2015, 2019). Two patterns of methane depth distribution have been defined to reflect the distinctive contrast in methane occurrence between the southern and northern parts of the USCB (Kotas, 1994; Kędzior *et al.,* 2013; Kędzior, 2015, 2019). In the northern USCB region where the upper parts of the Carboniferous coal-bearing strata were significantly degassed, a zone of high methane content (c. 4.5 m^3/t coal) occurs below a depth of c. 600–1,000 m (primary methane zone). However, in the southern part of the USCB, an additional upper secondary zone of elevated methane content lies just beneath the impermeable Miocene cover and is separated from a lower primary zone by an interval of low methane (Kędzior, 2009, 2015, 2019). Thus, gas content in the USCB varies greatly both vertically and horizontally due to outgassing.

The CBM pattern that likely resulted in coalification developed immediately after deposition during the late Carboniferous, and the exhumation/erosion of the basin was caused by the Variscan tectonic inversion at the transition between the Carboniferous and Permian periods. Exhumation caused a change in pressure conditions and the migration of hydrocarbons. Exhumation of the upper part of upper Carboniferous strata was developing in a long period from the Permian to the Miocene (Kotarba, 2001; Botor, 2014; Kędzior, 2015, 2019). The pattern of present-day gas content in coals in the USCB indicates that during the post-Carboniferous period of erosion/exhumation, the lack of an effective seal caused part of the thermogenic gas to be lost, owing to migration to the surface. Weniger *et al.* (2012b) concluded that the increase of sorption capacity during uplift alone was not sufficient to explain the gas undersaturation of most coal seams, indicating that a significant amount of gas, generated during coalification, was lost during times of uplift and erosion. However, the emplacement of Carpathian nappes in the southern part of the USCB, as well as the deposition of Miocene sediments of the Outer Carpathian Foredeep c. 12–15 Ma, formed a seal below which hydrocarbon gases were also accumulated (Martinec and Schejbalová, 2004; Kędzior, 2009, 2015, 2019).

Previous studies related to the burial and thermal history of the study area

In the area of the Moravo-Silesian Basin located west of the USCB, maximum temperatures, inferred from mean vitrinite reflectance, illite crystallinity and conodont alteration indices, reached c. 150 to 350 °C, showing a distinct regional trend of decreasing thermal alteration from the NW interior of the orogen to the SE foreland (e.g., Dvořák, 1989; Franců *et al.*, 2002; Bábek *et al.*, 2006; Botor *et al.*, 2017a, b). In the USCB, which developed in the Variscan foreland, maximum temperatures were in a lower range of c. 60–200 °C (Bełka, 1993; Środoń, 1995; Probierz and Lewandowska, 2004; Środoń *et al.,* 2006; Botor, 2014; Geršlová *et al.,* 2016).

The present-day thermal field of the USCB is poorly correlated with coal rank data; therefore, the coalification pattern reflects a hotter thermal regime in the past compared to the present (e.g., Majorowicz, 1978; Bełka, 1993; Środoń, 1995; Karwasiecka, 1996, 2001a, b; Kotas, 2001). In the USCB, thermal maturity increases with depth and stratigraphy, but the vertical coal rank changes are not linear in some wells; their gradients are markedly varying throughout the basin area (Kotas *et al.,* 1983; Kotas, 2001). Therefore, it seems that the coal rank was determined by complex coalification factors. Although coal rank increases with depth, many deviations from this trend are known in the study area. This reflects elevated pressures, the influence of igneous rocks and/or palaeo-weathering (e.g., Kotas *et al.,* 1983; Jurczak-Drabek, 1996, 2000; Kędzior, 2009; Sivek *et al.,* 2008; Adamczyk *et al.,* 2018). Kotas (1995, 2001) and Kotas and Adamczyk (2004) assumed that coalification occurred in two main stages: (1) a pre-orogenic stage during foredeep burial in the late Carboniferous before tectonic inversion, (2) a post-orogenic stage in Permian and Mesozoic to Neogene times, resulting in further coalification due to heating in a tensional tectonic regime. However, Bełka (1993), on the basis of conodont CAI data, ESR spectra of the conodonts and a few VR well profiles, has shown that coalification developed in the late Carboniferous; however, the maximum temperatures occurred just after the Asturian tectonic inversion in the latest Carboniferous but definitely before the Early Triassic (Bełka, 1993). The synorogenic late Carboniferous age of coalification in the USCB was postulated based on VR anisotropy in coal seams (Komorek, 1996; Pozzi, 1996; Morga, 2000). Low thermal maturity (below 0.5%VR) in Triassic and younger sediments also is not indicative of increased coalification after the Permian (Kołcoń and Wagner, 1983; Marynowski *et al.,* 2007; Marynowski and Wyszomirski, 2008; Rybicki *et al.,* 2016, 2017). Miocene sediments in the Carpathian Foredeep also have low (below 0.5%VR) thermal maturity (Nowak, 1999; Szafran and Wagner, 1999, 2000; Kotarba, 2001).

Post-Variscan tectonic movements caused only minor subsidence of the upper Carboniferous strata, which precluded the renewal of the coalification process at the regional scale due to burial. Similar conclusions are also given about the Czech part of the USCB by Weniger *et al.* (2012a, b) and Geršlová *et al.* (2016) based on thermal maturity modelling. Geršlová *et al.* (2016) have shown that the thermal maturity reflects the geological setting during the end of the Carboniferous and was related to the thickness of the Palaeozoic sedimentary sequences, rather than to various thermal regimes. The tectonic reburial of Carboniferous sequences during the development of the Carpathian Foredeep and the Carpathian overthrust in the Miocene was most likely too small to reinitiate further coalification and gas generation in either the Czech part of the USCB (Weniger *et al.,* 2012a, b; Geršlová *et al.,* 2016) or the Polish part of the USCB (Kotarba *et al.,* 2004). However, Poprawa *et al.* (2006), on the basis of preliminary maturity modelling, claimed that thermal maturity does not show burial or heat flow changes, but rather indicates fluid flow events, which was also suggested earlier by Jura (2002).

Illite K-Ar ages from Carboniferous ash layers indicate a Jurassic thermal event in the eastern part of the USCB and a late Carboniferous event in the western part of the basin (Środoń *et al.,* 2006). Apatite fission-track dating revealed that a major cooling event occurred in the late Permian to Triassic; therefore, maximum temperatures (above c. 100 °C) in the Carboniferous strata were reached between the late

Carboniferous and early Permian periods. This implies that coalification was mainly controlled by processes related to a deep Variscan burial (Botor, 2014). The apatite fission-track ages of Carboniferous samples are younger than sample stratigraphic ages, indicating a substantial (above 100 °C) increase of post-depositional temperature. Samples from the western and middle parts of the basin show Permian to Late Triassic apatite fission-track ages. Mean track lengths and unimodal distributions show a rapid post-Variscan cooling to below 60°C that is consistent with exhumation during the Variscan tectonic inversion of the basin in the latest Carboniferous. However, in the NE part of the basin, samples reveal Late Triassic to Early Cretaceous apatite fission-track ages. A mixed fission-track length distribution with shorter mean values of track length and higher standard deviation suggests a more complicated thermal evolution within the partial annealing zone of the fission tracks, i.e., c. 60–120 °C. Early Cretaceous apatite helium ages indicate post-Variscan inversion-related slow cooling or possible Mesozoic reheating, but in a temperature range c. 60–70 °C, i.e., in a lower range than the maximum in the late Carboniferous. An increase in temperature during this event caused partial helium loss from the apatite but was not enough to change the fission-tracks record in most areas of the basin. However, in the NE part of the basin, Mesozoic reheating was likely able to raise the temperature to c. 70–85°C, which caused partial change of the apatite fission-track ages record. Mesozoic reheating could be related to a fluid-flow event due to tectonic extension (Botor, 2014), because in the Middle Triassic strata in the NE part of the USCB, Mississippi Valley Type (MVT) Zn-Pb ores, the origin of which is related to a Late Triassic–Jurassic (Sas-Gustkiewicz and Dżułyński, 1998) or early Cretaceous fluid-flow event (Hejlen *et al.,* 2003), occur.

METHODS

Computer modelling of the degree of coalification (thermal maturity modelling) was carried out using the PetroMod software (1-D version 9.0, Schlumberger). The modelling procedure allows for burial history reconstruction based on lithostratigraphy and petrophysical parameters, the thermal regime and thermal maturity (Hantschel and Kauerauf, 2009). The modelling was performed as forward modelling, in which the numerical simulation starts with the deposition of the oldest sediment layer and continues with decreasing geological time until the present day. Initially, a simplified present-day stratigraphic section is defined and it includes lithological and petrophysical data and thicknesses. The model is based on a chronology of events, i.e., sedimentation, erosion, non-deposition and tectonic events (Fig. 3). The backstripping method that includes a decompaction correction was applied to establish the burial history. Petrophysical parameters were used and based on the PetroMod library according to lithologic types identified in the wells analysed (Tab. 1). These values are similar to those given by Chmura (1970) for rocks from the USCB. Models were calibrated using present-day, corrected borehole temperature data taken from maps (Karwasiecka, 1996, 2001a) and measured values of VR (Jurczak-Drabek, 1996, 2000; Adamczyk and Porszke, 2002; Adamczyk *et al.,* 2010; Kędzior, 2015, 2019), as well as density and porosity data (Kleczkowski and Witczak, 1967; Różkowski and Witkowski, 1988; Kotas, 1994; Różkowski, 1995; Wagner, 1998; Poprawa, 2018). The basic parameter used to build the model of coalification was the mean random vitrinite reflectance (VR), calculated using the algorithm of Sweeney and Burnham (1990). Several tests of the change of heat flow in time, erosion/exhumation of the Carboniferous overburden and a combination of both was performed. The calculated VR value was compared with the measured VR value and the model was adjusted until the best fit of the VR *versus* depth was achieved. Numerical modelling of hydrocarbon generation was performed by applying the Lawrence Livermore National Laboratory (USA) kinetic model for Type III kerogen (Burnham *et al.,* 1987; Braun and Burnham, 1990) for each lithostratigraphic series in the USCB. Hydrogen Index (HI) was set at 200, and total organic carbon (TOC) values were used as given in Figure 3. Only coal seams were considered here, because the percentage of coal content is known in the given lithostratigraphic units of the USCB. A broader discussion of the applied maturity modelling method is provided elsewhere, for example, in Waples *et al.* (1992a, b), Hantschel and Kauerauf (2009) and Botor *et al.* (2013).

RESULTS AND DISCUSSION

Maturity modelling was conducted across the study area on the stratigraphic sections of 17 boreholes (Fig. 1). The conceptual model (Tab. 2) is based on a generalized description of lithostratigraphy (Fig. 3). The most important, typical and representative examples of burial and thermal history are shown for the Poręba-Żegoty IG-1, Czechowice IG-1, Wyry IG-1 and Szczygłowice IG-1 boreholes (Figs 4–7).

