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GAS GENERATION IN CARBONIFEROUS SOURCE ROCKS OF THE VARISCAN FORELAND BASIN: IMPLICATIONS FOR A CHARGE HISTORY OF ROTLIEGEND DEPOSITS WITH NATURAL GASES

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Abstract: Numerical modelling of the Carboniferous–Permian petroleum system in the Polish Basin was carried out using PetroMod software. The Carboniferous source rocks contain organic matter mostly of a humic nature (gas-prone Type III kerogen). Subordinately, only in the Lower Carboniferous deposits, kerogen of algal marine origin and mixed Type II/III kerogen occur. The quantity of dispersed organic matter is variable, but usually below 2% TOC. In the Carboniferous section, a progressive increase in the maturity of organic matter with depth was observed, from approximately 0.5% Rr at the top of the Westphalian in marginal parts of the Carboniferous basin to over 5.0% Rr at the bottom of the Lower Carboniferous in the eastern Fore-Sudetic Homocline. The thermogenic generation of hydrocarbons continued from the late Westphalian (eastern Fore-Sudetic Homocline and partly Pomerania) throughout the Mesozoic, up to the Late Cretaceous. The advancement of this process is variable in different parts of the Carboniferous basin, reaching up to 100% of kerogen transformation in the zones of maximum maturity of organic matter. However, the most intensive periods of gas generation and migration were the Late Triassic and the Late Jurassic. The most prospective areas are located NE of Poznań–Kalisz line and SW of Poznań.

Key words: Poland, Polish Basin, organic matter, hydrocarbon potential, petroleum source rock, maturity modelling, gas generation.

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INTRODUCTION

The Rotliegend basin, extending from the UK to Poland (Kiersnowski *et al.*, 1995; Doornenball and Stevenson, 2010; Gast *et al.*, 2010), has significant hydrocarbon potential with vast hydrocarbon reserves, probably still not found, particularly in Poland (e.g., Karnkowski, 2007; Górecki, 2008; Burzewski *et al.*, 2009; Pletsch *et al.*, 2010; Botor, 2012a). Therefore, the Rotliegend basin is a major exploration target in Poland (Karnkowski, 2007). By even conservative estimates, the hydrocarbons capacity of the Polish Rotliegend basin is considered to exceed by far the amount of gas discovered to date (Burzewski *et al.*, 2009). Thus far, only 120×10^9 m^3 of recoverable gas reserves were found, whilst the undiscovered hydrocarbon potential was determined to be in the order of 1490×10^9 m^3 of gas (Burzewski *et al.*, 2009). During the fifty years of research and petroleum exploration in the Rotliegend basin of western Poland, over 80 gas fields have been found (Karnkowski, 1999, 2007).

The Carboniferous–Permian petroleum system in the Polish Basin includes the Tournasian to Westphalian (?) source rocks of the Variscan foreland basin (Fig. 1), as well as the reservoir (Rotliegend, Zechstein Limestone Ca1) and seal (mainly Zechstein evaporites) rocks of the succeeding Permo-Mesozoic Polish Basin (Pletsch *et al.*, 2010). In this paper, the results of 1-D hydrocarbon generation modelling and 3-D gas migration modelling are presented together with the resulting regional maps of kerogen transformation ratio and gas migration. They collectively explain the major factors, influencing the charge history of the Polish Rotliegend gas reservoirs. The timing and magnitude of gas generation in the Carboniferous rocks studied are extremely important for an understanding of trap formation and filling in Rotliegend reservoirs. Because petroleum generation and expulsion in the Carboniferous sediments of the Lublin Basin were described by Botor *et al.* (2002b), Botor and Littke

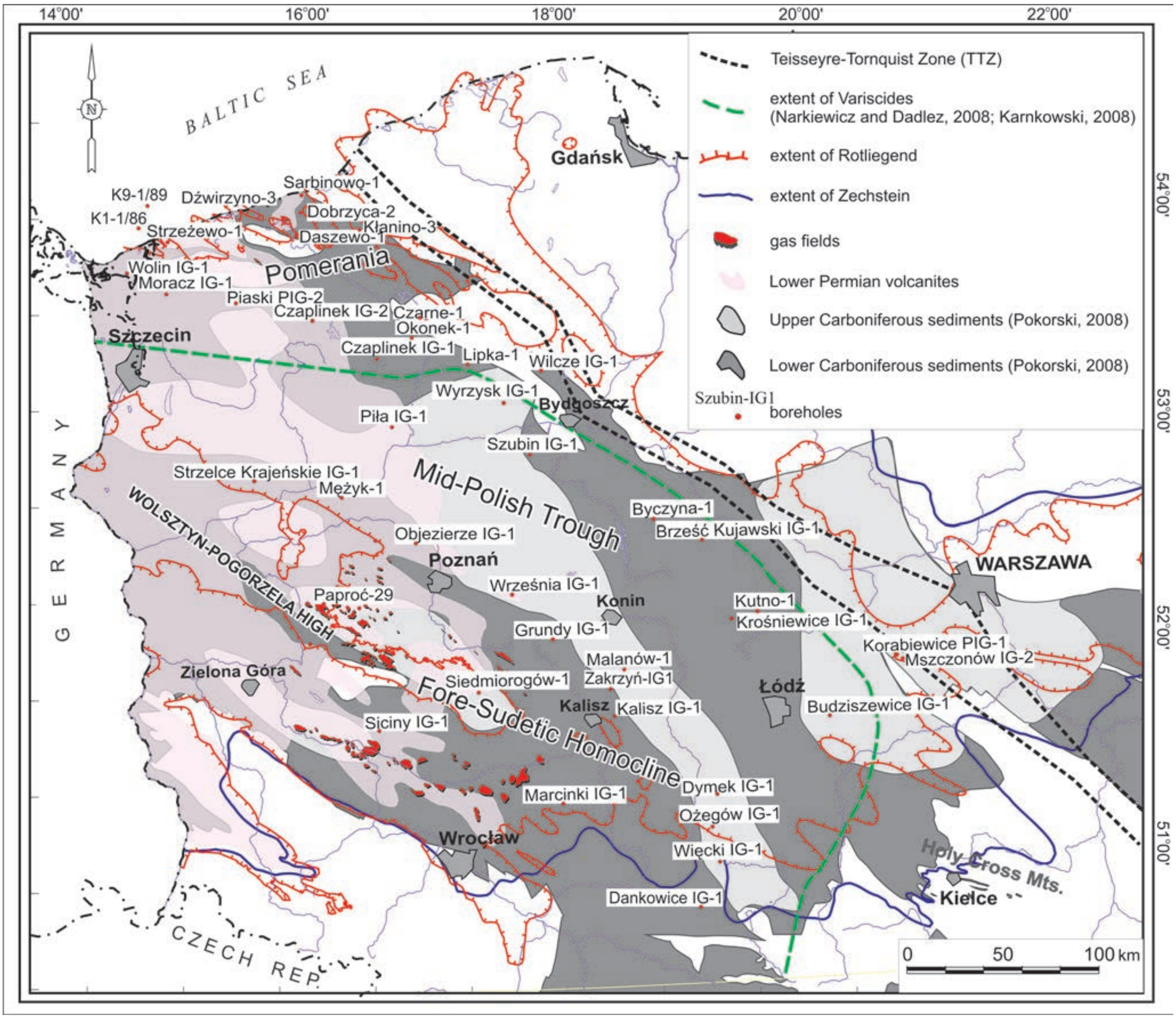

Fig. 1. Main elements of Carboniferous–Permian petroleum system in Polish Basin (based on Reicher, 2008): Carboniferous subcrop (source rocks), Rotliegend (reservoir rocks), and Zechtein (seal rock). Extent of Early and Late Carboniferous based on Pokorski (2008)

(2003) and Karnkowski (2003), this paper focusses on the Carboniferous Variscan foreland basin, from the Fore-Sudetic Homocline to Pomerania and central Poland (Kujawy).

GEOLOGICAL SETTING

The Permo-Mesozoic Polish Basin extends between the Sudetes at the edge of the Variscan interdnides to the south and the Baltic Sea to the north. The Mesozoic rocks are unconformably overlain in that area by a Cainozoic sedimentary succession, up to 350 m thick. The thickness of the Permo-Mesozoic strata gradually increases towards the north from about 1 km near the Sudetes to about 8 km in the centre of the NE–SW trending Mid-Polish Trough (MPT), an elongated depocentre which parallels the Teisseyre–Tornquist Zone. The MPT was inverted into the Mid-Polish Anticlinorium at the end of Cretaceous by a Laramide compressional event. At the same time, the SW part of the Polish Basin was tilted in response to the Laramide compression and simultaneous uplift of the Bohemian Massif to form the Fore-Sudetic Homocline (FSH), with strata dippping to the NE at the low angle of a few degrees. The substratum of the Permo-Mesozoic Polish Basin is formed by the thick Carboniferous clastic succession of the Variscan foreland basin (Fig. 1; e.g., Mazur *et al.*, 2006a, 2010). The erosional top surface of the Carboniferous at the base of the Polish Basin plunges below the Permo-Mesozoic strata and becomes inaccessible to drilling in the northern FSH and MPT.

The Carboniferous sedimentary succession in western Poland consists of clastic marine sedimentary rocks, locally deformed before the Permian (Żelichowski, 1964; Grocholski, 1975; Wierzchowska-Kicułowa, 1984; Pożaryski *et al.*, 1992). The thickness of the Carboniferous sediments penetrated by wells (e.g., Siciny IG-1 well) is a minimum of 2,500 m of monotonous Viséan to Namurian turbidites that are locally capped by Westphalian to Stephanian shallow-water sediments (Żelichowski, 1980; Witkowski and Żelichowski, 1981). Further away from the Variscan internides, in Pomerania, the Holy Cross Mts, and the Upper Silesian Block, the Carboniferous clastic succession transgress upon the Upper Devonian carbonate platform. In these areas, the Lower Carboniferous is represented by shallow marine, mostly carbonate and clayey rocks, succeeded by Namurian and/or Westphalian clastic sediments (Żelichowski, 1995; Zdanowski and Żakowa, 1995). In the Lublin Trough, onlapping the East European Craton, the Carboniferous sucession commenced in the uppermost Viséan and was laid down directly upon Devonian bedrock (Żelichowski, 1995).

Further details on the Carboniferous basin are given in the monograph by Zdanowski and Żakowa (1995). Recently, the Devonian–Carboniferous evolution of the area was described by Narkiewicz (2007) and Mazur *et al.* (2006a, b, 2010), whereas the Permian to Cainozoic development of the Polish Basin was summarized by Mazur *et al.* (2005), Kiersnowski and Buniak (2006) and Krzywiec (2006a, b). The origin and petroleum geology of the Rotliegend basin were discussed by Karnkowski (1999, 2007). The geological history of the area studied is briefly outlined below with a focus on aspects, relevant to the modelling study by the present authors.

SUMMARY OF GEOLOGICAL EVOLUTION

Variscan evolution

The sedimentary and tectonic history of the easternmost Variscides is relatively well-understood after decades of geological investigations and recently was summarized by Mazur *et al.* (2006) and McCann *et al.* (2006). The distal parts of the Carboniferous basin were deposited upon a Middle to Late Devonian carbonate platform that occupied the southern section of the Laurusian passive margin. In Poland, the Laurusian shelf extended from Pomerania in the NW, through the Holy Cross Mountains into the Upper Silesian Block and the Moravo-Silesian domain in the SE. At the end of Devonian, the platform was segmented by faults and drowned by a marine transgression, but its distal parts persisted into the Viséan. In the deeper parts of the basin, carbonates were capped by pelagic shales, passing upward into flysch-type Culm sediments. During the Viséan, the Carboniferous basin subsided rapidly in response to thrust-loading, caused by an advancing Variscan orogenic wedge. Consequently, in the proximal parts of the evolving foreland basin, thick Viséan to Namurian turbiditic sequences were deposited. Subsidence of the Variscan foreland basin in front of the developing orogen was associated with a rapid N- and NE-ward advance of late-orogenic clastic systems across Wielkopolska and Upper Silesia and Małopolska; it finally reached the Lublin Trough in the east and Pomerania in the north (Fig. 1). In the distal parts of the Carboniferous basin, sedimentation was halted locally in the late Namurian and earliest Westphalian. After a transient period of non-deposition, sedimentation resumed during the Westphalian A to B. Development of such a hiatus, e.g. in northern Pomerania, is thought to have been caused by late-orogenic compression, transferred from the Variscan orogenic wedge to its foreland (Ziegler *et al.*, 2002). The ensuing compressional stresses gradually changed their direction during the Westphalian and early Stephanian from north to north-east (Narkiewicz, 2007). Despite the increasing body of data, the trace of the Variscan deformation front is still ill-defined in western and central Poland (Jubitz *et al.*, 1986; Pożaryski *et al.*, 1992), owing to only local development of Late Carboniferous deformation, poor seismic imaging of the sub-salt succession and the scarcity of borehole data.