Heat flow

Present-day heat flow values, calculated using mean temperature data in boreholes (Karwasiecka, 1996, 2001a) and the default thermal conductivity data of PetroMod software, are in the range of c. 59–82 mW/m^2 (Fig. 8A), which is only slightly higher than heat flow values during the maximum late Carboniferous burial (50–71 mW/m^2; Fig. 8B). The calculated present-day heat flow values are similar to the values given earlier by Karwasiecka (2001a). The tectonic position of the USCB is analogous to other basins of the same type, in which the heat flow is from 45 to 80 mW/m^2 (e.g., Littke *et al.,* 1994, 2000), which is typical of foreland basins (Allen and Allen, 2005). Assuming that the lithology of the removed upper Carboniferous strata was similar to the occurring strata, it can also be assumed that the values of the geothermal gradient were similar. Considering the low VR gradient (Karwasiecka, 2001b) in most boreholes (except the Jastrzębie area in the SW part of the USCB), the geothermal palaeogradient corresponding to it and thus the heat flow were likely also relatively low, such as, e.g., the heat flow values calculated in the modelling.

The regional, geological data do not point to the intense development of magmatic processes in the USCB area (except the NE margin; see geological setting). Thus,

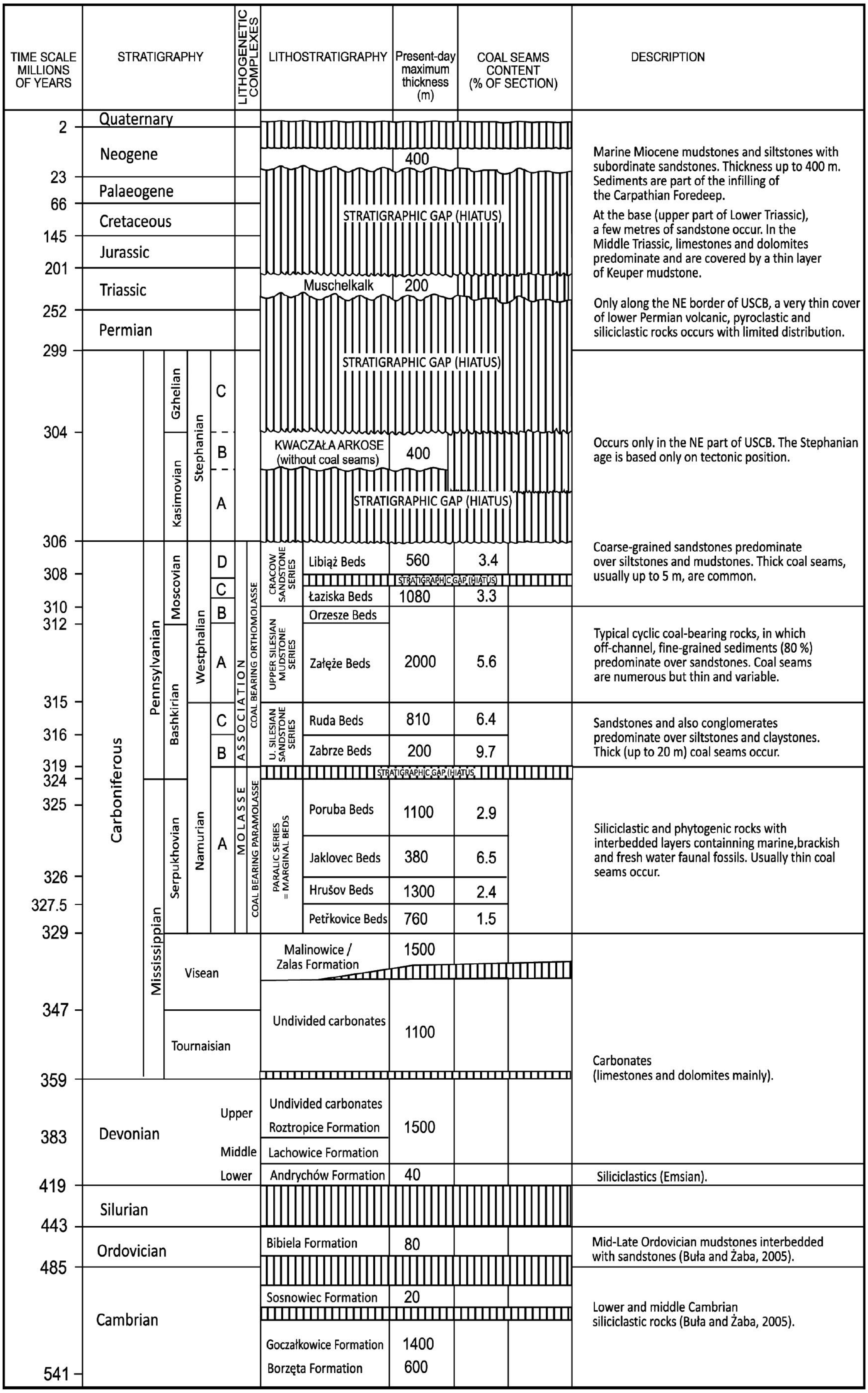


Fig. 3. Simplified lithostratigraphy of study area based on Dembowski (1972) and Kotas (1995) but changed after Buła and Żaba (2005) – lower Palaeozoic; Narkiewicz (2007) and Kalvoda *et al.* (2008) – Devonian to lower Carboniferous. Generally, time scale based on Cohen *et al.*, (2013), but the Carboniferous is based on various sources, including Heckel and Clayton (2006) and Jirásek *et al.* (2018).

Table 1

Basic petrophysical properties used as a part of an input data in modelling by means of PetroMod software. In lithologic types, the following system was applied for abbreviation: LIMEdolom (first lithology in capitals and second in small letters): 70% limestone and 30% of dolomite; SAND&SHALE (both lithologies in capitals): 50% sandstone and 50 % shale.

Lithology	Density (g/cm^3)	Initial porosity (%)	Compressibility (1/Pa)		Thermal conductivity (W/m×K)		Heat capacity (cal/g×K)	
			Min.	Max.	at 20 °C	at 100 °C	at 20 °C	at 100 °C
Coal	1.680	52	10	130000	0.5	0.46	0.204	0.248
DOLOMITE	2.836	35	10	250	3.81	3.21	0.202	0.229
LIMEdolom	2.752	28	10	180	3.18	2.82	0.198	0.226
LIMEmarly	2.707	33	10	300	2.63	2.41	0.201	0.235
LIMEsandy	2.695	37	20	700	2.93	2.62	0.190	0.219
LIMESTONE	2.710	24	10	150	2.83	2.56	0.195	0.223
MARL	2.687	50	10	940	2.23	2.11	0.208	0.248
SAND&SHALE	2.669	45	10	2800	2.65	2.38	0.197	0.236
SAND&SILT	2.665	49	10	1900	2.59	2.31	0.192	0.229
SANDcongl	2.663	37	10	330	2.93	2.63	0.184	0.217
SANDsilty	2.664	48	10	1200	2.97	2.64	0.188	0.223
SANDSTONE	2.660	42	10	500	3.12	2.64	0.178	0.209
SHALE	2.680	65	10	60000	1.98	1.91	0.213	0.258
SHALE&LIME	2.695	53	20	1500	2.39	2.24	0.208	0.246
SHALE&SAND	2.669	52	10	2800	2.65	2.38	0.197	0.236
SHALE&SILT	2.674	61	10	13000	2.09	1.97	0.207	0.251
SHALEsand	2.674	57	10	9000	2.32	2.12	0.205	0.248
SHALEsilt	2.677	62	10	25000	2.05	1.94	0.210	0.254
SILT&SAND	2.665	49	10	1900	2.59	2.31	0.192	0.229
SILT&SHALE	2.674	61	10	13000	2.09	1.97	0.207	0.251
SILTsandy	2.666	52	10	3000	2.55	2.33	0.192	0.230
SILTshaly	2.675	58	10	15000	2.09	1.98	0.203	0.245
SILTSTONE	2.672	56	10	8000	2.14	2.03	0.201	0.242

the heat flow in the discussed area could have not been high, which was also emphasized by Kotas (2001), who postulated that the Carboniferous was characterized by a low heat flow that then increased between the Triassic and Miocene, which would be reflected in VR borehole profiles. Here, in the models presented (Figs 4–7), Carboniferous heat flow successively decreases with the increase of burial (during late Carboniferous), because the rate of heat flow decrease is proportional to the rate of subsidence (Ceriani *et al.*, 2006; Carr and Uguna, 2015). Consequently, rapid deposition of molasse sediment caused a downward deflection of the isotherms (e.g., Mazurek *et al.*, 2006), which is typical of foreland basins. Then, heat flow increased immediately during the inversion phase (here, in the early Permian). The increasing-upward force was associated with an increase of heat flow, as it is not possible to perform the mechanical work required to uplift the basin without generating additional amounts of heat (Carr and Uguna, 2015). Finally, the heat flow decreased to present-day values (Figs 4–7).

The USCB was formed in the final stages of the evolution of the extensive Moravo-Silesian Palaeozoic Basin in the eastern part of the Central European Variscides. It occupies a similar structural position as other European bituminous coal basins (e.g., the Ruhr Basin), aligned in a belt stretching from the British Isles across Germany and Poland to the eastern part of the European Variscides. The recent structural framework of the coal-bearing deposits represents only the erosional relicts of an originally more extensive system

Table 2

Input data for Wyry IG-1 well. In mixed lithologic types, the following system was applied for abbreviations: SANDcongl (first lithology in upper case and second in lower case): 70% sandstone and 30% of conglomerate; SAND&SHALE (both lithologies in upper case): 50% sandstone and 50% shale.

Unit/event	Top	Bottom	Thickness (present-day)	Thickness (exhumed)	Deposition		Exhumation		Lithology
					from	to	from	to	
	(metres)				(Ma)				
Quaternary	0	16	16		2	0			SILT&SAND
Miocene	16	121	105		20	15			SILTSTONE
Triassic	121	144	23		237	228			LIMEdolom
exhumed Carboniferous			0	2700	309	300	300	250	SANDsilty
Łaziska Beds	144	554	410		311	309			SANDsilty
Orzesze Beds	554	984	430		315	311			SILTsandy
Załęże Upper Beds	984	1393	409		316	315			SILTsandy
Załęże Lower Beds	1393	1699	306		317	316			SILTSTONE
Zabrze-Ruda Beds	1699	2008	309		319	317			SANDSTONE
Poruba Beds	2008	2037	29		320	319			SILTsandy

of more-or-less connected sedimentary basins. The USCB shows geological features similar to those in the Ruhr Basin in Germany (Littke *et al.,* 1994, 2000), where heat flow values during maximum burial in the late Carboniferous did not exceed 68 mW/m^2, with the average value in fifty wells equal to 58 mW/m^2 (Littke *et al.,* 2000). Therefore, heat flow values calculated in this study for the USCB are very similar and plausible.

Burial and thermal history

Variscan evolution

The maximum depth of burial of Carboniferous strata was very diverse in different parts of the basin (Figs 4–7). Burial of the base of the upper Carboniferous strata analysed in boreholes probably reached from 3.2 km (Poręba-Żegoty IG-1, Fig. 4A) in the NE to 5.5 km (Szczygłowice IG-1, Fig. 7A) in the west at the end of the Carboniferous period (c. 300 Ma). Generally, the deepest burial was in the west and SW (Szczygłowice IG-1, Ruptawa IG-1, Drogomyśl IG-1 wells). In the late Carboniferous, each burial curve in the USCB shows an initial, very rapid increase due to tectonic subsidence. Usually, by the end of the Carboniferous, over 90% of the total subsidence had occurred and hence the maximum burial and maximum temperature were achieved in the latest Carboniferous just before the final Variscan shortening event at the end of the Carboniferous (Kotas 1994, 1995). After burial sedimentary layers lose porosity, owing to mechanical compaction of the sediments; however, it can be partially changed by physical or chemical processes, e.g., cementation and recrystallization (Hantschel and Kauerauf, 2009). The amount of erosion/exhumation was assessed by iterative fitting of measured and computed mean VR, porosity and density values and by applying different working hypotheses as suggested by, e.g., Waples (1992a, b). The best modelling results were obtained by assuming that the thickness of eroded/exhumed upper Carboniferous sediments increases from the east (c. 1700 m) to west and SW (c. 4500 m; Figs 4–7 and 9).

Sensitivity analysis of alternative models suggests that models assuming no erosion completely do not fit with measured VR, porosity and bulk density data (Figs 4–7). However, one of the possible scenarios (Fig. 10) is to assume a lower thickness of the eroded overburden (c. 850 m to 2000 m) and higher palaeo-heat flow (c. 80–100 mW/m^2), which allows a correct fitting to be achieved in the case of VR (e.g., Botor and Bábek, 2019). Nevertheless, these models are not plausible enough with reference to the porosity and density data available in the Polish part of the USCB analysed. The alternative models show no correct fit of compaction-related data (Fig. 10). Heat flow values that are much higher even than those in alternative models (Fig. 10) were given earlier by Šafanda *et al.* (1991), who proposed that heat flow in the Carboniferous was 115–190 mW/m^2. However, such high values seem to be unrealistic for a foreland basin (Allen and Allen, 2005). Nevertheless, both types of burial and thermal history scenarios lead to similar thermal maturity development in the late Carboniferous, with the maximum value at the end of the Carboniferous (Fig. 11).

Another feature, which is observed in at least some VR profiles in the USCB, is the occurrence of nonlinear or rather, not fully linear VR profiles, with two or three nonparallel segments (e.g., Fig. 10A–B). These VR profiles might be the result of thermal gradient perturbations caused by heat

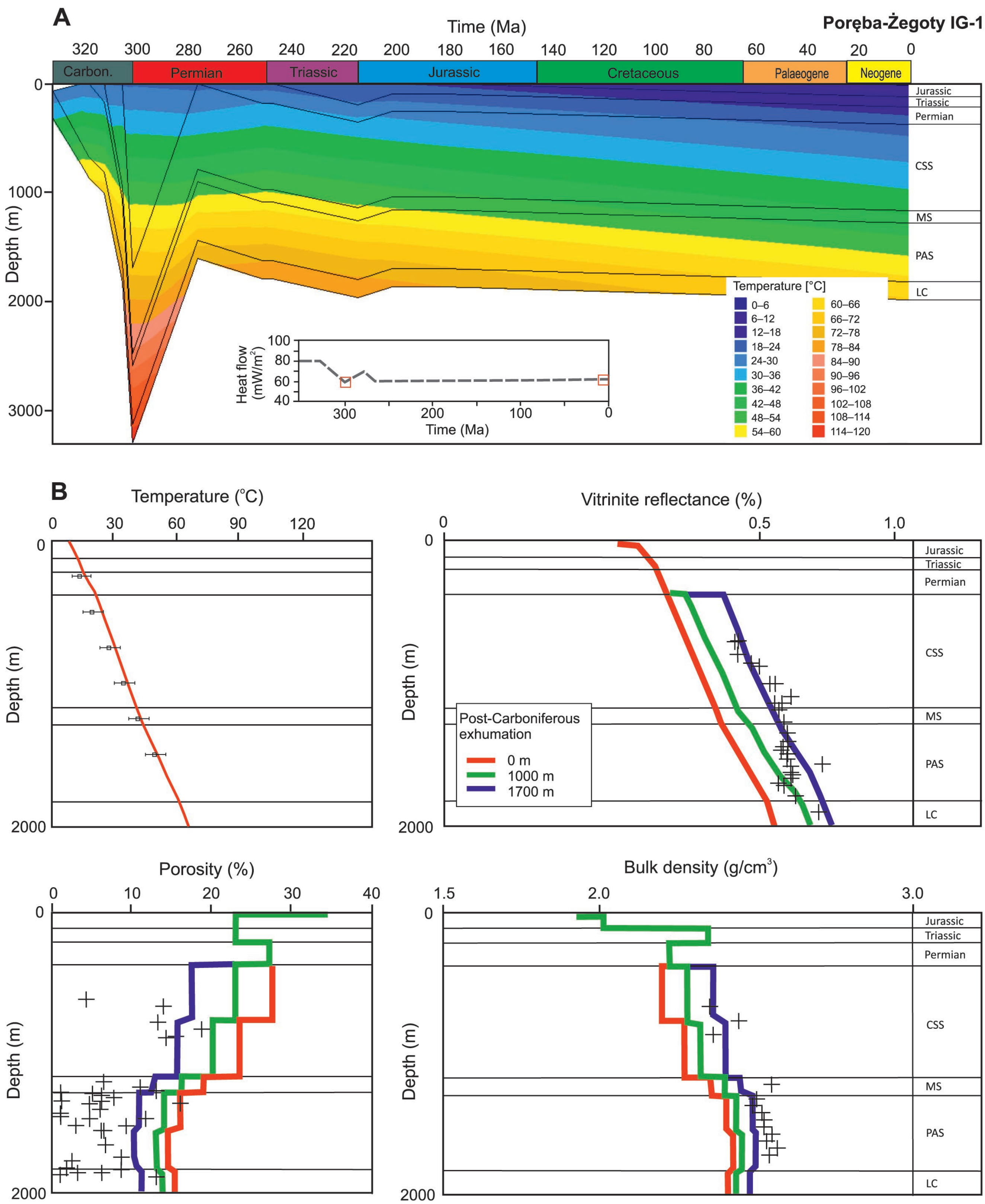


Fig. 4. Burial and thermal history model for the Poręba-Żegoty IG-1 well in the eastern part of the Upper Silesian Coal Basin including calibration. **A.** The burial and thermal history model. **B.** Calibration of the model using present-day temperature, VR, porosity and density data in the well. CSS – Cracow Sandstone Series, MS – Mudstone Series, PAS – Paralic Series, LC – lower Carboniferous. Details of stratigraphy are given in Figure 3. Squares represent the measured temperature in a well at a given depth; however, the values are taken from maps, and therefore they are shown with an error bar of 5 °C. Crosses represent measured values of VR, porosity and density in each plot, respectively. Colour curves represent calculated values by model. Further discussion in the text.

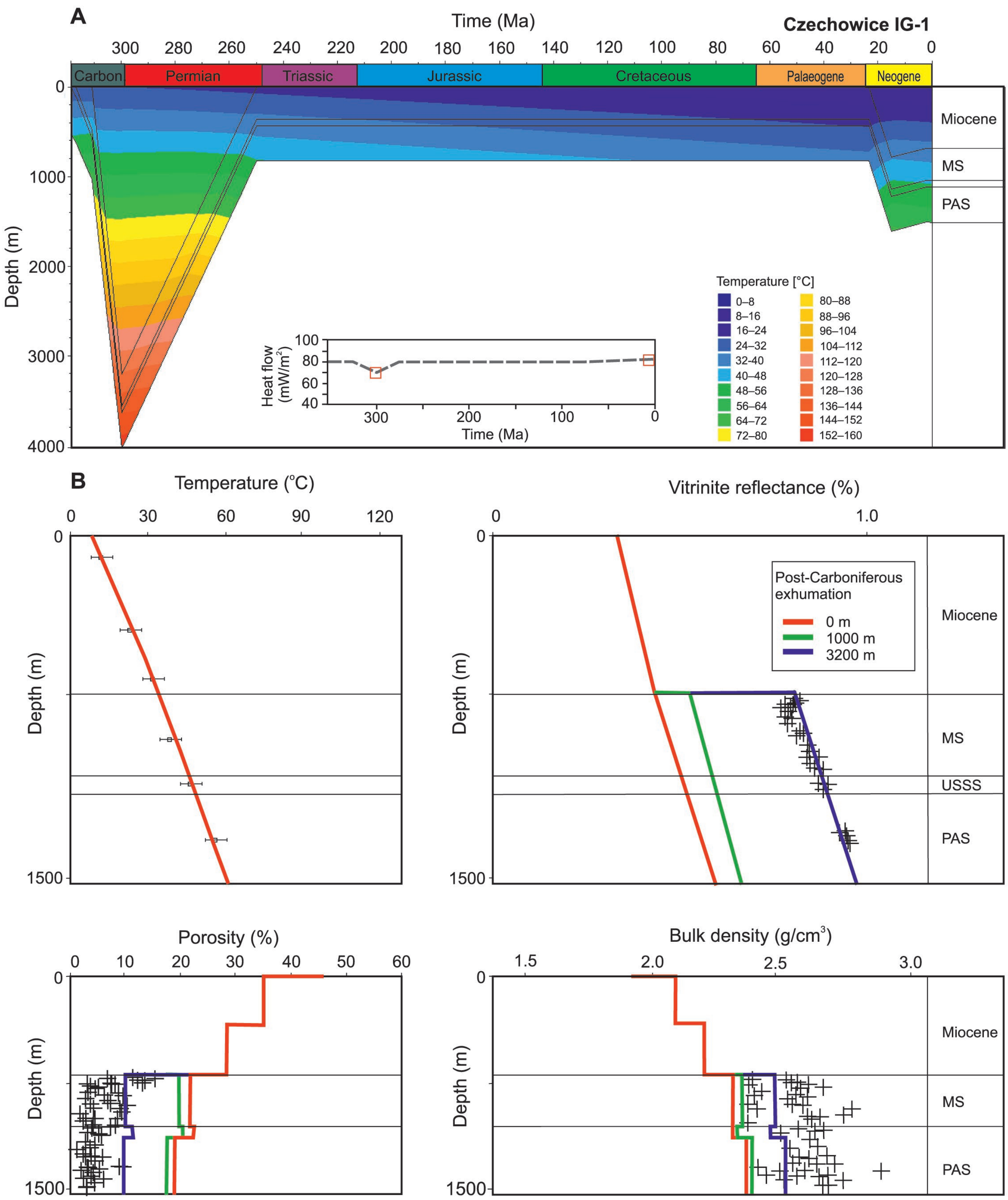


Fig. 5. Burial and thermal history model for the Czechowice IG-1 well in the southern part of the Upper Silesian Coal Basin including calibration. **A.** The burial and thermal history model. **B.** Calibration of the model using present-day temperature, VR, porosity and density data in the well. USSS – Upper Silesian Sandstone Series. See explanations in Figure 4.

transfer processes associated with the development of abnormally high pressure, as described in the Rocky Mountain Foreland Basins (Law *et al.*, 1989). Such a high-pressure development was related to the Variscan stage of evolution in the late Carboniferous.