The compressional event, marking the end of the Variscan Orogeny, was followed by a Stephanian to Early Permian tectono-magmatic cycle (Ziegler, 1990; Benek *et al.*, 1996). At the boundary of the Stephanian and Autunian (~302–293 Ma; Breitkreuz *et al.*, 2007), intense magmatism developed in NE Germany (up to 2000 m of volcanic rocks) and NW Poland (e.g., Benek *et al.*, 1996). In Poland, it is represented by a few hundred metres of volcanogenic rocks (particularly well developed in the Szczecin Trough) that gradually thin out towards the east.

Post-Variscan history

The outline of the post-Variscan history of western and central Poland was provided by, for example, Mazur *et al.* (2005) and McCann *et al.* (2006). The Polish Basin was initiated at the beginning of the Permian, owing to a rifting event following the cessation of the Variscan orogeny. The basin comprises a succession of siliciclastics, carbonates and thick Zechstein evaporites, several kilometres thick. The total thickness of the Permian to Cainozoic sediments reaches 8 km, with a NW–SE oriented depocentre in the MPT (Ziegler, 1990; Dadlez *et al.*, 1998; Van Wees *et al.*, 2000; Stephenson *et al.*, 2003). In the Polish Basin, a rifting stage at the boundary between the Carboniferous and the Permian was associated with widespread magmatic activity and the emplacement of volcanic rocks, the amount of which increases westwards. A post-rift thermal subsidence phase commenced already in the Early Permian time, as manifested by the deposition of thick non-marine Rotliegend clastics. The successive transgressions by a shallow Zechstein sea brought about the sedimentation of up to 2 km of Upper Permian evaporites (e.g., Dadlez *et al.*, 1995, 1998; Kiersnowski *et al.*, 1995; Benek *et al.*, 1996; Wagner, 1998; Stephenson *et al.*, 2003). Furthermore, thermal subsidence continued from the Late Permian throughout the Mesozoic until the Late Cretaceous. The subsidence rate was variable in time, with three distinct pulses of accelerated subsidence in Zechstein to Scythian time, from the Oxfordian to the Kimmeridgian, as well as in the early Cenomanian (Dadlez *et al.*, 1995; Stephenson *et al.*, 2003). Regardless of evolving extensional stresses that were exerted on the Polish Basin, the main depocentre was consistently located in the MPT, following the NW–SE structural grain. Some modifications of the subsidence pattern were only related to salt movements that were initiated in the Early Triassic (Dadlez, 2003; Krzywiec, 2004). The sedimentary succession of the Polish Basin is subdivided by several erosional episodes, notably during the Late Triassic, the early/Middle Jurassic and the Late Jurassic/Early Cretaceous (Marek and Pajchlowa, 1997). The presently observed depositional architecture of the Polish Basin was shaped not only by Permo-Mesozoic extensional tectonics, but also by subsequent basin inversion in the Late Cretaceous and Palaeocene (Krzywiec, 2002).

A change of stress regime in the Polish Basin was initiated in the Late Cretaceous, probably from the end of the Turonian and was initially manifested by the reversal of fault kinematics (e.g., Dadlez *et al.*, 1995; Poprawa, 1997; Lamarche *et al.*, 2003; Stephenson *et al.*, 2003; Mazur *et al.*, 2005; Krzywiec, 2006a, b). Subsequently, inversion led to uplift of the axial part of the MPT and its subsequent erosion. Therefore, the MPT, still comprising the thickest Permo-Mesozoic sediments, presently is transformed into the Mid-Polish Swell that defines a regional anticlinorium. Furthermore, the sediments uplifted in the axial part of the Mid-Polish Swell were eroded from the top of the Cretaceous down to the Lower Jurassic and locally to the Upper Triassic. The Mesozoic sedimentary sequence is uncomformably covered by Cainozoic sediments, up to 350 m thick (Piwocki, 2004).

CARBONIFEROUS SOURCE ROCKS IN THE STUDY AREA

It is widely accepted that the gases accumulated in the Rotliegend reservoirs were derived from Carboniferous source rocks (e.g., Kotarba *et al.*, 1992, 1999, 2004, 2005; Karnkowski, 1999). Analyses of the elemental and isotopic compositions of the Rotliegend gases, together with investigations of the organic matter in the Carboniferous sediments, indicated that the gas accumulations of the Fore-Sudetic Homocline (Fig. 2) and Pomerania (Fig. 3) are genetically related to hydrocarbon sources, occurring in the Carboniferous source rocks (Kotarba *et al.*, 1992, 1999, 2004, 2005; Lokhorst, 1997). However, the Polish part of the Rotliegend Basin is not fully comparable to the West European part, where Westphalian coals are the main source rock for Carboniferous and Permian gas accumulations (Pletsch *et al.*, 2010; Botor, 2012a). Because of the extensive Permo-Mesozoic cover in western-central Poland (MPT), it remains largely unknown whether the coal-bearing Late Carboniferous molasse is present in that area. However, without taking the Westphalian coals into account, the amount of dispersed organic matter contained in the Upper and the Lower Carboniferous sediments that form the substratum of the Rotliegend Basin (Fig. 1), is high enough to provide a source for the gas, documented in borehole data from the shallower parts of the Polish Basin.

Pomerania

Tournaisian, Viséan and Westphalian black shales are the main source rocks across Pomerania (Figs 4A, 5A). Their hydrocarbon potential ($S_1 + S_2$) is fair to excellent, particularly in the case of the Lower Carboniferous sediments (Fig. 5A). Thin Westphalian bituminous coal streaks and interbeds also occur in that area and usually are less than 0.5 m thick (Matyasik, 1998; Kotarba *et al.*, 2004; Grotek, 2005, 2006; Kosakowski *et al.*, 2006; Matyja, 2006; Pletsch *et al.*, 2010). The Tournaisian and Viséan shales contain 1.5% and 1.1% TOC on average, with maxima around 10.7% and 4%, respectively (Pletsch *et al.*, 2010). Westphalian shales typically contain 0.3% TOC, up to a maximum value of 2.7% (Bachleda-Curuś *et al.*, 1996; Burzewski *et al.*, 1998; Matyasik, 1998; Kotarba *et al.*, 2004, 2005; Grotek, 2005, 2006; Kosakowski *et al.*, 2006; Bahranowski *et al.*, 2007; Pletsch *et al.*, 2010). The kerogen in the rocks is a mixture of gas-prone Type III and Type II (Fig. 4A). Average hydrogen indices (HI) decrease upwards from the Lower Carboniferous (550 mg) to the Upper Carboniferous (50 mg), but variation is typically very wide (Fig. 4A). Although HI values for the Lower Carboniferous deposits in Pomerania demonstrate wide variability (20–550), their average between 160–200 slightly exceeds the median for all Carboniferous samples (110 in sum) (Bachleda-Curuś *et al.*, 1996; Burzewski *et al.*, 1998; Matyasik, 1998; Kotarba *et al.*, 1999, 2004, 2005; Pletsch *et al.*, 2010). Subordinate kerogen of algal origin (Type II kerogen) and mixed Type II/III kerogen occur only in the Lower Carboniferous deposits. The Lower Carboniferous clayey-marly Sąpolno Formation (of the lagoonal and slope-to-basin facies) contains considerable amounts of oil-prone sapropelic organo-mineral associations with liptinite (Type II kerogen) (Kotarba *et al.*, 1999, 2004, 2005; Grotek, 2005, 2006; Bahranowski *et al.*, 2007). However, the Carboniferous kerogen, has a low hydrogen content, indicating its rather gas-prone character (Kotarba *et al.*, 2004; Pletsch *et al.*, 2010). This fact establishes the nature of the Carboniferous organic matter as a source of gaseous hydrocarbons (Botor *et al.*, 2002b; Pletsch *et al.*, 2010). The proportion of stable isotopes of carbon in natural gas from the Rotliegend samples confirms a major contribution from Carboniferous organic matter with type III kerogen (Kotarba *et al.*, 2004, 2005). Both Rock-Eval T_{max} (408 to 454°C; Fig. 4A) and vitrinite reflectance values (~0.4–1.0% Rr) indicate that the Carboniferous source rocks for the most part are marginally mature to mature. Only kerogen in the southern part of Pomerania shows the highest present-day maturity of up to 1.9% Rr, indicating the gas-generating potential of the Carboniferous in this area (Pletsch *et al.*, 2010).

Fore-Sudetic Homocline

In the Fore-Sudetic Homocline (FSH), Carboniferous source rocks are mainly shales with dispersed organic matter. Their hydrocarbon potential ($S_1 + S_2$) varies from poor to very good (Fig. 5B). The organic carbon content is generally lower than in the other parts of the Polish Basin and ranges from 0.5 to 2%, but rarely reaches 4% (Fig. 5B) (Nowak, 2003, 2007; Pletsch *et al.*, 2010; Poprawa, 2010;). The organic matter dispersed in the Carboniferous source rocks is principally of humic character (gas-prone Type III kerogen), but highly mature or overmature (Fig. 4B; Nowak, 2003, 2007; Pletsch *et al.*, 2010; Poprawa, 2010). The organic matter mainly consists of vitrinite group macerals, with subordinate macerals of the inertinite and liptinite groups. Lesser quantities of oil-prone and mixed II/III Type

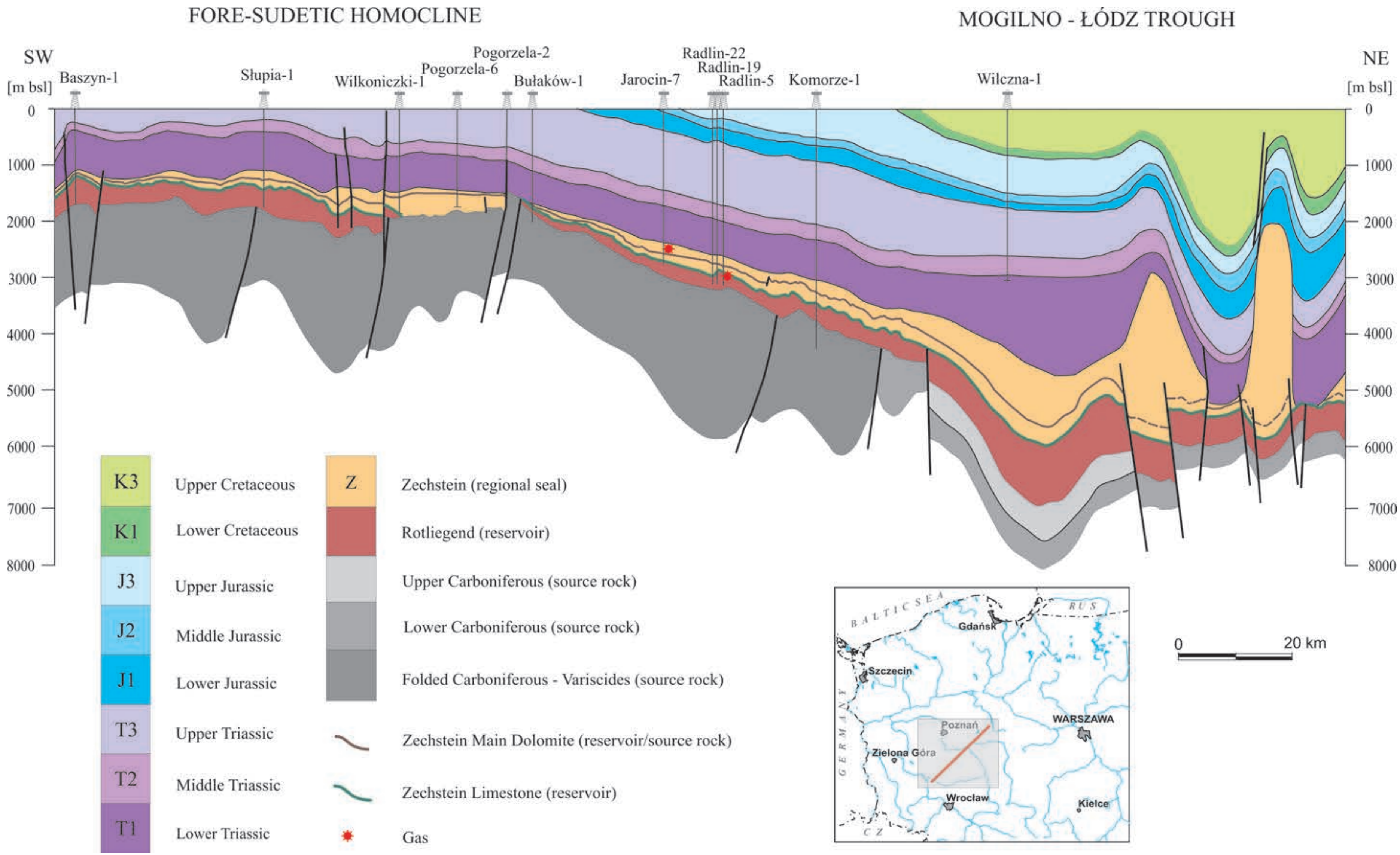

Fig. 2. Schematic cross-section across Fore-Sudetic Homocline (Cainozoic section removed; modified after Górecki, 2006; Pletsch *et al.*, 2010)