In all wells analysed, the base of the Paralic Series was not reached by drilling: therefore, all values for the Paralic Series refer only to the upper part, which was drilled in the wells studied. Therefore, calculated values of temperature, VR and kerogen transformation ratio are very similar or overlapping. The maximum temperature calculated in four lithostratigraphic series of the USCB varies: from c. 100 to 170 °C at the base of the analysed part of the Paralic Series (Fig. 12A), from c. 100 to over 170 °C at the base of the Upper Silesian Sandstone Series (Fig. 12B), from c. 95 to over 155 °C at the base of the Mudstone Series (Fig. 12C) and from c. 90 to over 110 °C at the base of the Cracow Sandstone Series (Fig. 12D).

The VR was calculated for the base of each lithostratigraphic series of the USCB (Fig. 12): from c. 0.6 to 1.7%VR at the base of the Paralic Series (Fig. 13A), from c. 0.6 to 1.8%VR at the base of the Upper Silesian Sandstone Series (Fig. 13B), from c. 0.6 to over 1.15%VR at the base of the Mudstone Series (Fig. 13C) and from c. 0.5 to over 0.7%VR at the base of the Cracow Sandstone Series (Fig. 13D). For the base of the Carboniferous section, a VR map is not given because of a lack of suitable data on the depth to

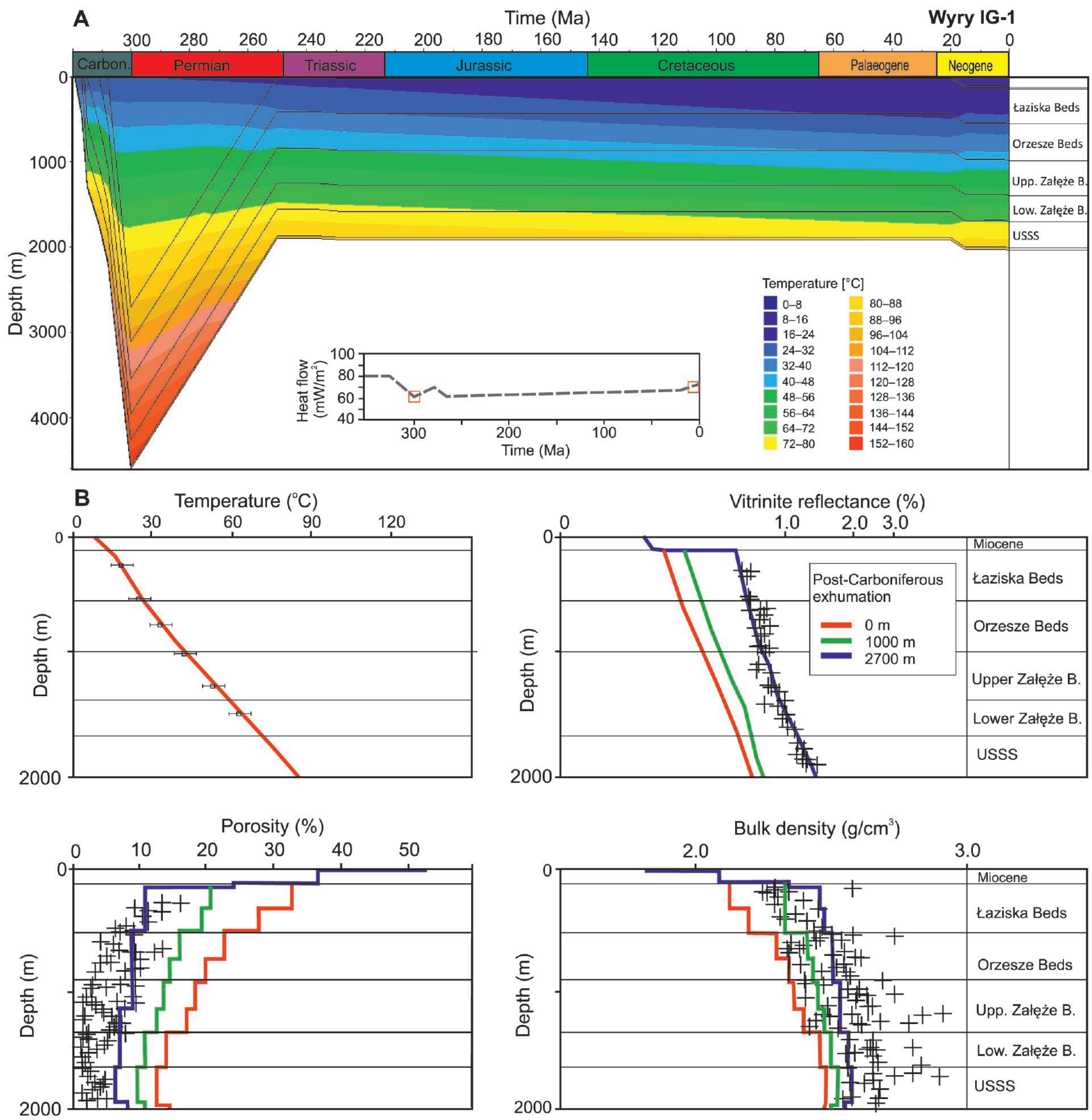


Fig. 6. Burial and thermal history model for the Wyry IG-1 well in the north-central part of the Upper Silesian Coal Basin including calibration. **A.** The burial and thermal history model. **B.** Calibration of the model using present-day temperature, VR, porosity and density data in the well. See explanations in Figures 4, 5.

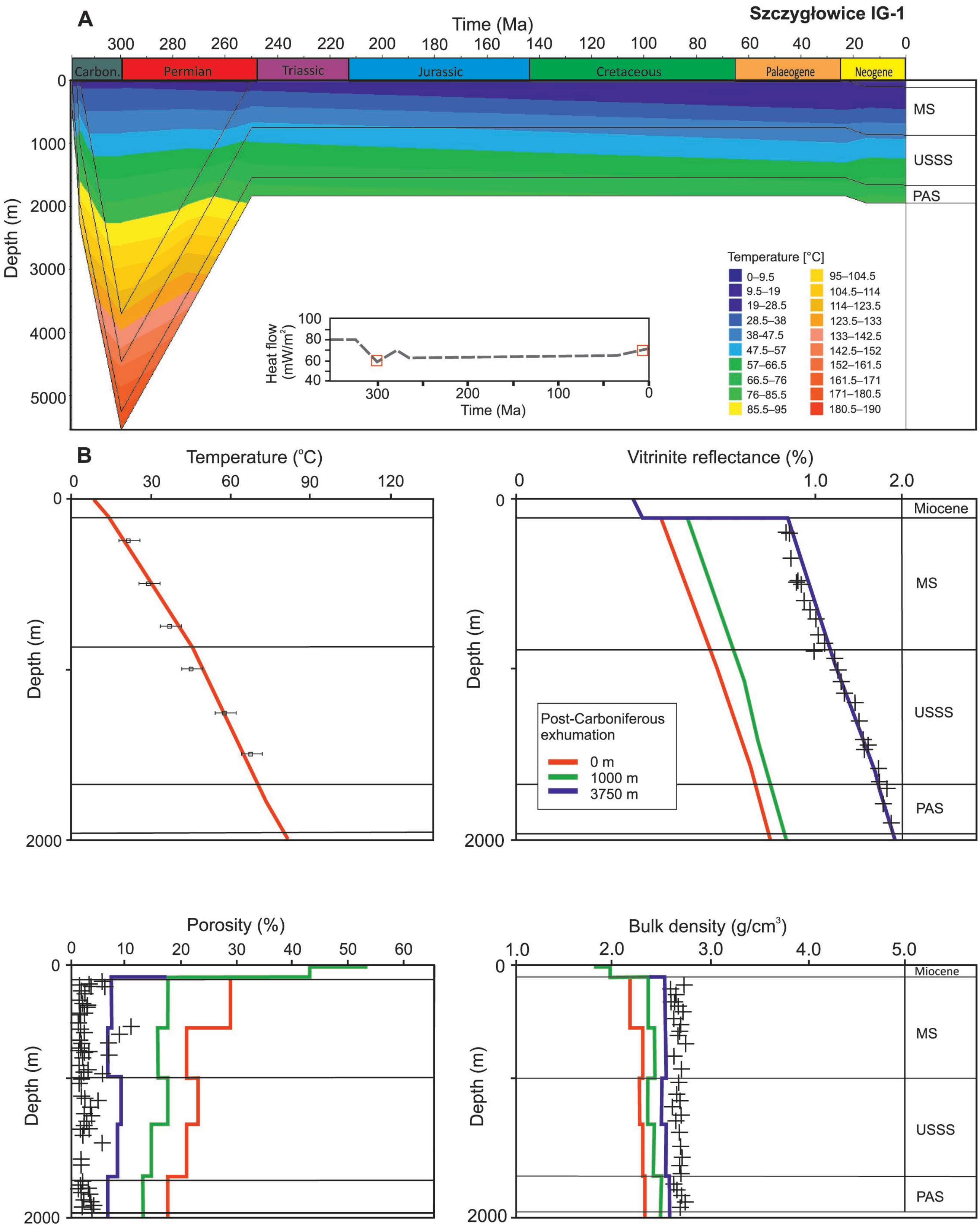


Fig. 7. Burial and thermal history model for the Szczygłowice IG-1 well in the western part of the Upper Silesian Coal Basin including calibration. **A.** The burial and thermal history model. **B.** Calibration of the model using present-day temperature, VR, porosity and density data in the well. See explanations in Figures 4, 5.

the pre-Carboniferous substratum. Most wells in the USCB did not reach the base of the upper Carboniferous sedimentary sequence. The VR map calculated from 1-D modelling results (Fig. 13) generally coincides very well with VR measurement findings of previous studies (e.g., Jurczak-Drabek, 1996, 2000). The calculated VR values increased up to the maximum temperature, which occurred at the transition between the Carboniferous and the Permian. Temperatures which occurred later were too low for a further increase in coalification (see Botor, 2014). The small number of data points on the calculated maps preclude more detailed analysis in connection with tectonics.