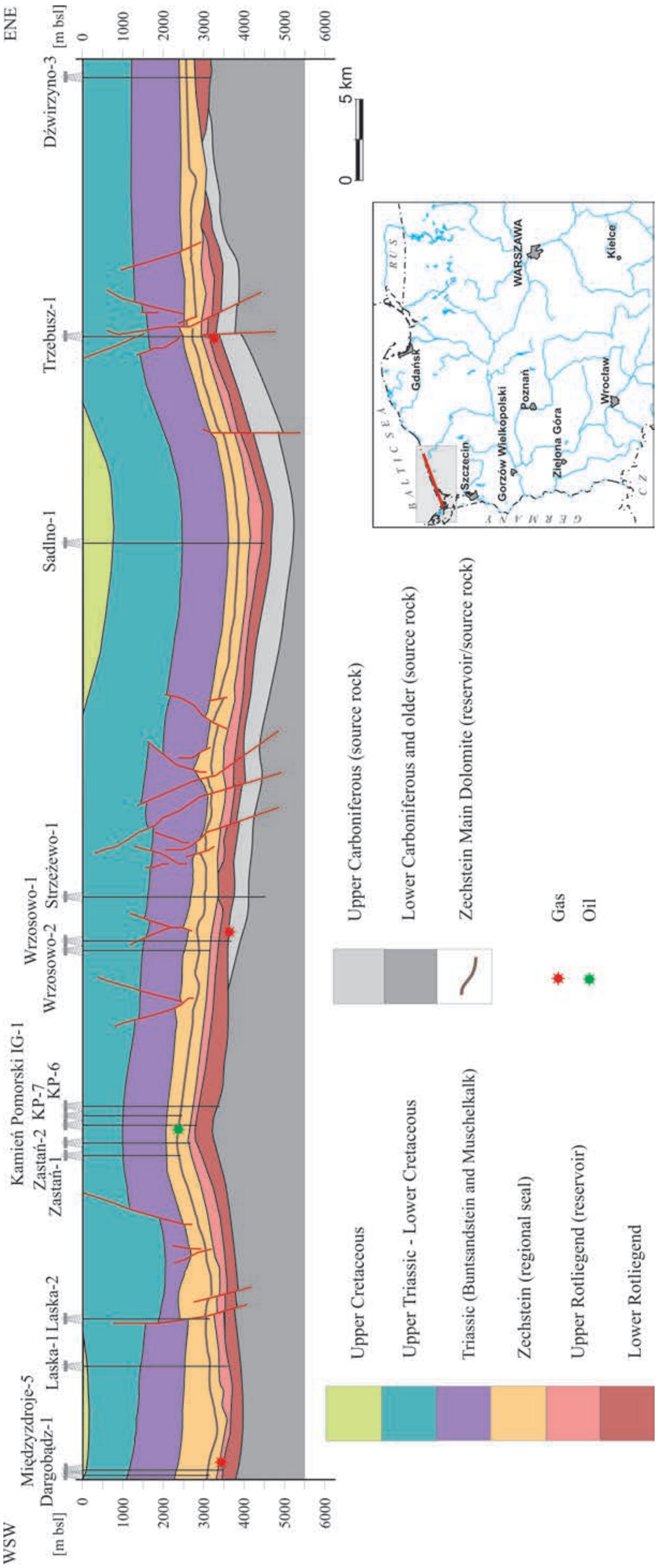

Fig. 3. Schematic cross-section across Pomerania (Cainozoic section removed; modified after Górecki, 2008; Pletsch *et al.*, 2010)

kerogen have been found in Lower Carboniferous sediments (Nowak, 2003, 2007; Pletsch *et al.*, 2010; Poprawa, 2010). However, a reliable characterisation of the original kerogen is severely hampered, owing to the high maturity of most samples collected from the area (Dembicki, 2009). In general, Carboniferous source rocks in the Fore-Sudetic Homocline are overmature over wide areas, because of deep burial, Early Permian magmatism and hydrothermal activity (Maćkowski, 2005; Poprawa *et al.*, 2005). The maturity increases in two directions, towards the axial part of the MPT and the eastern part of the FSH. T_{max} values range from 440 to 520°C (Fig. 5B) and vitrinite reflectance from 1.0 to 5.0% (Karnkowski, 1999; Wagner, 1999; Nowak, 2003, 2007; Poprawa *et al.*, 2005; Grotek, 2006; Maćkowski *et al.*, 2008; Pletsch *et al.*, 2010; Poprawa, 2010). However, in the vicinity of the gas fields the maturity is in the range of 0.7 to 2.0% Rr.

Kujawy–Masovia

In the Kujawy–Masovia area, only a few wells penetrated the Carboniferous strata, because of the deep burial and the amount of data on the quality of the source rocks is limited (Fig. 4C and 5C). Most samples come from the wells located near Warsaw (Korabiewice PIG1, Mszczonów IG1, Nadarzyn IG1). The hydrocarbon potential ($S_1 + S_2$) is very variable from poor to exellent (Fig. 5C). The organic carbon content ranges from 0.3 to 15%, but in some samples reaches ~80%, owing to the occurrence of coal streaks and interbeds (Fig. 5C) (Matyasik, 1998; Botor *et al.*, 2002b; Pletsch *et al.*, 2010). The kerogen is a mixture of gas-prone Type III and Type II (Fig. 4C). In the Westphalian samples, humic organic matter (Type III) dominates (Fig. 4C). Hydrogen indices values for the Carboniferous organic matter demonstrate a wide scatter (11–620), but their mean value is around 160 (Fig. 4C). Rock-Eval T_{max} (420 to 455°C; Fig. 4C) and vitrinite reflectance in the range ~0.7–1.0% (Kozłowska and Poprawa, 2004) show that the Carboniferous organic matter is marginally mature to mature (Pletsch *et al.*, 2010).

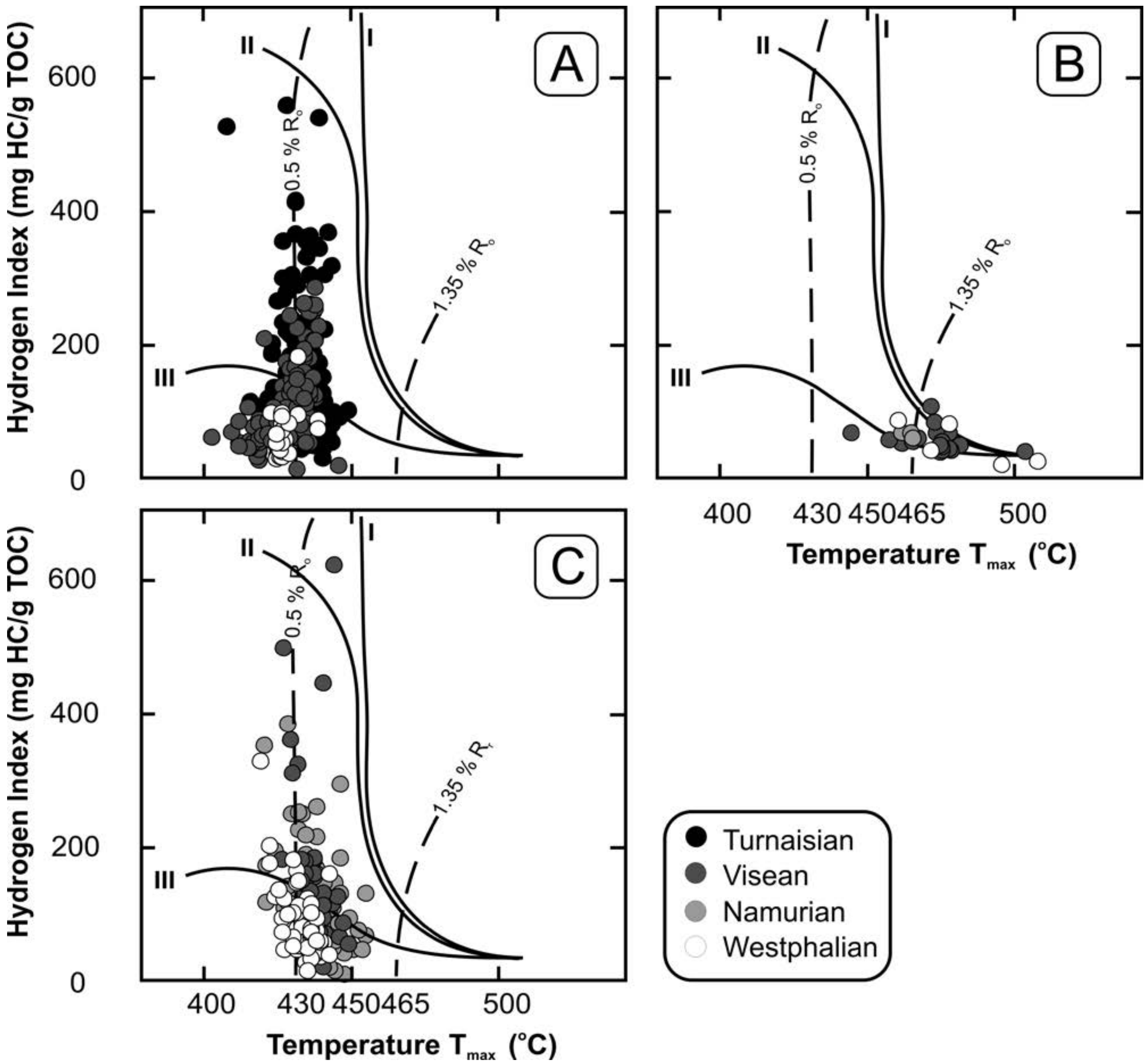

Fig. 4. Rock Eval Hydrogen Index *versus* temperature Tmax for Carboniferous strata in (**A**) Pomerania, (**B**) Fore-Sudetic Homocline and (**C**) Masovia–Lublin area. Genetic curves for kerogen from Espitalié *et al.* (1985). Data modified after Bachleda-Curuś *et al.* (1996), Burzewski *et al.* (1998), Matyasik (1998), Nowak (2003), Kotarba *et al.* (1999, 2004, 2005), Kosakowski *et al.* (2006), Pletsch *et al.* (2010), and Poprawa (2010)

RESERVOIR ROCKS AND GAS DEPOSITS

The Carboniferous–Permian petroleum system in the Polish Basin comprises reservoirs of variable age and lithology (Fig. 6), belonging to two separate petroleum provinces, Pomerania and Wielkopolska (Fore-Sudetic Homocline) in the north and south, respectively (Niedbalec and Radecki, 2007). The regional seal is mainly Zechstein evaporites and partially Rotliegend claystone (Fig. 1). The traps are both structural and stratigraphic, but are usually small and often accompanied by faults (Pletsch *et al.*, 2010).

Natural gas in the Pomeranian reservoirs is rich in nitrogen (40–78%) and contains 22 to 58% of methane, some ethane, propane and helium. The nitrogen content increases westwards and less obviously to the south**.** The composition of natural gas in the FSH is diverse. North of the Wolsztyn-Pogorzela High, it is mostly methane (70–90%) with admixtures of nitrogen (<25%), higher hydrocarbons (<2%), CO_2 (<2%) and traces of helium. The gas quality decreases southwards from the Wolsztyn-Pogorzela High, where fields contain 16–80% of methane, 20–80% of nitrogen, similar CO_2 and higher hydrocarbon contents, but with increased helium concentrations of up to 0.6% (Lokhorst, 1997; Pletsch *et al.*, 2010).

Pomerania

The oldest reservoir unit is represented by faulted Carboniferous strata. Small structural and stratigraphic traps were discovered in the Visean limestones (porosity 2–16%,

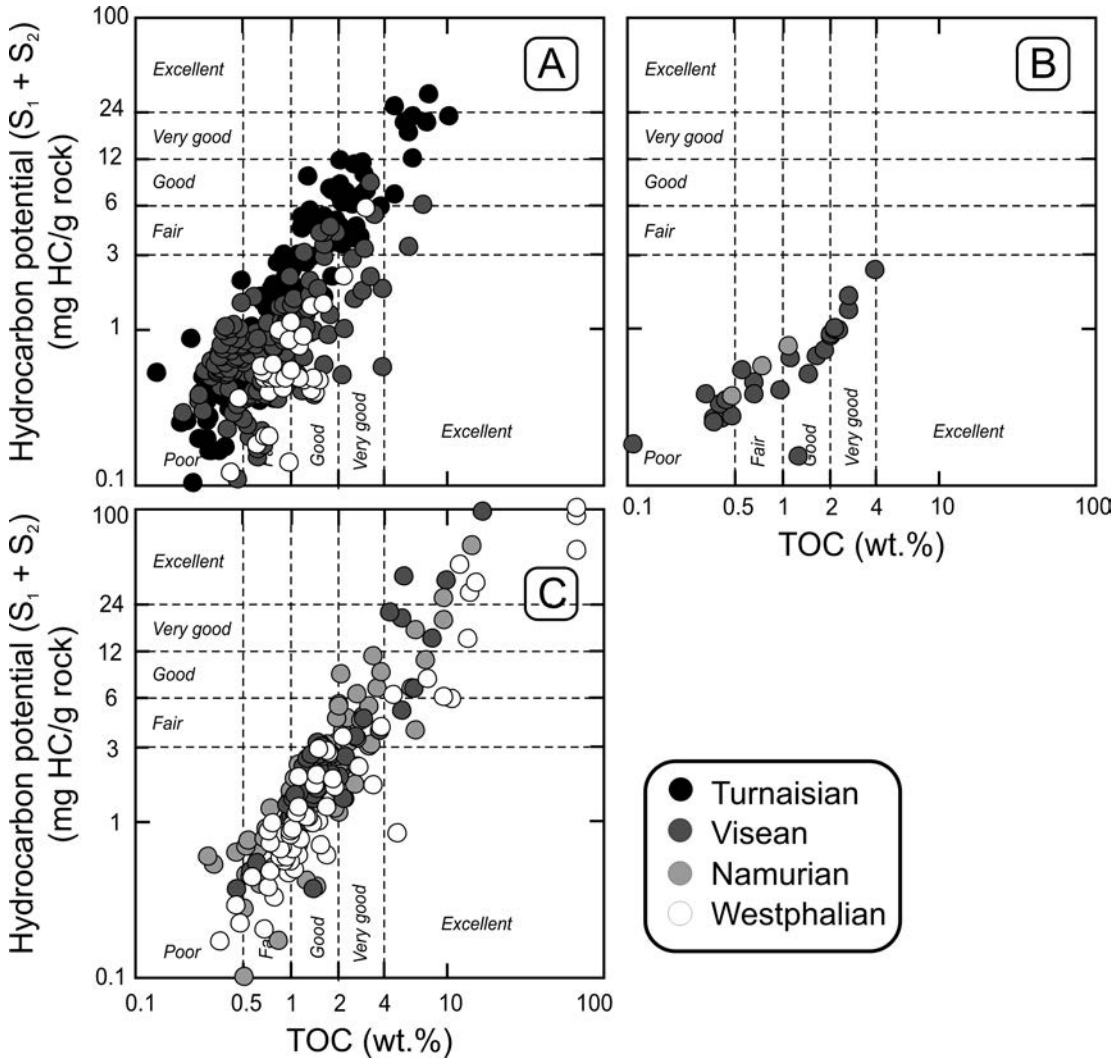

Fig. 5. Petroleum source quality diagram for Carboniferous strata in (**A**) Pomerania, (**B**) Fore-Sudetic Homocline and (**C**) Masovia–Lublin area. Classification after Hunt (1979) and Peters and Cassa (2002). Data modified after Bachleda-Curuś *et al.* (1996), Burzewski *et al.* (1998), Matyasik (1998), Nowak (2003), Kotarba *et al.* (1999, 2004, 2005), Kosakowski *et al.* (2006), Pletsch *et al.* (2010), and Poprawa (2010)

permeability 100–400 mD), Namurian (porosity 16–23%; permeability: up to 270 mD), and Westphalian (porosity 5–15%; permeability up to 190 mD). In the Rotliegend, all but one conventional gas accumulation were discovered at the top of the aeolian sandstones, both in the Pomerania and Wielkopolska petroleum provinces. In Pomerania, the thickness of the aeolian sandstones rarely exceeds 50 m, while fluvial sandstones are often up to 750 m thick. The Rotliegend succession contains a number of potential reservoirs in fluvial and playa sediments (Papiernik *et al.*, 2010), which can contain conventional or tight gas. Both the fluvial and aeolian sandstones have fair porosities (0–13%, generally <5%), but their permeabilities remain mostly less than 1 mD (Pletsch *et al.*, 2010). Therefore, only eleven Carboniferous-sourced conventional gasfields have been proven in Pomerania (Pletsch *et al.*, 2010).

Fore-Sudetic Homocline

Since the Lower Carboniferous rocks of the FSH are rather poor reservoirs, only the Paproć C conventional gas accumulation was discovered there (Karnkowski, 1999). However, considerable tight gas accumulations are expected in the basement of the FSH (Poprawa and Kiersnowski, 2008, 2010). This assumption was recently substantiated by promising results from the Siciny-2 test well (San Leon, 2013). The most important reservoir unit of the FSH, as in Pomerania, is the Upper Rotliegend (Fig. 6). It consists of sandy-shaly sediments, representing three main desert depositional systems: aeolian (dune and interdune environments), fluvial (comprising fluvial channels and alluvial fans) and playa (Kiersnowski, 1997; Jarzyna *et al.*, 2009). Their spatial distribution and variable thickness reflect deposition within an asymmetric continental half-graben (Kiersnowski, 1998; Pokorski, 1998).

On the basis of its reservoir rocks and gas composition, the Fore-Sudetic Homocline is subdivided into 3 regions that correspond to the Wolsztyn-Pogorzela High and the areas to the north and south of it. Thirty-eight gasfields occur in the uppermost Rotliegend sandstones north of the Wolsz-

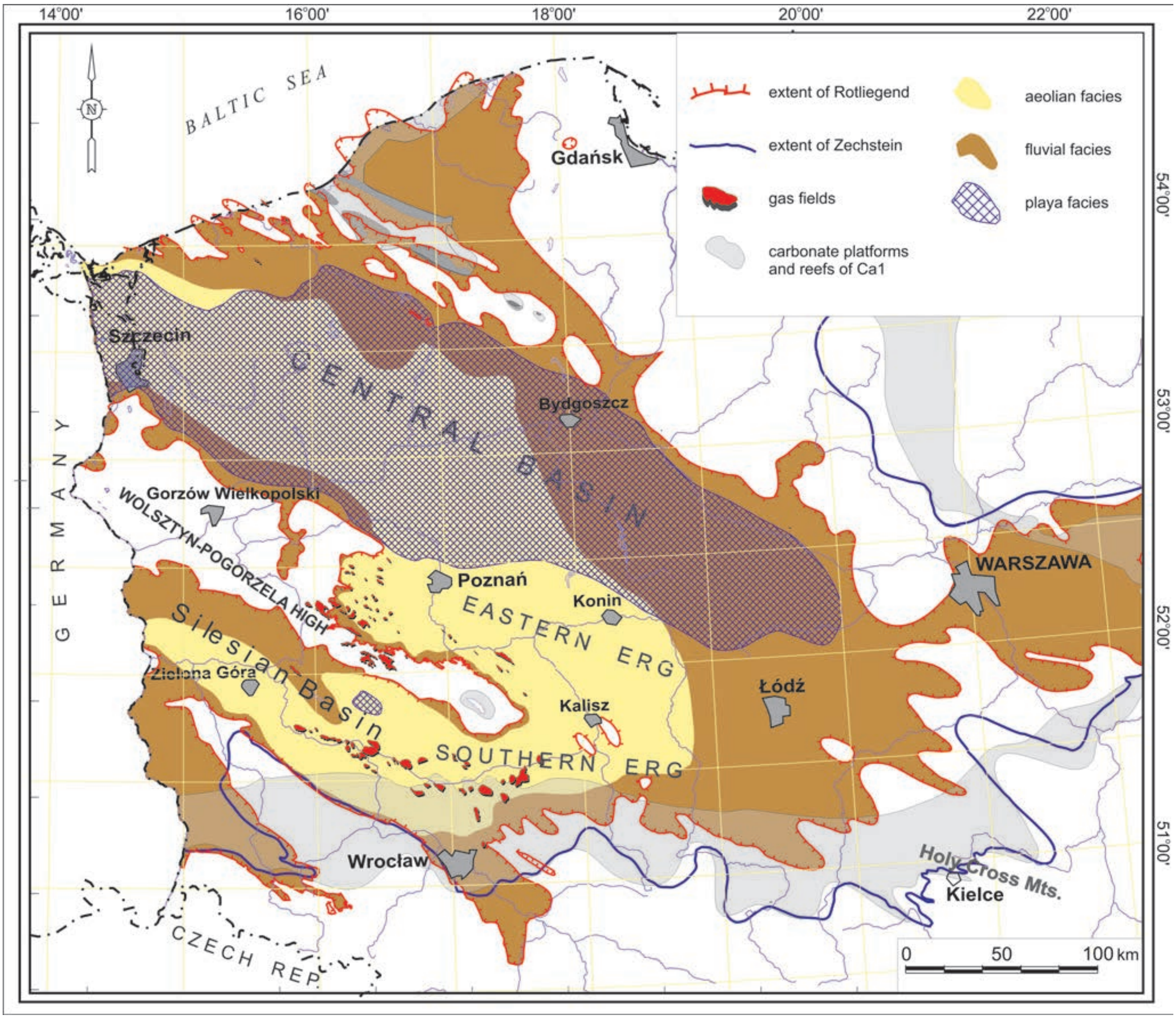

Fig. 6. Location map of Rotliegend reservoirs and Zechstein Limestone (Ca1) in the light of reservoir facies distribution (modified after Papiernik *et al.*, 2008)

tyn-Pogorzela High. In that area, the reservoir sandstones display porosities ranging from 0 to >20%, (on average 12%), irregularly but consistently decreasing with depth (Papiernik *et al.*, 2008; Papiernik *et al.*, 2010). The permeability of aeolian sandstones is over 100 mD close to the Wolsztyn-Pogorzela High, but decreases to slightly more than 1 mD farther north (Papiernik *et al.*, 2008).

The second region is situated to the S and SW of the Wolsztyn-Pogorzela High, where over 30 gasfields were found in the uppermost Rotliegend sandstones, in the Zechstein Limestone, or commonly in both (Fig. 6; Papiernik *et al.*, 2008). The gas-bearing aeolian sandstones display excellent porosity, frequently exceeding 30% (on average 15%) and fairly good permeability, ranging from a few to hundreds of millidarcies (median on average in productive intervals ~10 mD; Papiernik *et al.*, 2010, 2012). In the southernmost part of the FSH, shallow marine carbonate platform and oolitic barriers are reflected in grainstones, boundstones, packstones, as well as mudstones and wackestones in the zones of lower energy (Papiernik *et al.*, 2008; Słowakiewicz and Mikołajewski, 2011). The carbonates display porosities of 0–34% (average 6.3%) and permeabilities of 0–~500 mD (average 12.9 mD), while in the oolitic barriers the porosities are 0–34% (average 5.5%) and permeabilities 0–190 mD (average 6.8 mD). The most extensively developed open marine sediments, dominated by mudstones and wackestones, display very poor reservoir properties.

The third region is the Wolsztyn-Pogorzela High, representing a pre-Permian ridge, where the Rotliegend reservoir sandstones are absent and the Zechstein strata directly overlie Carboniferous sediments and pre-Carboniferous metamorphic rocks. There are six gasfields in the Zechstein Limestone of the Werra cyclothem on the Wolsztyn-Pogorzela High. They were found in massive reef structures, in the vicinity of Kościan. The porosities of these rocks are up to 45% (average ~15%) and the maximum permeability more than 1000 mD.

METHODS AND DATA

A total of 120 1-D models was constructed, using the PetroMod software (Schlumberger, 2013a), including 52 for wells and 68 for pseudo-wells. Gas migration analysis was carried out, using the PetroMod 3D flowpath modelling software (Schlumberger, 2013a). The most important results were shown on regional maps of heat flow, eroded overburden, kerogen transformation ratio and gas migration. The basic characteristics of the burial and thermal history, as well as the gas generation history of selected wells, are also provided. All maps were created by means of the PETREL software (Schlumberger, 2013b).