The burial and thermal history modelling results are consistent with the earlier results based on coal rank, illite-smectite, conodont colour alteration index data and apatite thermochronology (Bełka, 1993; Kotas, 1994, 2001; Środoń *et al.*, 2006; Botor, 2014); they cannot be caused by a present-day geothermal field of the USCB. Indeed, the thermal maturity of the Carboniferous strata of the USCB predominantly was caused by a Variscan burial or/and geothermal gradients (and heat flow) in the late Carboniferous to early Permian. These maturity modelling results agree with apatite fission-track dating, which indicated that rapid cooling, from temperatures above c. 120 °C to below 60 °C, had already occurred from the Permian to the Early Triassic: therefore, the maximum temperature had to be reached earlier in the most areas of the USCB, at least from the western border of the USCB to the Jaworzno area (Fig. 1; Botor, 2014).

Sedimentological reconstruction of the basin fill indicates that the thickness of the Carboniferous strata, removed by erosion from above the present-day surface, decreased by c. 4–5 km between the western and eastern parts of the basin

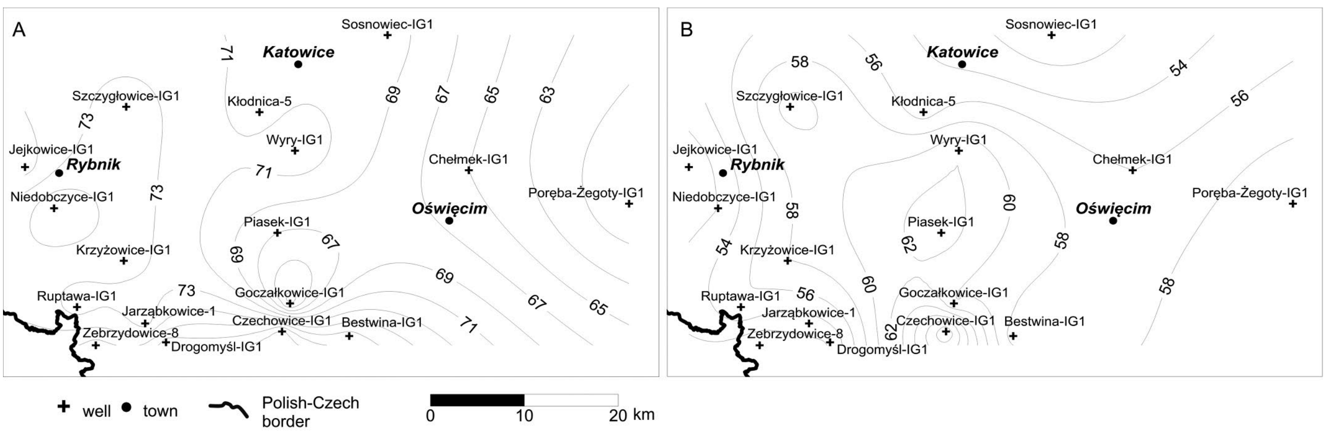


Fig. 8. Heat flow data for selected wells in the Upper Silesian Coal Basin **A.** Calculated present-day heat flow (in mW/m²). **B.** Calculated heat flow (in mW/m²) at the time of maximum burial at the end of the Carboniferous (c. 300 Ma).

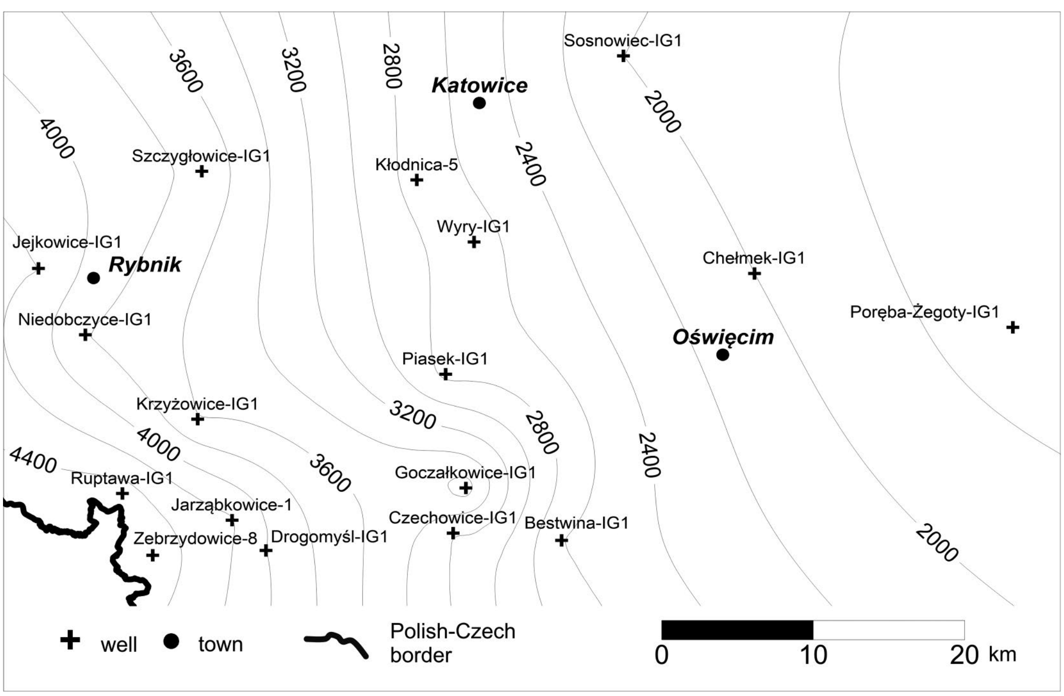


Fig. 9. Distribution of calculated thickness of exhumed/eroded Carboniferous overburden (in metres) in the Upper Silesian Coal Basin due to the Variscan tectonic inversion.

(Fig. 1C; Kotas, 1995). However, by applying a linear extrapolation of the coalification gradients, Bełka (1993) estimated the thickness of the eroded pre-Triassic (Palaeozoic) sediment pile as 1,200 m in the east and 3,000 m in the western part of the USCB. These values are supported by the results of this maturity modelling, but with higher values, in the range 1,700–4,500 m, which are necessary owing to the application of porosity and density data for calibration. Apatite fission-track data can be used to infer a high exhumation rate in the Permian, followed by a decrease in the Mesozoic

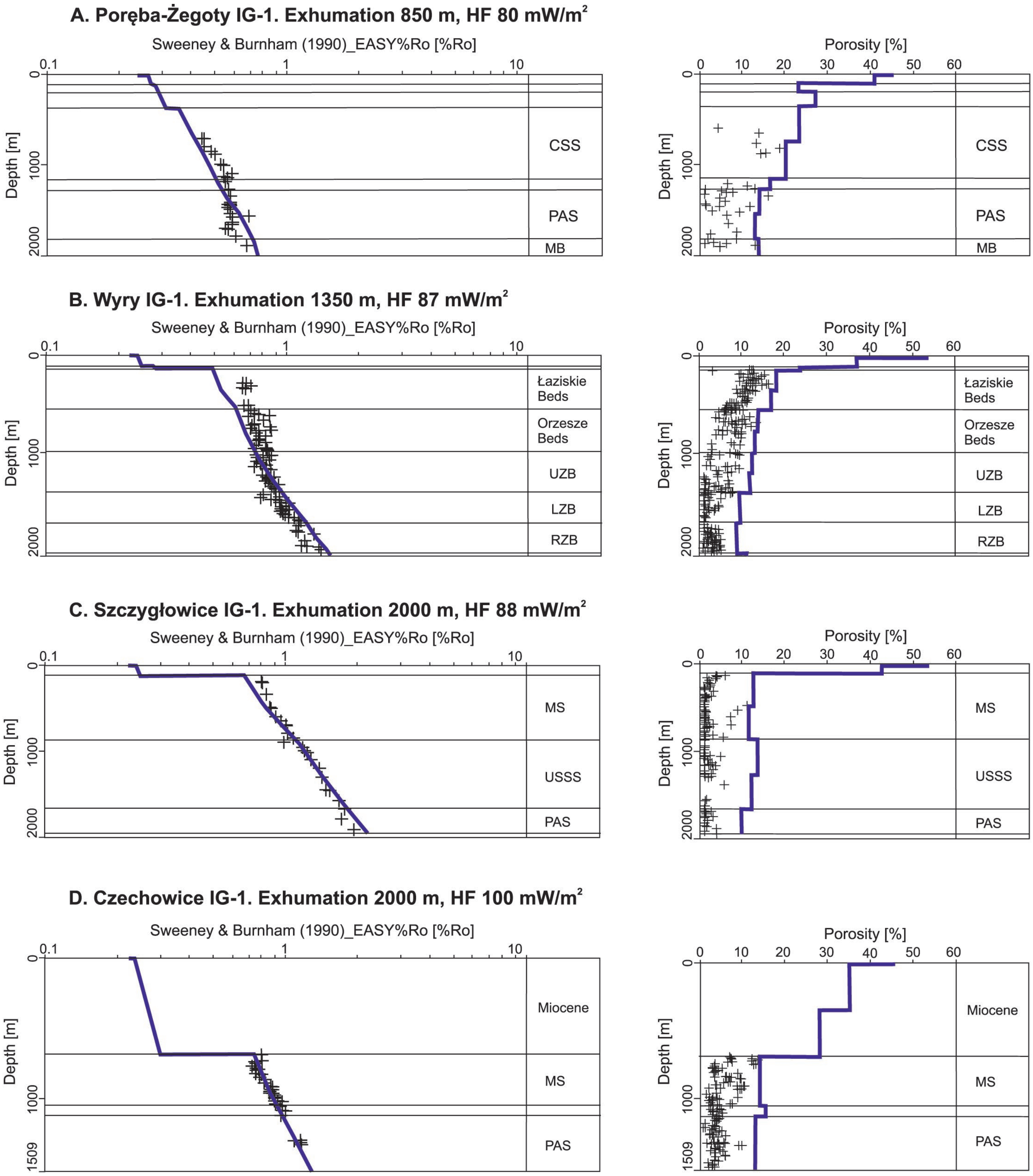


Fig. 10. Alternative calibration of burial and thermal history for selected models. These models use lower exhumed overburden and higher heat flow values. Model calibration done by applying vitrinite reflectance is similar to the preferred models (from Figs 4–7), but compaction data (porosity) show that these models underestimate the thickness of the exhumed overburden, which is necessary to accurately predict porosities. CSS – Cracow Sandstone Series, LZB – Lower Załęże Beds, MB – Malinowickie Beds, MS – Mudstone Series, PAS – Paralic Series, RZB – Ruda-Zabrze Beds, USSS – Upper Silesian Sandstone Series, UZB – Upper Załęże Beds.

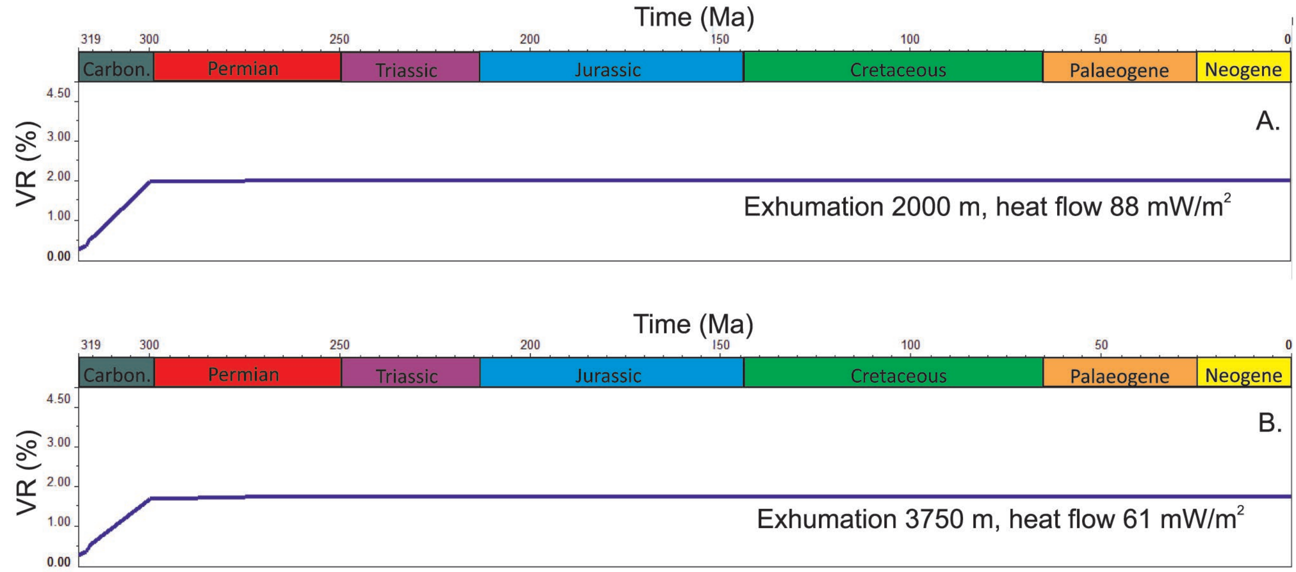


Fig. 11. Time *versus* mean vitrinite reflectance curves for the Paralic Series in Szczygłowice IG-1 well: (**A**) applying a model assuming 2000 m post-Variscan exhumation and 88 mW/m^2 heat flow during maximum burial and (**B**) applying the preferred model assuming 3750 m exhumation and 61 mW/m^2 heat flow during maximum burial. Both models show the same quality of calibration and similar timing of coalification.

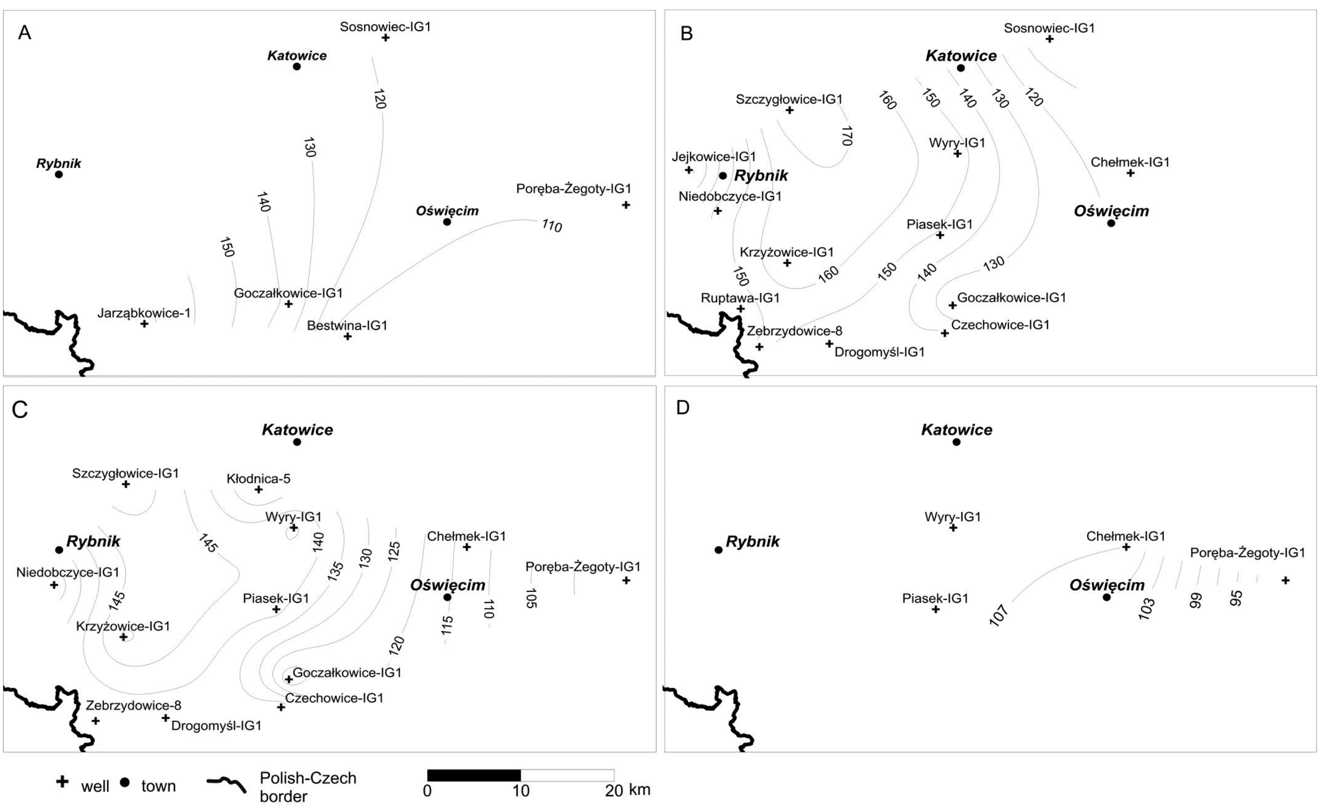


Fig. 12. Calculated maximum temperature (in °C) of the Upper Silesian Coal Basin at the base of (**A**) Paralic Series, (**B**) Upper Silesian Sandstone Series, (**C**) Mudstone Series, and (**D**) Cracow Sandstone Series.

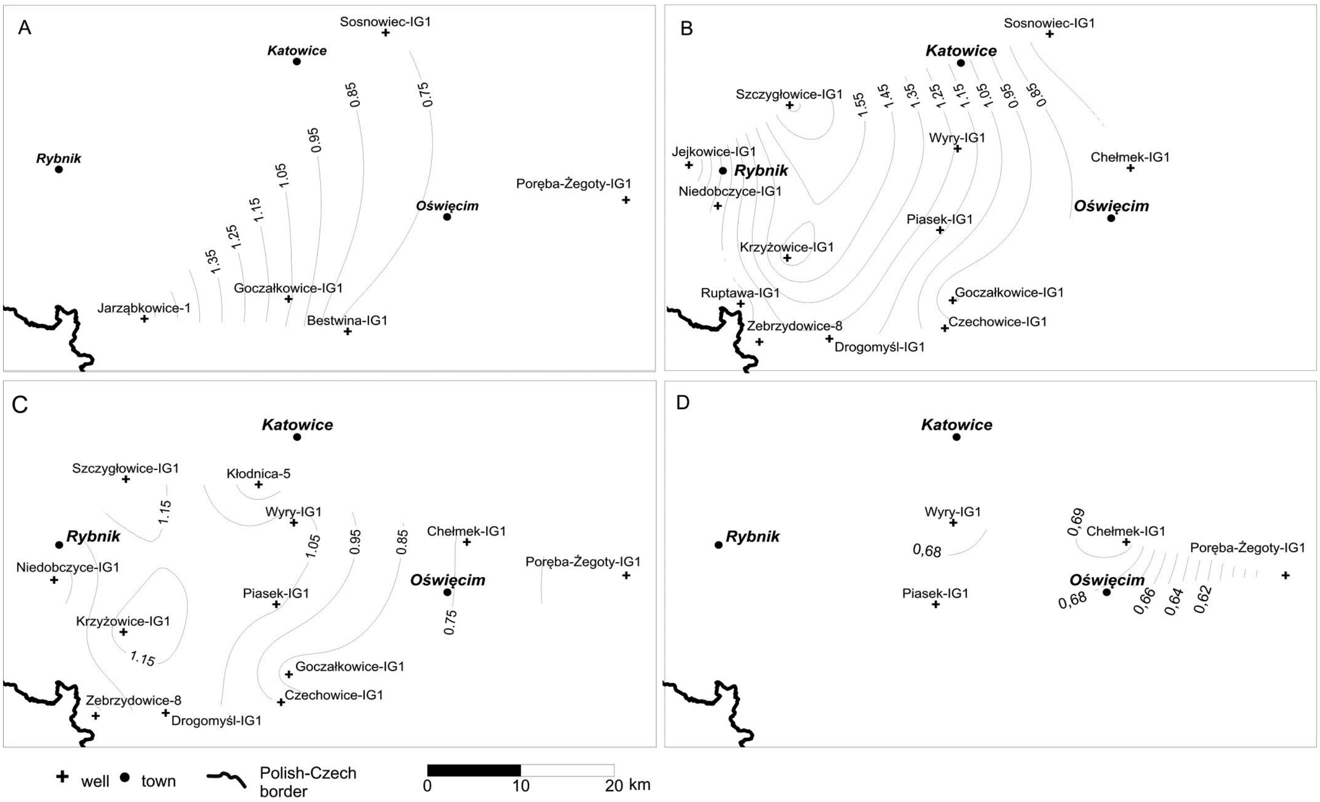


Fig. 13. Calculated vitrinite reflectance (in %) of the Upper Silesian Coal Basin at the bottom of (**A**) Paralic Series, (**B**) Upper Silesian Sandstone Series, (**C**) Mudstone Series, and (**D**) Cracow Sandstone Series.

and the Cenozoic (Botor, 2014). These estimates of exhumation would require Carboniferous sedimentation to have lasted longer than presumed. The exhumation rate reaches >5–10 km/Ma in active orogenic settings (Ring *et al.*, 1999). The average rate of mechanical erosion of the drained part of the continents is c. 52 m/Ma. Therefore, the calculated exhumation level (1700–4500 m) proposed in this modelling of the USCB can be partitioned among several discrete events between the Variscan shortening (c. 300 Ma) and the Miocene deposition in the Carpathian Foredeep (c. 15 Ma) in most areas of the USCB. However, most of the exhumation/erosion occurred before the Triassic.