Basin modelling technique

Numerical modelling techniques permit the simulation of the complex set of interacting physical and chemical processes, taking place during the evolution of a sedimentary basin. A starting point for the modelling exercise is a conceptual model (Waples *et al.*, 1992; Poelchau *et al.*, 1997; Yalcin *et al.*, 1997), which describes the geological evolution of the study area, including geological, geophysical and geochemical data. A discretized numerical model, which represents the conceptual model, is then used for simulation purposes (Yalcin *et al.*, 1997).

The geological history of a specific location, e.g. a single borehole or a so-called pseudo-well (Poelchau *et al.*, 1997), is calculated by the finite difference method. A modelling framework of the conceptual model is built in the time dimension. Geological events, scaled in time, create the framework of a model and govern the data input. The data set for each event consists of duration, depositional or erosional thickness, lithology, bathymetry, sediment/water interface or surface temperature, and heat flow. Petrophysical parameters, such as porosity, density, thermal conductivity, etc., are then defined on the basis of lithology. After each simulation run, the calculated results have to be compared with the measured values, in order to calibrate the model and check its geological reliability. Major calibration parameters are recent borehole temperatures, mean random values of vitrinite reflectance and Rock-Eval maturity indices. Calibration is usually performed by varying the palaeoheat flow or the original thickness of the now eroded sedimentary units within geologically reasonable limits (Wygrala, 1989; Waples *et al.*, 1992; Yalcin *et al.*, 1997).

Initially, heat flow estimates for the past stages of basin history are assigned on the basis of tectonic setting (Yalcin *et al.*, 1997). In the following iterations, the palaeo-heat-flow values are adjusted through the modelling procedure, in order to achieve the best fit between the calculated model and the measured calibration parameters. Heat flow values are best constrained for times of maximum temperature, which correspond to the maximum burial in many cases (Waples *et al.*, 1992). During modelling, different burial-uplift scenarios are tested to find a model, which is best calibrated with the maturity values measured in rock samples. Application of the kinetic EASY %Rr approach enables calculation of the mean random vitrinite reflectance up to the value 4.6% Rr (Sweeney and Burnham, 1990).

More details on the principles of the modelling technique are given in, for example in Wygrala (1989), Sweeney and Burnham (1990), Waples *et al.* (1992), Poelchau *et al.* (1997), Yalcin *et al.* (1997), and Hantschel and Kauerauf (2009). In Polish, the details of maturity modelling are given in Botor and Kosakowski (2000) and Botor *et al.* (2002a).

Modelling input data

A set of stratigraphic and lithologic data was compiled for the wells studied within the framework of a conceptual model of the evolution of the study area. The conceptual model was based on published data and interpretations of the geological development of the Carboniferous Basin and its later Permian–Cainozoic evolution. Palaeothickness and palaeofacies maps of the Permian and Mesozoic sequences and regional cross-sections across the study area were particularly useful (Dadlez *et al.*, 1994; Marek and Pajchlowa, 1997; Dadlez, 2006). Stratigraphic and lithologic data were also compiled from papers by Burzewski (1984), Wierzchowska-Kicułowa (1984), Górecka-Nowak (2007), and Nowak (2007).

Periods of sedimentation and erosion/non-deposition, sediment types and thicknesses were identified for each well. Litostratigraphic data for the pseudo-wells were compiled, on the basis of geological regional maps and cross-sections (Maćkowski *et al.*, 2008). The age (in Ma) of standard chronostratigraphic units is given after Gradstein *et al.* (2004). The timing of Permian volcanism was adopted from the geochronological data by Breitkreuz *et al.* (2007). If necessary for modelling purposes, specific lithologies, representing the best approximation to different sedimentary packages, were assigned to certain stratigraphic units (including eroded intervals). Fixed PetroMod lithologies (with petrophysical properties determined for each rock type) were defined on the basis of detailed lithological descriptions of the core and cutting material included in the documentation of wells. Thermal conductivity was computed, using the method developed by Deming and Chapman (1989). Matrix thermal conductivity values were specified for each lithology and then calculated for mixed lithologies, using geometric averages. Heat flow values, used in conjunction with each thermal conductivity set, were selected, on the basis of the quality of the fit between the model predictions and the actual observations of present-day temperature-depth and maturity-depth profiles. The present-day heat flow values were interpolated from the surface heat flow maps (Plewa, 1994; Szewczyk and Gientka, 2009). The values obtained range from 40 to 78 mW/m^2. Mapping was based on the latest available geothermal data from boreholes all over the Polish Basin, carefully verified in order to exclude unreliable (mostly non-equilibrium) measurements. Methodological problems, related to heat flow calculation and mapping, were recently discussed in Szewczyk and Gientka (2009). However, present-day heat flow values do not influence the maturation history of inverted basins (like the Polish Basin), which is mainly governed by palaeo-heat flow in a pre-inversion period (Waples *et al.*, 1992; Poelchau *et al.*, 1997).

Mean random vitrinite reflectance and Rock-Eval Tmax measurements were implemented in the numerical modelling procedure as major parameters, calibrating the burial and thermal history of the basin (e.g. Yalcin *et al.*, 1997; Senglaub *et al.*, 2006). Thermal maturity values included several sources of data (Bachleda-Curuś and Semyrka, 1990; Bachleda-Curuś *et al.*, 1996; Burzewski *et al.*, 1998; Grotek, 1998, 2005, 2006; Grotek *et al.*, 1998; Matyasik *et al.*, 1998; Wagner, 1999; Botor *et al.*, 2002b; Nowak, 2003, 2007; Górniak *et al.*, 2004; Kotarba *et al.*, 2004, 2005; Resak *et al.*, 2008).

Basic assumptions

Numerical modelling was carried out on a regional scale for the entire the Polish Basin. It was necessary to simplify several aspects of the conceptual model and methodical approach, such as the structural-thickness model of the Carboniferous and Permian to Mesozoic strata or the influence of salt bodies. The initial petrophysical parameters of rocks are default values of the PetroMod software. Also the reconstruction of sediment palaeotemperatures as a function of time and depth was based on some assumptions, since it requires specification of heat flow and thermal conductivity values of the rock column. Consequently, several heat transfer assumptions were used in the modelling: (1) heat transfer was by conduction, (2) steady state thermal conditions were used to model heat flow at the base of sedimentary section to the surface, (3) heat was assumed to come from the basement, but not from radiogenic heat sources within the rocks, (4) the basement heat input was not differentiated between radiogenic heat production and heat from mantle convection. Owing to the rifting of the Mid-Polish Trough (Dadlez *et al.*, 1995; Karnkowski, 1999; Stephenson *et al.*, 2003; Mazur *et al.*, 2005, 2006) generally higher heat flow values than present-day were assumed for the Permian–Early Triassic period, which generally dropped down to the present-day values.

RESULTS

Burial and thermal history

The first phase of basin modelling was the reconstruction of the burial and thermal history of the Carboniferous source rocks, a pre-requisite for further petroleum generation and migration modelling. However, since the quality of the calibration data is variable, in many cases the thermal history models are not unique (e.g. Majorowicz *et al.*, 1984; Speczik and Kozłowski, 1987; Górecki *et al.*, 1995; Burzewski *et al.*, 1996; Karnkowski, 1996, 1999; Burzewski, 1997; Poprawa *et al.*, 2005). The measured vitrinite reflectance from shallow boreholes in the northern and central parts of the basin in many cases does not permit unique conclusions on the palaeogradient. However, it is possible to assess the firm and weak points in the alternative concepts of geological and thermal evolution. The lack of boreholes (Fig. 1) with Rr measurements between Szczecin – Gorzów Wielkopolski – Zielona Góra renders all results in this area (particularly west of these cities) somewhat hypothetical.

The burial and thermal history of the Polish Basin is relatively well known and the present paper does not provide new data for further calibration. Accordingly, burial and thermal history models were adopted in the present 1-D petroleum system modelling study from among the best-fit models, published by (1) Burzewski *et al.* (1996, 1998), Resak *et al.* (2008) for Pomerania, (2) Botor (2011a) for Kujawy and the northern FSH, (3) Poprawa *et al.* (2002), Kozłowska and Poprawa (2006) for Masovia, and (4) Botor (2012a, b), Botor *et al.* (2012), Botor (2011b), Poprawa *et al.* (2005) for the FSH. Detailed discussion of the burial and thermal history, model calibration and sensitivity analysis can be found in the above mentioned papers. In the present account, the burial and thermal history is only summarised on a regional scale in the context of further gas generation and migration modelling.

The most important and typical examples of burial and thermal history are given in Figs 7, 8. In Pomerania, Carboniferous source rocks were buried to depths of 3–6 km. However, the depth of burial is variable across the basin. In the Pomeranian Swell region, the burial history from well data is mostly characterized by relatively rapid subsidence from the Permian to the Triassic or the Jurassic, followed by less intensive subsidence in the Cretaceous (Fig. 7A–C). In the Late Cretaceous/Palaeogene, a rapid phase of uplift occurred. The former event marks the onset of the MPT and is associated with considerable crustal extension (Dadlez *et al.*, 1995). Between the Early Triassic and Late Cretaceous, the area subsided almost continuously, with only sporadic insignificant erosional events, due to salt doming in Keuper times. After the Early Triassic, sedimentation rates were much lower, particularly in the latest Triassic and Cretaceous. Finally, the Late Cretaceous/Palaeogene uplift resulted in the removal of 900–1800 m of sediments (Fig. 7A–C). The best modelling results (i.e. the best fit between the measured and calculated Rr values) were obtained, assuming a thickness of eroded Upper Cretaceous of 300–700 m and heat flow of about 30–50 mW/m^2 during this time (Figs 7A–C, 10A). For the Carboniferous to Early Triassic, the heat flow assigned was around 55–93 mW/m^2 (Fig. 10B). Higher values were adopted, because of the assumed rifting of the MPT (Dadlez *et al.*, 1995). However, it is difficult to assess the heat flow evolution for this period, because of major Mesozoic burial, which caused overprinting of the Variscan Rr response. Further details of the burial and thermal history are given in Resak *et al.* (2008) and Burzewski *et al.* (1998).

In the Kujawy area and the central part of the MPT (Fig. 7D, E), the burial history is also characterised by very rapid subsidence in the Late Permian to Early Triassic, followed by slower subsidence from the Late Triassic to the Cretaceous. Finally, Mesozoic subsidence was interrupted by the Late Cretaceous/Palaeogene uplift, which caused erosion of variable amounts, affecting the late Mesozoic section (from nil to c. 3 km in the case of the Budziszewice IG1 well). In the best fit models, the heat flow for the Byczyna well was assumed to be 55 mW/m^2 (in the Mesozoic–Cainozoic), and for the Budziszewice IG1 well, 55 mW/m^2 from the Late Permian to the Jurassic, 40 mW/m^2 in the Cretaceous, and 60 mW/m^2 in the Cainozoic. Owing to the major Mesozoic

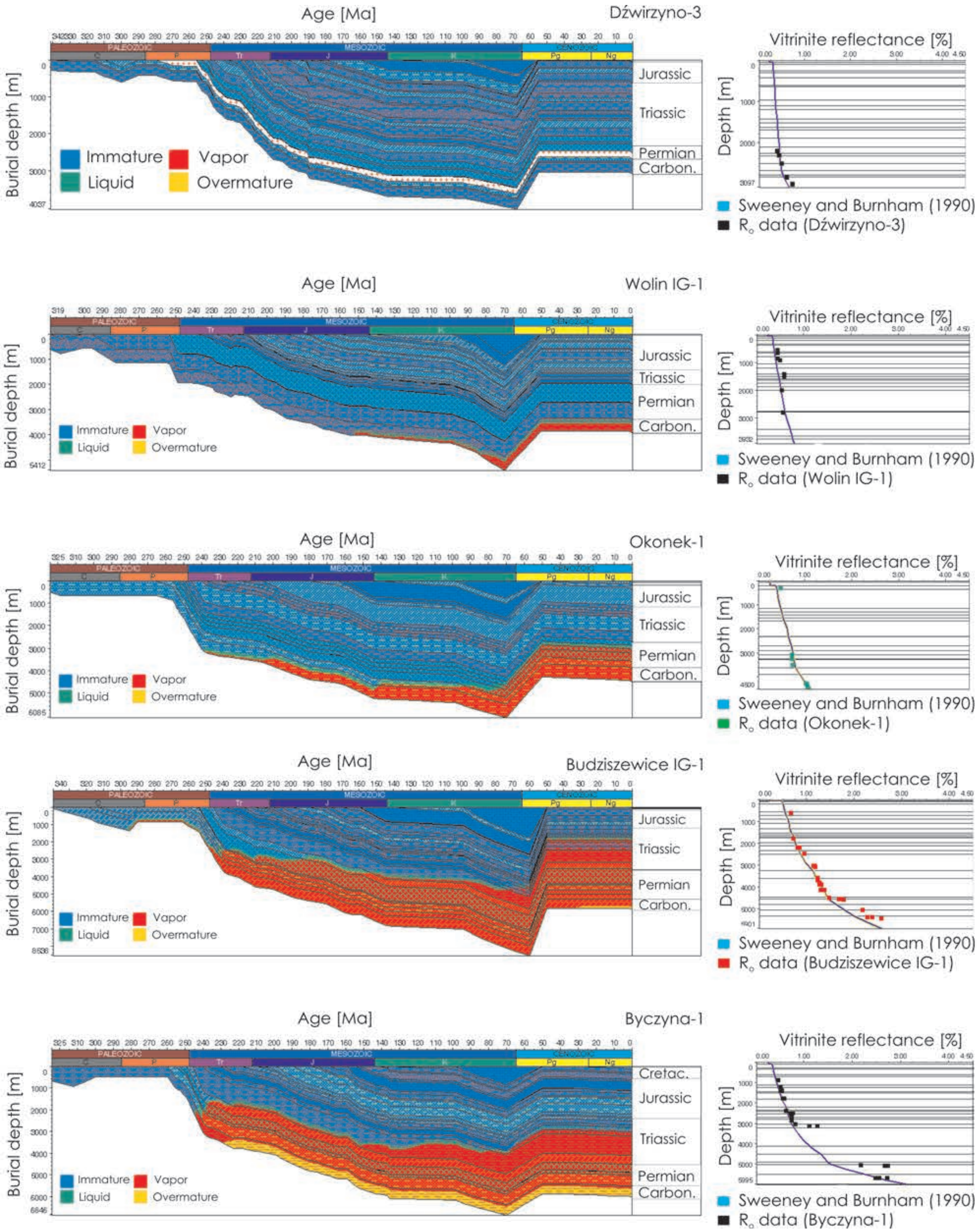

Fig. 7. Examples of selected models: Dźwirzyno-3, Wolin-IG1, Okonek-1, Budziszewice IG1, Byczyna IG-1,

burial, it is difficult to assess heat flow (~60–110 mW/m^2) for Carboniferous to Early Permian time (Botor, 2011a). Further details of burial and thermal history of this area are given in Botor (2011a).

In the Masovia area (Fig. 8A, B), the burial history is characterized by more or less continuous subsidence from the Carboniferous to the end of the Cretaceous. An acceleration of the subsidence rate is observed in the Late Carbonif-

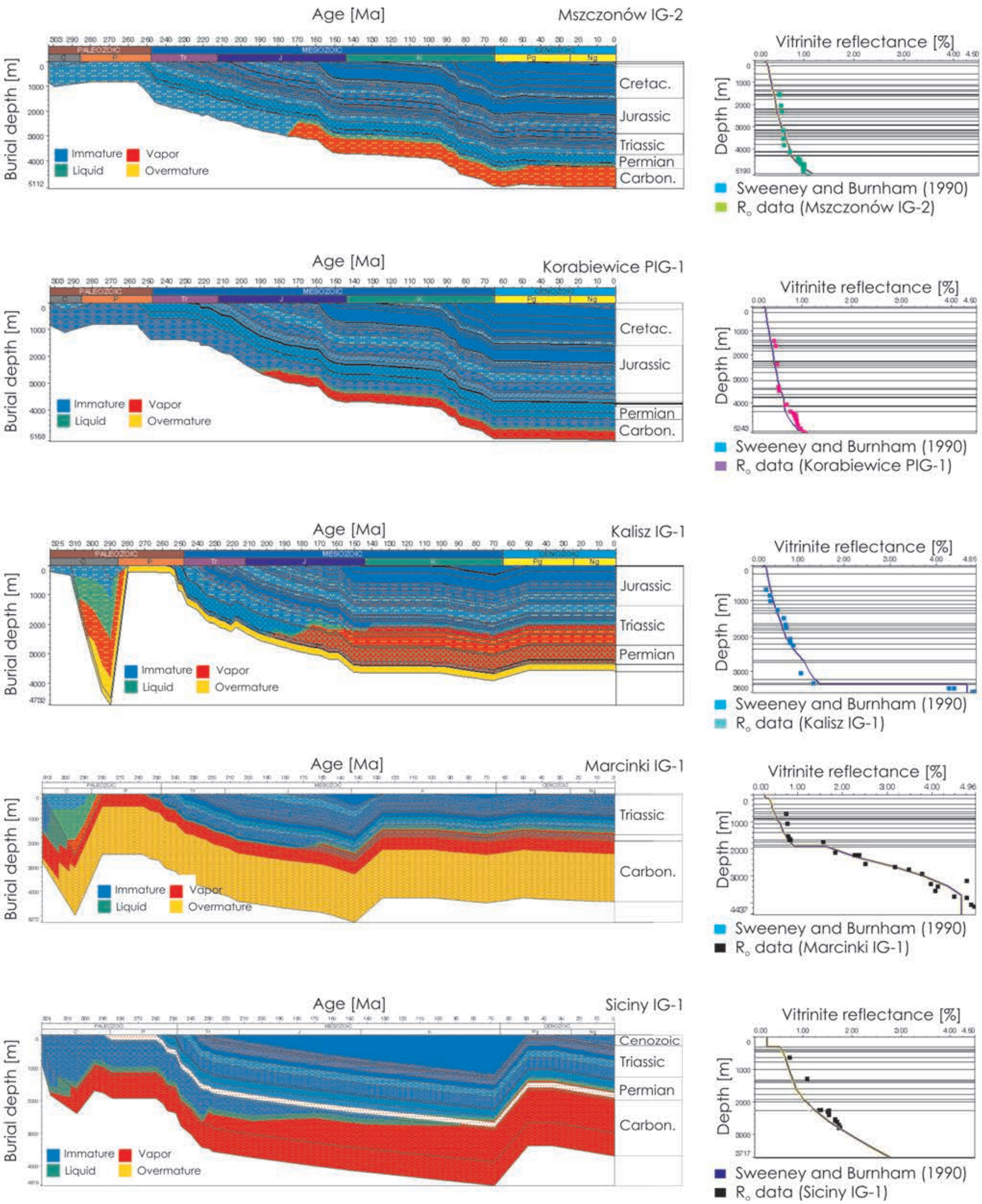

Fig. 8. Examples of selected models: Mszczonów-IG2, Korabiewice-PIG1, Kalisz-IG1, Marcinki-IG1, Siciny-IG1

erous, Late Permian to Early Triassic, and Late Jurassic and Late Cretaceous. A major period of uplift and denudation was in the latest Carboniferous to Early Permian, while the Late Cretaceous/Palaeogene uplift was not significantly marked in this area. Thermal history models for Masovia assume a short-lived hydrothermal (?) Jurassic event, in order to achieve the best fit between the measured and calculated Rr that was suggested by Kozłowska and Poprawa (2004).

In SW Poland, the Carboniferous sedimentary succession generally exceeds 2,500 m in thickness and is predominantly composed of clastic marine sedimentary rocks, tectonised (folded and thrust-faulted) before Permian times (Mazur *et al.*, 2006, 2010). The Carboniferous sediments are overlain discordantly by the Permian and Mesozoic sedimentary cover of the Polish Basin, the south-western part of which is referred to as Fore-Sudetic Homocline. Thermal maturity of the organic matter in the eastern FSH shows a significant difference in vitrinite reflectance values between the top of the Carboniferous succession and the lower part of the Permo-Mesozoic cover (Fig. 8C; Maćkowski, 2005; Poprawa *et al.*, 2005).

The results of the 1-D maturity modelling clearly indicate that Carboniferous sediments in the eastern part of the FSH attained their thermal maturity prior to the Late Permian (Botor *et al.*, 2012). Owing to deep burial, and magmatism (of Early Permian age), as well as possible hydrothermal processes, gas source rocks are mostly overmature. In most models, the best-fit calibration has been achieved by applying high heat-flow values in the Carboniferous–Early Permian period (~90–140 mW/m^2; Fig. 10A), and decreasing heat flow for the younger periods, successively dropping down to the present-day values (Botor, 2011b, 2012a, b; Botor *et al.*, 2012). A possible reason for the high heat flow in Carboniferous–Permian time was probably volcanic, as well as hydrothermal activity in the study area (Karnkowski, 1999; Poprawa *et al.*, 2005; Maćkowski *et al.*, 2008). Burial and thermal history models for the FSH show extremely deep burial and very high heat flow in the Carboniferous (Fig. 8C–E). In the eastern FSH, the great thickness of the eroded section in the range of 2–4 km was reconstructed from maturity modelling (Fig. 7C, D; Maćkowski, 2005; Poprawa *et al.*, 2005; Botor, 2011b, 2012a, b; Botor *et al.*, 2012). The Late Permian–Mesozoic and Cainozoic burial, as well as moderate heat flow (~50–70 mW/m^2), did not change the maturity profile of the Carboniferous sediments in the eastern FSH area (Botor, 2011b, 2012a, b; Botor *et al.*, 2012).

In the central-western part of the FSH (the Siciny IG1 well area), the burial and thermal history models are different from those above mentioned for the eastern FSH area. The thermal maturity profiles do not show any breaks (as in the eastern FSH) in vitrinite reflectance values between the top of the Carboniferous and the lower part of the Permo-Mesozoic (Fig. 8E; Maćkowski *et al.*, 2008). Therefore, the thermal maturation of Carboniferous organic matter (and gas generation) was mainly developed in Mesozoic time (Maćkowski *et al.*, 2008; Botor, 2011b, 2012b; Botor *et al.*, 2012). The most important and obvious evidence is the occurrence in this area of gas fields (Fig. 1) that would not have existed, if all of the maturation had been completed before the Permian, as suggested by Poprawa *et al.* (2005). The burial history of the strata, penetrated by the Siciny IG1 well, is characterised by a prolonged subsidence during the Mesozoic (Fig. 8E). There were two major periods of uplift and denudation: (1) in the Late Carboniferous to the Early Permian and (2) in the Late Cretaceous/Palaeogene. The first one is difficult to quantify, owing to high burial in the Mesozoic, while the second may have involved denudation of 1200 m of sediments (Fig. 8E). However, because there is no break in the Rr profile and Rr values are much smaller than in the eastern FSH, it seems likely that the burial depth in the Carboniferous was not very high (Fig. 8E). The best-fit calibration was achieved by applying increased heat-flow values (~95 mW/m^2) in the Carboniferous–Early Permian period. They probably were related to the volcanic and hydrothermal activity in the study area. Late Permian–Mesozoic and Cainozoic times were characterised by moderate heat flow in the range 50–70 mW/m^2 (Fig. 10B; Botor, 2011b, 2012b, Botor *et al.*, 2012).

EROSION

Up to now, the thickness of eroded overburden (Carboniferous to Mesozoic) was analysed with reference to mechanical compaction (only in Pomerania) (Stefaniuk *et al.*, 1996; Dadlez *et al.*, 1997; Maćkowski *et al.*, 1998), applied to thickness trends of the sedimentary fill (Papiernik and Reicher, 1998), and maturity modelling (Burzewski *et al.*, 1996, 1998; Karnkowski, 1996, 1999; Poprawa *et al.*, 1997; Kozłowska and Poprawa, 2004; Poprawa *et al.*, 2005; Resak *et al.*, 2008; Botor, 2011a, b; Botor *et al.*, 2012). However, the results obtained are not very consistent across the basin.

The values given below for the major erosional events, the post-Variscan (Late Carboniferous–Early Permian) and the post-Laramide (Late Cretaceous–Palaeogene), are based on estimates that allowed the best-fit calibration between values of measured and calculated vitrinite reflectance. The values calculated in 1-D models are shown as a map view in Fig. 9A, B.

Fore-Sudetic Homocline

The post-Variscan erosion varies from ~700–800 m in the SW part of the FSH (Siciny IG1 well area) to over 4,000 m in the eastern and SE part of the FSH (Kalisz–Dymek area; Fig. 9A). In the majority of areas, the post-Variscan erosion ranges from 1,000 to 2,500 m. The lower values obtained from the SW part of FSH are probably related to deep Mesozoic burial, which makes quantitative assessment of the Variscan erosion impossible. Post-Laramide erosion is much less variable, increasing from NE (below 200 m) to SW (~1,500 m) (Fig. 9B).