The modelling results are consistent with the major exhumation phase of Carboniferous strata during the late Variscan tectonic inversion of the basin and are also consistent with K-Ar ages of illite-smectite from ash layers in the western part of the USCB (Środoń *et al.,* 2006). Moreover, they are also consistent with VR anisotropy data (Komorek, 1996; Pozzi, 1996; Morga, 2000), which show a synorogenic coalification. More evidence for a period of exhumation before the Triassic is given by the scarcity of Permian sediments, which are restricted to a narrow zone along the NE margin of the USCB, where the sequence does not exceed c. 200 m (Siedlecka, 1964; Harańczyk, 1979; Kotas, 1995).

There is another explanation for the relatively low heat flow values and very high thicknesses of the exhumed sedimentary sequence calculated in the modelling. It might have been an effect of low coalification gradients that could be a result of transient heating by the Variscan hot circulating fluids, as in the Alpine molasse of Switzerland (e.g., Schegg, 1992). However, the approach applied cannot detect such short-lived processes in the crust. Nevertheless, the modelling performed does not preclude their existence. For a more detailed discussion on the effect of convective heat transport on the temperature distribution in sedimentary basins, see, e.g., Majorowicz and Jessop (1993).

Post-Variscan evolution

The Carboniferous strata were below c. 60 °C in most of the USCB during the Mesozoic. However, Carboniferous rocks from the most NE part of the USCB remained in a temperature range of c. 60–120 °C (i.e., the apatite partial annealing zone) for most of the Mesozoic (Botor, 2014; Fig. 1, yellow hatched area). Because some of the Carboniferous samples from the NE part of the USCB show Jurassic to Early Cretaceous fission-track ages (Botor, 2014), it seems that towards the east, the Mesozoic increase of temperature was slightly higher (up to c. 70–85 °C) than it was in the western part of the UCSB (up to 60–70 °C). A Mid-Mesozoic temperature increase is also indicated by Early Cretaceous apatite helium ages (Botor, 2014) and illite K-Ar ages in the NE part of the USCB (Środoń *et al.,* 2006). A Mid-Mesozoic thermal event may be explained by elevated heat flow due to crustal extension and basin-forming processes that were affecting Central Europe from the latest Triassic to mid-Jurassic times (Hanish, 1984; Oberc, 1993; Dadlez *et al.,* 1995; Scheck *et al.,* 2002), because Mesozoic sedimentary cover did not exceed a few hundred metres

(Marcinowski, 1989; Dadlez *et al.,* 1995; Kotas 1995). This NE area is located close to the Kraków-Lubliniec Fault Zone (Oberc, 1993; Buła *et al.,* 1997; Żaba, 1999). The timing and magnitude of this mid-Mesozoic heating event are poorly constrained by the apatite fission-track record because the temperatures were too low and/or operated for too short a time (< 1 Ma), to change the existing fission-track record. Such a short-lived, mid-Mesozoic thermal event was most likely related to hot fluid flow, from which Zn-Pb ore deposits of the Mississippi Valley Type in the Middle Triassic dolomites were formed (Sas-Gustkiewicz and Dżułyński, 1998). Fluid inclusion homogenization temperatures in the Triassic rocks indicate that these hot fluids had temperatures c. 80 °C to 160 °C (Kozłowski, 1995; Sas-Gustkiewicz and Dżułyński, 1998), although the thermal effect on rocks surrounding the conduits was likely limited to a narrow zone.

The kinetics of VR have a strong temperature dependence, which is reflected in the high activation energies in Sweeney and Burnham's (1990) Easy%VR model; therefore, a second stage of heating markedly affects VR values only if it again reaches a temperature higher than the earlier temperature of the first heating stage in a similar period of heating time. If the second temperature is only 5 °C lower than the temperature during the first stage, the effect of the second heating of equal duration on VR is <0.015%VR, and thus it is negligible (e.g., Mazurek *et al.,* 2006). Therefore, an increase in temperature during reheating needs to be significantly higher (at least c. 10–20 °C) than the first maximum in the basin in order to change the VR pattern from the first event. Relatively hot, but short-lived fluids (< 1 Ma) would not affect the coalification of the organic matter in the Carboniferous strata. Although mid-Mesozoic thermal event(s) are unlikely to have played an important regional role in the coalification of Carboniferous organic matter, which requires much higher temperatures and longer times, they might have been enough to remobilize pre-existing methane deposits, causing a remigration phase.

In the border zone between the Małopolska and Upper Silesia blocks, no reheating is observed after rapid Permian cooling, because the apatite fission-track age (275±13 Ma) and the mean helium age (265±15 Ma) of the early Permian Filipowice Tuff from the Kowalska Góra outcrop show a small (10 Ma) time gap (Botor, 2003). These cooling ages, together with a narrow unimodal track lengths distribution characterized by mean values of 14.01 μm with standard deviation 0.9 μm, clearly show that this tuff was rapidly cooled in the Permian and was not heated later (Botor, 2003).

The relatively low thermal maturity of Carboniferous strata under the Carpathian overthrust and a coal rank pattern similar to the more northern part of the USCB not covered by the Carpathians (e.g., Filipiak *et al.*, 2002), as well as thermal modelling results (Kotarba *et al.,* 2004; Geršlová *et al.,* 2016), show that the Carpathian overthrust had no effect on Carboniferous coalification. Moreover, low thermal maturation of dispersed organic matter (c. 0.2–0.5%VR) in the Triassic to Miocene rocks (Kołcoń and Wagner, 1983; Nowak, 1999; Szafran and Wagner, 1999, 2000; Marynowski *et al.,* 2007; Marynowski and Wyszomirski, 2008; Rybicki *et al.,* 2016, 2017) also supports the idea that major coalification of the Carboniferous sediments was achieved before the Triassic, i.e., in the late Carboniferous.

Hydrocarbon generation

Coals and dispersed sedimentary organic matter in the upper Carboniferous sediments of the USCB are of terrestrial origin (gas-prone Type III kerogen). Admixtures of algal organic matter (Type II kerogen, liptinite-rich, particularly in sapropelic coals) are negligible (Kotarba 2001; Kotarba *et al.,* 2002, 2004). Type III kerogen is characterized by a low hydrogen index (HI), which is usually much below 200 mg of hydrocarbon per gram of total organic carbon (TOC). Therefore, the type III kerogen has a low potential for generating liquid hydrocarbons, but it is an important source of natural gases dominated by methane (e.g., Cornford, 1998; Kotarba, 2001). As thermogenic gases are generated from kerogen mainly in the range of 0.80–1.85%VR (Cornford, 1998; Kotarba and Lewan, 2004; Schimmelman *et al.,* 2006), the Carboniferous source rocks were able to generate a significant amount of hydrocarbons, because the Carboniferous thermal maturity is in this range. Both the best fit models and the alternative models (Figs 4–10) showed that maximum temperature and thermal maturity were reached in the late Carboniferous (Fig. 11); therefore, the hydrocarbon generation took place mainly during the late Carboniferous, reaching a maximum before the tectonic shortening in the latest Carboniferous.

The results of the gas generation modelling are shown as the kerogen transformation ratio (% TR) (Fig. 14) and the bulk methane (dry gas) generated (Fig. 15). TR calculated values are given at the bottom of each lithostratigraphic series in the USCB (Fig. 14). It reached values below 5% in the east to over 60% in the SW at the base of the Paralic Series (Fig. 14A), from c. 10% to over 75% at the base of the Upper Silesian Sandstone Series (Fig. 14B), from c. 5% to over 55% at the base of the Mudstone Series (Fig. 14C) and below 5% at the base of the Cracow Sandstone Series (Fig. 14D). Gas generation development reveals considerable diversification in particular zones of the USCB. Calculated values generally increase from the east towards the west and SW (Fig. 15): from c. 4 mg to over 80 mg hydrocarbons (HC)/g TOC at the base of the Paralic Series (Fig. 15A), from c. 5 mg to over 80 mg HC/g TOC at the base of the Upper Silesian Sandstone Series (Fig. 14B), from c. 5 mg to 60 mg HC/g TOC at the base of the Mudstone Series (Fig. 15C) and below 20 mg HC/g TOC at the base of the Cracow Sandstone Series (Fig. 15D). The highest TR values occur in the zones of maximum maturity of the organic matter. Modelling predicts that in the eastern part of the USCB only the early phase of hydrocarbon generation was reached, whereas towards the west and SW, hydrocarbon generation processes were more advanced.

Upper Carboniferous source rocks generated thermogenic gas in the late Carboniferous only, owing to insufficient burial in the post-Variscan stages of development. However, coalification possibly could have still occurred at shallower depths owing to relatively high heat flow in the early stages of the late Carboniferous (Pešek and Sýkorová, 2006), and/ or the heat redistribution of migrating brines could also