Pomerania

The calculated thickness of the eroded sedimentary fill after the Late Carboniferous (post-Variscan erosion) is generally low (~400–800 m) in Pomerania (Fig. 9A), whilst the Late Cretaceous/Palaeogene (post-Laramide) erosion is variable (Fig. 9B). The highest values were obtained in the inverted part of the Pomeranian Anticlinorium (~2,000–2,500 m), whereas the values are much lower in the Szczecin Depression and the Pomeranian Depression (0–1,000 m).

Kujawy and Masovia

In the area approximately between Piła–Bydgoszcz–Łódź, the calculated thickness of eroded Palaeozoic rocks is

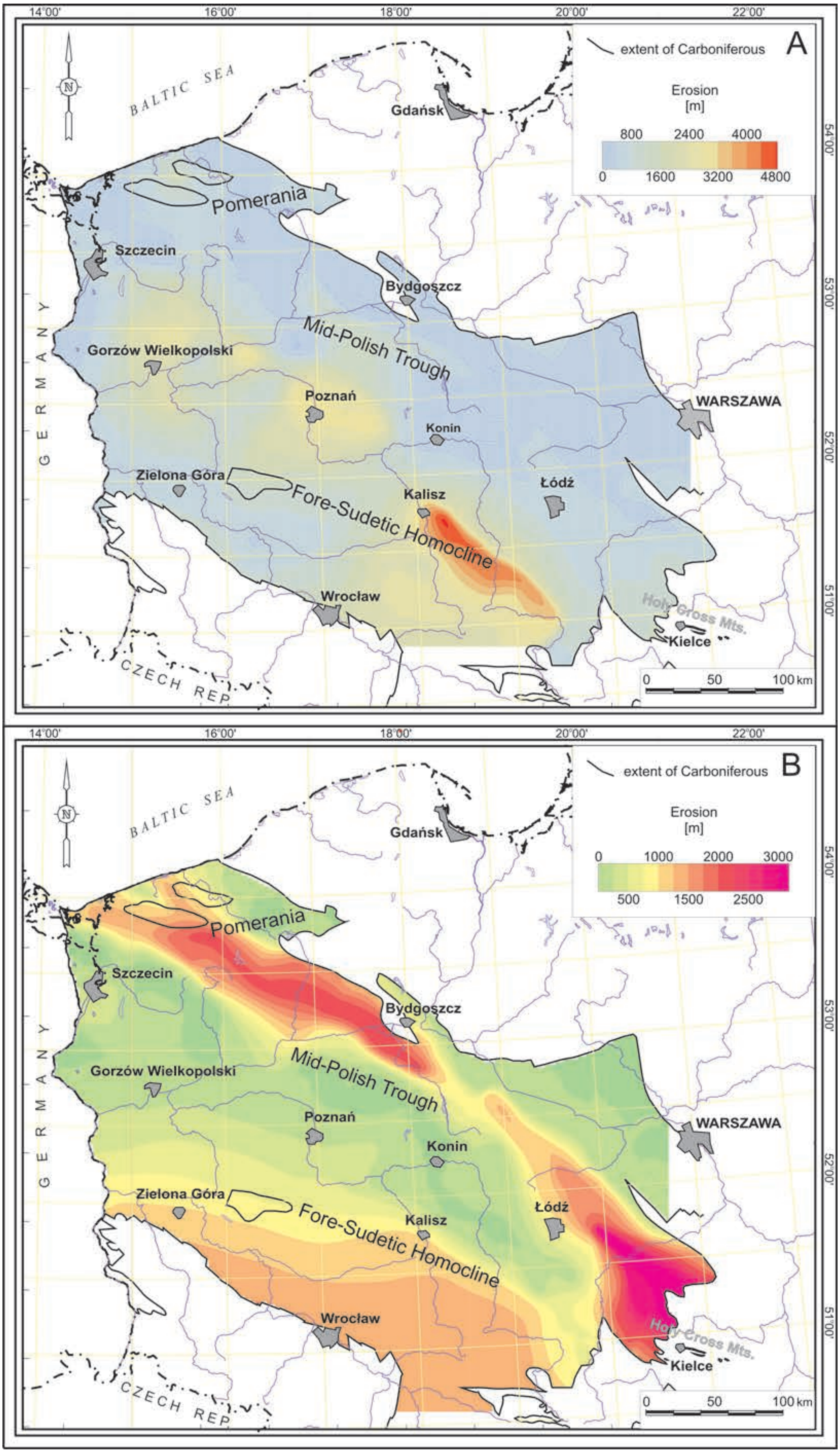

Fig. 9. Calculated erosion: post-Variscan (**A**), Laramide (**B**)

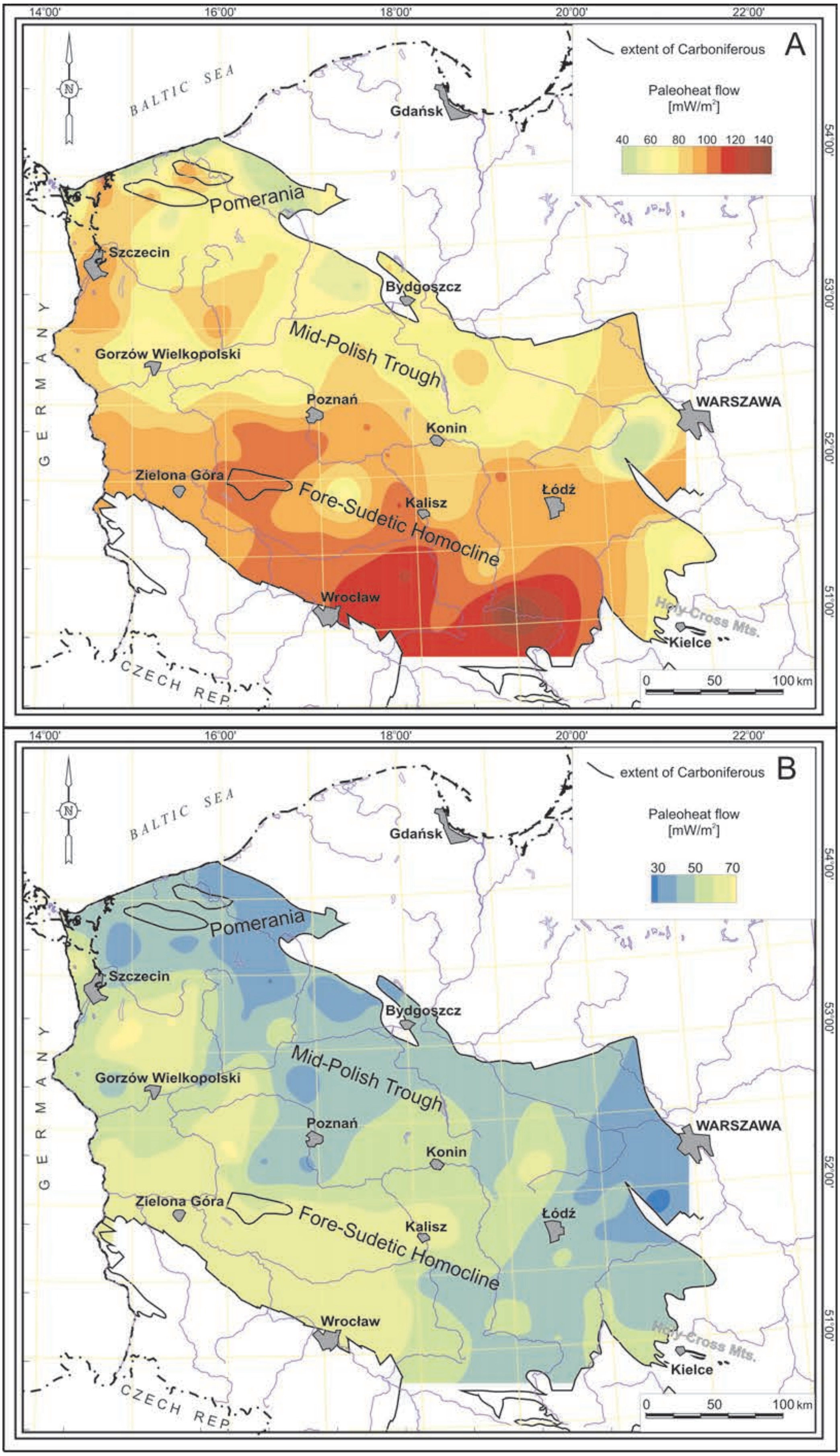

Fig. 10. Palaeo-heat flow: Variscan (**A**), Cretaceous (**B**)

relatively low, usually below 1,000 m (Fig. 9A). The post-Laramide erosion is also low (0–200 m) in the area, extending from SE of the Piła IG1 well to the Łódź area (Fig. 9B), whilst to the SE of Łódź (towards the Holy Cross Mts), it is extremely high (the Budziszewice IG1 well, up to 3 km) (Fig. 9B). In the Masovia area (Warsaw Depression), the calculated thickness of eroded Palaeozoic rocks is low, generally in the range of 400–800 m (Fig. 9A). The post-Laramide erosion in Masovia (Korabiewice PIG1 – Mszczonów IG1) is also low, at 0–200 m (Fig. 9B).

HEAT FLOW

The values of palaeo-heat-flow, provided in this study for the period from the Carboniferous to the Present, are arbitrary and based on estimates that give the best-fit calibration between measured and modelled vitrinite reflectances. The values of palaeo-heat-flow, calculated in the 1-D models, were used to create the maps in Fig. 10A, B.

Fore-Sudetic Homocline

In the SE and N parts of the FSH, heat-flow values were the highest (above 110 mW/m^2) and the lowest (~60–70 mW/m^2), respectively (Fig. 10A). In most of the FSH, the calculated Carboniferous heat-flow values were above 85 mW/m^2 (Fig. 10A). The Cretaceous heat flow generally was above 60 mW/m^2 and only in the Poznań area values are in the range of 40–50 mW/m^2 (Fig. 10B).

Pomerania

The Carboniferous heat-flow values increase in Pomerania from NE (40 mW/m^2) to SW (95 mW/m^2) (Fig. 10A). The Cretaceous heat flow increases from NE (30 mW/m^2) to SW (70 mW/m^2) in a more regular manner (Fig. 10B), and in the majority of Pomerania is in the range of 40–50 mW/m^2 (Fig. 10B).

Kujawy and Masovia

In Kujawy, the calculated Carboniferous and Cretaceous heat flows were in the range of 60–80 W/m^2 (increasing slightly to the SW) and 40–50 mW/m^2, respectively (Fig. 10A, B). In Masovia (Warsaw Depression), the calculated Carboniferous heat flow was in the range 40–50 W/m^2, (Fig. 10A), while the Cretaceous heat flow varied between 30–45 mW/m^2 (Fig. 10B).

THERMAL MATURITY

The vitrinite reflectance map (Fig. 11) was calculated for the top of the Carboniferous. It is in generally good agreement with previous measurements of Rr (Bachleda-Curuś and Semyrka, 1990; Bachleda-Curuś *et al.*, 1996; Burzewski *et al.*, 1998; Grotek, 1998, 2005, 2006; Grotek *et al.*, 1998; Matyasik *et al.*, 1998; Wagner, 1999; Botor *et al.*, 2002b; Nowak, 2003, 2007; Górniak *et al.*, 2004; Kotarba *et al.*, 2004, 2005; Resak *et al.*, 2008; Botor *et al.*, 2012). In the vicinity of the gas fields, the maturity is in the range of 0.7 to 2.0% Rr (Fig. 11).

Fore-Sudetic Homocline and Pomerania

In western and central FSH, Rr values at the top of the Carboniferous are in the range of 0.7–2.0% (Fig. 11). However, in the eastern FSH, maturity locally reaches the highest values of ~5.0% Rr (Fig. 11; see also Karnkowski, 1999; Wagner, 1999; Nowak, 2003). In Pomerania, maturity increases from the north and NE (below 1.0% Rr) towards the south and SW (up to 2–3% Rr) (Fig. 11). The highest values are in the Czaplinek–Piła area.

Kujawy and Masovia

The Rr values in Kujawy are usually very high (2–3%) reaching a maximum of 4–4.5% Rr in the area Krośniewice–Kutno–Brześć Kujawski (Fig. 11). In contrast, vitrinite re- flectance values are generally below 1.5% in Masovia (Fig. 11).

GAS GENERATION

The final results of gas-generation modelling were shown as a kerogen transformation ratio (% TR) (Figs 12–14). TR values at the top of the Carboniferous were calculated for the most important phases of basin evolution: (1) the latest Carboniferous (Variscan period; Fig. 12), (2) latest Late Triassic (Cimerian phase; Fig. 13), and (3) latest Cretaceous (Laramide inversion; Fig. 14).