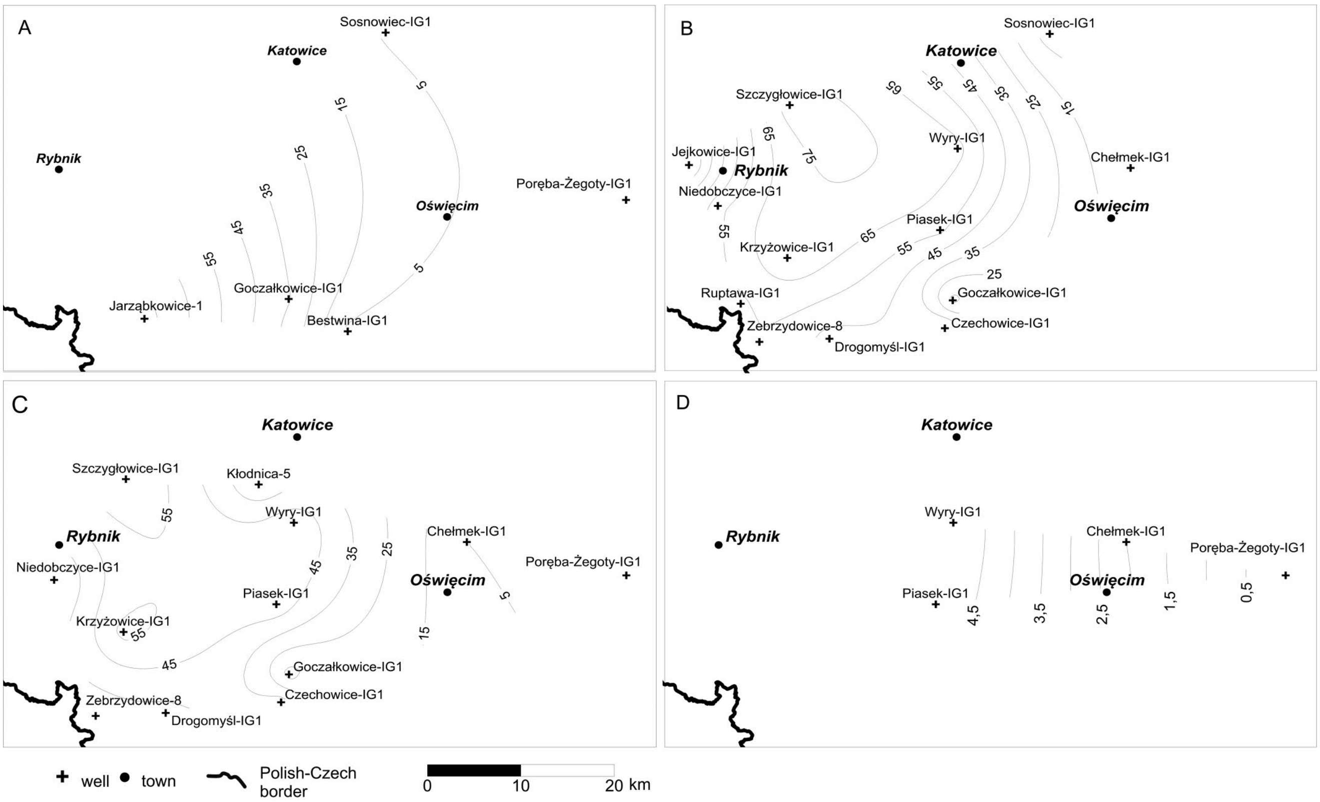


Fig. 14. The calculated kerogen transformation ratio (in %) of the Upper Silesian Coal Basin at the bottom of **A.** Paralic Series, **B.** Upper Silesian Sandstone Series, **C.** Mudstone Series, **D.** Cracow Sandstone Series.

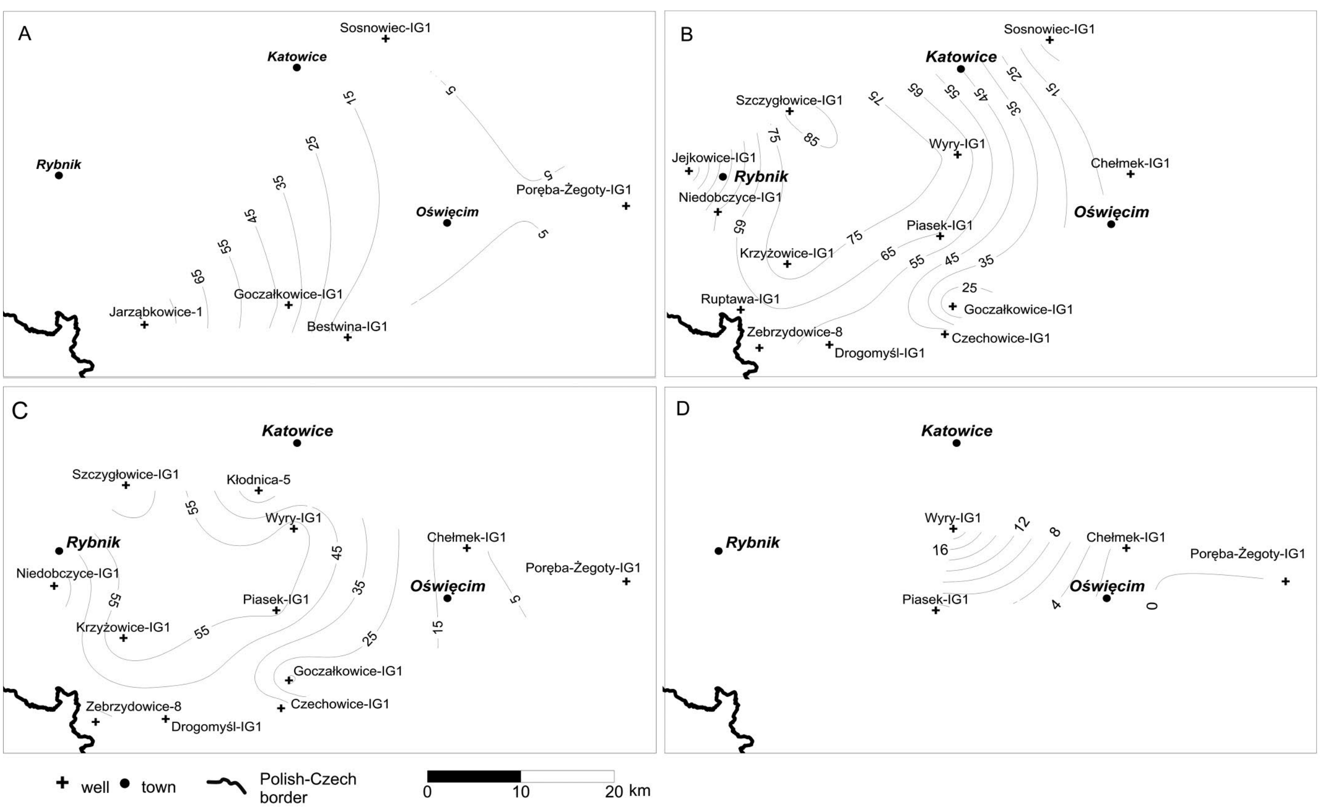


Fig. 15. Calculated bulk hydrocarbon potential (mg methane per gram TOC) using a kinetics model for type III humic kerogen at the base of selected lithostratigraphic units. **A**. Paralic Series. **B**. Upper Silesian Sandstone Series. **C**. Mudstone Series. **D**. Cracow Sandstone Series.

have had an effect on coalification in the late Carboniferous (e.g., Hower and Gayer, 2002; Poprawa *et al.,* 2006).

Because the modelling results of Ney and Kotarba (1995) predict that considerably more gas may be generated by the USCB coals than the coals can store in the deeper areas of the basin, it is expected that a considerable amount of methane probably migrated from the coals to nearby sandstone/siltstone reservoirs and to the atmosphere. Most hydrocarbons were lost due to dispersion after the tectonic inversion that was associated with intensive exhumation/erosion from the Permian period to the Mesozoic and Cenozoic periods (Kędzior, 2009; Kędzior *et al.,* 2013; Dreger, 2019; Kędzior and Dreger, 2019). The total quantity of methane generated in coals and in dispersed organic matter in siltstones has been recently calculated using 4-D numerical modelling by Słoczyński and Drozd (2018), and it amounts to more than 23,000 billion m^3in an area of 1,300 km^2 (25% of the total area of the Polish part of the USCB) in the western part of the USCB. Słoczyński and Drozd (2018) estimated that a huge part of the generated hydrocarbons was dispersed (c. 93% from 23,000 billion m^3), but more than 1,570 billion m^3 of gas were accumulated. This is comparable to an earlier estimation of c. 5,200 billion m^3 of gas (Ney and Kotarba, 1995) that was calculated for the entire USCB (area c. 5000 km^2). In the USCB, a substantial amount of methane is released into the atmosphere (e.g., Dreger, 2019; Kędzior and Dreger, 2019; Sechman *et al.,* 2020b). It has been estimated that c. 540 million m^3 of methane was released in 2018 by the ventilation systems of coal mines in the USCB (PGI, 2020). Moreover, methane is also capable of vertical migration and microseepage through rock overburden. In this case, methane escapes through a system of faults, cracks and microfractures in rocks (Thielemann *et al*., 2001; Karacan and Olea, 2014). A general increase in methane content is observed toward the south and west in the USCB along with increasing coal rank (Kędzior, 2009; Kędzior *et al.,* 2013). However, the fact that there is no clear relationship between coal rank and methane should be no real surprise, considering the complex pattern of methane migration and accumulation, reflecting burial and exhumation of the coal-bearing sediments as well as the hydrodynamics of the basin (Kędzior, 2015). Long-lasting basin uplift during the post-Variscan period and the related exhumation of the Carboniferous rocks, caused the degassing now reflected in methane undersaturation (Kędzior, 2009; Kędzior *et al.,* 2013). It should be noted, however, that undersaturation can also be the result of pressure and temperature changes that promote a higher present-day sorptive storage capacity, compared to the time of maximum burial and gas generation.

CONCLUSIONS

The upper Carboniferous strata in the Polish part of the USCB were heated to temperatures in the range c. 90–170 °C, and this is in accordance with the moderate to high levels of thermal maturity of these rocks. Heating was caused mainly by sedimentary burial with a low to moderate heat flow (50–71 mW/m^2) during the maximum burial phase in the latest Carboniferous (c. 300 Ma). A significant thickness of sediments (c. 1700–4500 m) was eroded. The final coal rank pattern in the USCB was produced before the Variscan tectonic inversion of the basin at the transition between the Carboniferous and the Permian. This coalification level was not overprinted by any later thermal processes during the Mesozoic and the Cenozoic. The Variscan coalification processes resulted in natural gas generation (dry gas, methane-dominated). The main phase of hydrocarbon thermogenic generation over much of the USCB took place during the late Carboniferous and was terminated due to the Variscan tectonic inversion. The thermal maturity (c. 0.6–1.7%VR) and transformation ratio (c. 5–75%TR) values of organic matter are varied across the basin. Therefore, most coals generate varied but generally significant amounts of hydrocarbons, i.e., hydrocarbon generation reached over 80 mg of methane per gram of TOC in a deep sedimentary sequence of the USCB. The hydrocarbons occurring in the USCB were generated mainly during the bituminous stage of the coalification process. This process lasted no longer than a few million years and was probably completed before the early Permian. Although a large amount of the generated hydrocarbons was presumably lost because of a lack of seals during intense post-Variscan exhumation, the hydrocarbon potential of the basin is still substantial and worthy of exploration and exploitation.

Acknowledgments

I would like to thank Z. Buła, J. Jureczka, A. Kotas, M. Karwasiecka, A. Zdanowski (Geological Institute, Upper Silesian Branch, Sosnowiec, Poland) as well as O. Bábek and L. Hýlová (Palacký University in Olomouc, Czech Republic), M. Sivek and J. Jirásek (Vysoká Škola Báňská - TU Ostrava, Czech Republic) for fruitful discussion over the years. This manuscript was written during my sabbatical leave, which I spent at the Palacký University in Olomouc, thanks to the hospitality of Ondřej Bábek and the National Agency of Academic Exchange (Agreement no: PPN/BIL/2018/1/11/CZE/UMOWA/1, Warsaw). This work was partially supported by AGH Projects no 11.11.140.47; 11.11.140.562; and 16.16.140.315. The manuscript benefited from insightful reviews by Philip Weniger (BGR, Hannover, Germany) and an anonymous reviewer. Stanisław Mazur is thanked for his careful editorial work.

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