Thermogenic gases are generated from kerogen mainly in the range of 1–3.0% Rr (Cornford, 1998), because thermal maturity above 1% Rr is regarded as minimum for the generation of significant amount of gases (e.g. Cornford, 1998). However, this process starts even at lower Rr values (Hunt 1996). Gas generation reveals considerable variation in the different zones of the Carboniferous basin, where the kerogen transformation ratio (TR) reached values in the range of 20 to 100% (Figs 12–14). The highest TR occurs in the zones of maximum maturity of organic matter. Gas generation took place in several pulses: Late Carboniferous, Mesozoic (Middle–Late Triassic to Late Jurassic), and Cretaceous.

Fore-Sudetic Homocline

In the eastern FSH, significant gas generation commenced as early as in the Late Carboniferous and the kerogen transformation ratio reached approximately 100% by the end of this period (Fig. 12; Kalisz IG1 well – Dymek IG1 well). A peak thermal maturity of up to 5.0% Rr was locally obtained, leading to dry gas generation and overcooking. Consequently, gas generation in the eastern FSH was completed in Variscan times before the Zechstein cover and most of the hydrocarbons were lost. However, in the central, western and northern parts of the FSH, where petroleum potential still existed after the Carboniferous, generation re-

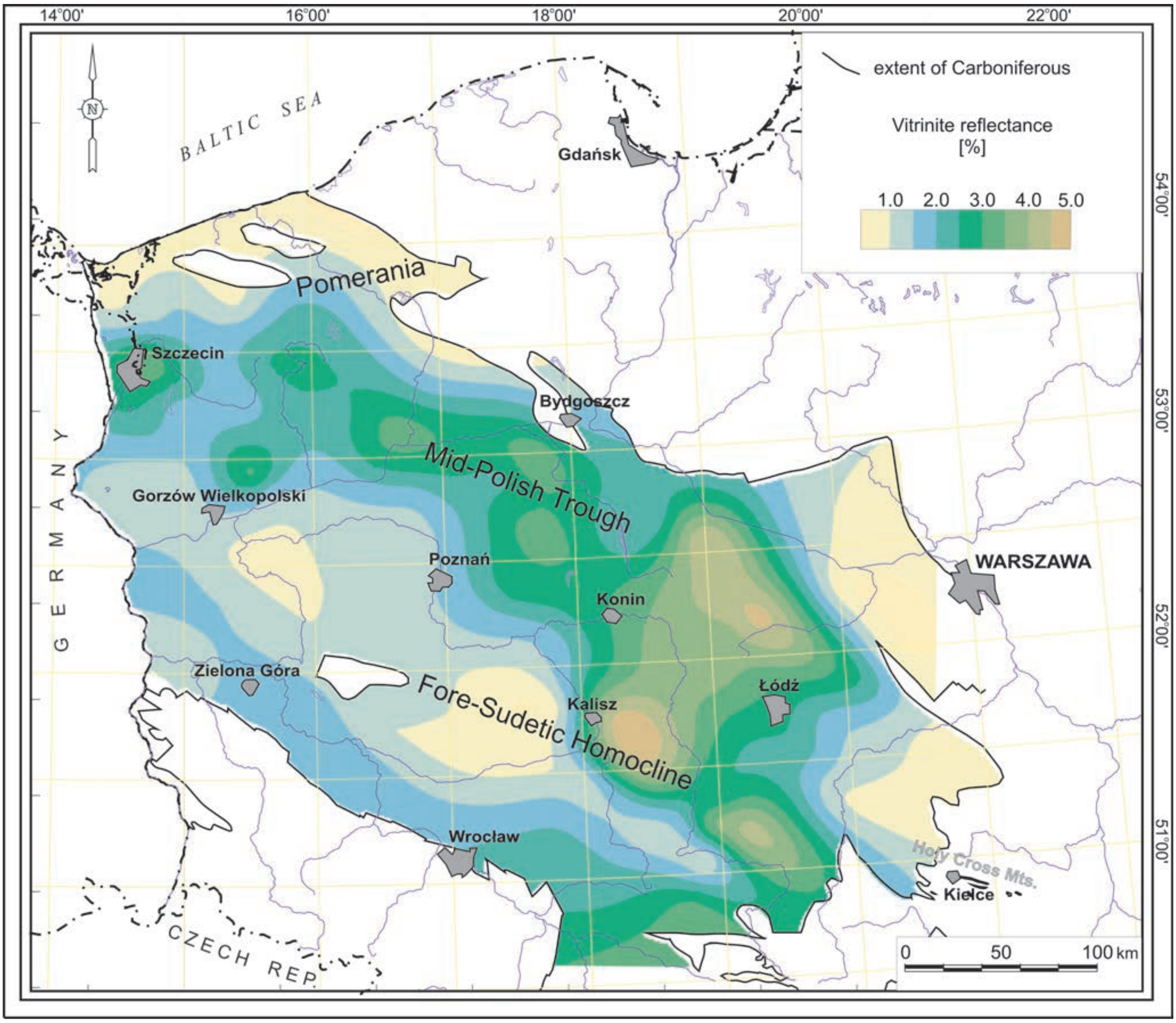

Fig. 11. Calculated present-day vitrinite reflectance at top of Carboniferous

sumed in Middle Triassic–Late Jurassic and Late Cretaceous times (Figs 13, 14), with the highest intensity in the Late Triassic to the Early Jurassic. In the NW of the FSH (Siciny IG-1, Paproć, Objezierze IG1, Strzelce Krajeńskie IG1 wells), the kerogen TR reached over 80% (Figs 12–14).

Pomerania

The lowest TR is in the NE part (eastern Pomerania and Masovia) of the Carboniferous basin, with values of below 40% (Figs 12–14). In Pomerania, a first-generation phase took place, probably in the Late Carboniferous (Fig. 12). However, the maturity was too low at that time to have a significant effect on gas generation. In most places, the petroleum potential was not exhausted during this early generation phase, which was followed by two more generative phases in the Triassic–Jurassic and the Late Cretaceous, when maturity reached more than 1.0% Ro (Figs 12–14).

Kujawy and Masovia

In the zones, where the hydrocarbon potential was not exhausted in the Carboniferous (most areas of the Carboniferous basin), two major episodes of hydrocarbon generation occurred in the Triassic and/or Jurassic (Fig. 13) and the Late Cretaceous (Fig. 14). The range of kerogen transformation was very variable in these Mesozoic phases (from 20 to more than 90%). During the Mezozoic, gas generation in the axial part of MPT began in the Early Triassic (Krośniewice Depression, Kutno–Łódź area) and gradually increased until the latest Jurassic. In the remaining parts of the MPT, gas generation began in the Late Triassic, reaching a maximum in the Early Jurassic, as in the western FSH. By the end of the Triassic, the TR reached 70% in the central parts of the basin (Fig. 13). In the Konin–Kalisz area, gas generation continued until the Late Cretaceous. By the end of Cretaceous, gas generation was for the most part completed, especially in the most deeply buried parts of the Carboniferous basin. In almost the entire area of Masovia, the TR values were low (below 40%) at the end of the Carboniferous (Fig. 12). By the end of the Cretaceous, the western part of Masovia reached 70% TR, while the TR still remained very low in the eastern part (Figs 12–14).

GAS MIGRATION MODELLING

Basic assumptions

Migration modelling of gases was performed, using flowpath analysis (Hantschel and Kauerauf, 2009). A migration flowpath connects the source-rock area, where the Carboniferous rocks are in the direct contact with clastic rocks of the Upper Rotliegend, and the top of the Upper Rotliegend reservoir rocks, sealed by Zechstein evaporites and playa sediments in the central part of the basin (Fig. 15). Cementation processes of the Upper Rotliegend reservoir rocks were disregarded in the simulation of gas migration, since it was assumed that the porosity and permeability evolution of the reservoir rocks through time was caused only by mechanical compaction.

Results of the gas migration modelling

The migration modelling results showed that gas migration in the deeper part of the Rotliegend basin is well reconstructed outside the limits of the volcanic cover (Fig. 15). In the case of gas accumulations close of the Wolsztyn-Pogorzela High (area D in Fig. 16), the reconstructed filling of traps is only due to long-distance migration. In migration modelling on a regional scale, gas migration along faults transecting the Autunian and Carboniferous strata was not taken into account. However, this mechanism may have been predominant in the Zielona Góra Depression, as well as in the area directly north of the Wolsztyn-Pogorzela High (Figs 15, 16).

The modelling results have shown that gas migration continued during the subsidence of the Polish Basin in the Mesozoic, mainly in the Late Triassic – Early Jurassic and Late Jurassic (Fig. 15), and was terminated by the Late Cretaceous inversion. In the central part of the MPT, migration commenced at the end of the Early Triassic in the Krośniewice Depression. Gas migrating to the NE during that time could have accumulated in the Szubin–Byczyna–Kutno anticlinal structure (area A in Fig. 16) that was formed during the Triassic. At the same time, a concentrated stream of gas migrated from a local generation centre north of Września towards the Fore-Sudetic Homocline (area C in Fig. 16). During the Late Triassic, the first gas accumulations were formed in the Poznań Trough as a result of long-distance gas migration from the generation centre along the Piła–Szubin–Objezierze line and short-distance gas migration from the sub-Permian basement of the Poznań Trough (Fig. 15). In the Mogilno–Łódź Depression, gas migration continued in the Jurassic, gradually declining through the Cretaceous. Consequently, the filling of traps in the Rotliegend was possible during the Jurassic–Cretaceous, even if those traps were formed relatively late (Fig. 15).

Modelling has shown that the greatest mass of gas underwent scattering in the marginal parts of the Polish Basin along the Teisseyre–Tornquist Zone from the end of the late Triassic to the end of the Early Jurassic and along the northern margin of Holy Cross Mountains from the Middle Jurassic to the end of the Late Jurassic. To a lesser extent, gas underwent scattering at the edge of the Wolsztyn-Pogorzela High. Because of the cessation of gas migration in the central part of the MPT already at the end of the Middle Jurassic and the subsequent Alpine inversion of the basin, large amounts of nitrogen in the gas composition can be expected in the deeply burried potential traps, located along the line Szubin–Byczyna–Kutno (Fig. 15, and area A in Fig. 16). The Piła–Konin zone could have supplied the Mężyk–Objezierze–Września potential accumulation zone (Fig. 15 and area C in Fig. 16). In the prospective zones discussed, the Rotliegend shows reservoir potential in the depth interval deeper than 3500–5500 m (Fig. 16).

DISCUSSION

Burial and thermal history

The subsidence analysis results reviewed in this paper document an initial Early Permian syn-rift phase in the evolution of the Polish Basin that led to the development of the MPT and was followed by significant thermal sagging in the Late Permian – Early Triassic (255–241 Ma). Repeated periods of accelerated subsidence also were noted for the Late Jurassic (157–152 Ma) and Cenomanian (~ 97–100 Ma) (Dadlez *et al.*, 1994; Stephenson *et al.*, 2003; Resak *et al.*, 2008). The development of the Polish Basin was terminated by the Late Cretaceous and/or Early Paleogene inversion that affected the entire Central European basin system (e.g., Mazur *et al.*, 2005; Gast *et al.*, 2010). In the axial part of the Mid-Polish Swell (inverted MPT), sediments in places were removed down to the Lower Jurassic or even the Upper Triassic, whereas elongated troughs at the flanks of the swell were filled with thick Upper Cretaceous syn-inversion deposits (e.g., Mazur *et al.*, 2005).

Karnkowski (1999) proposed a thermal model assuming constant heat flow in the MPT and a Permian–Jurassic thermal anomaly in the FSH area characterised by relatively high heat flow. The heat-flow evolution model proposed in this study is generally similar to that proposed by Karnkowski (1999) with some modifications applied. Firstly, a heat flow slightly lower than that of the present day was assumed for the Cretaceous in the axial part of the MPT, on the basis of the findings of Poprawa and Andriessien (2006). Secondly, an additional increase of heat flow was necessary in the eastern part of the MPT in the Triassic–Jurassic, as documented by K-Ar dating and diagenetic studies (Kozłowska and Poprawa, 2004). The calculated heat flow values in the Palaeozoic ranges from 80 to 140 mW/m^2, decreasing in the Mesozoic and Cainozoic (Fig. 10A, B). For the Permian–Jurassic the heat-flow model postulated here coincides with that of Karnkowski (1999) in the MPT only. In the SE part of Polish Basin, the higher heat-flow values were predicted for the Permian–Jurassic.

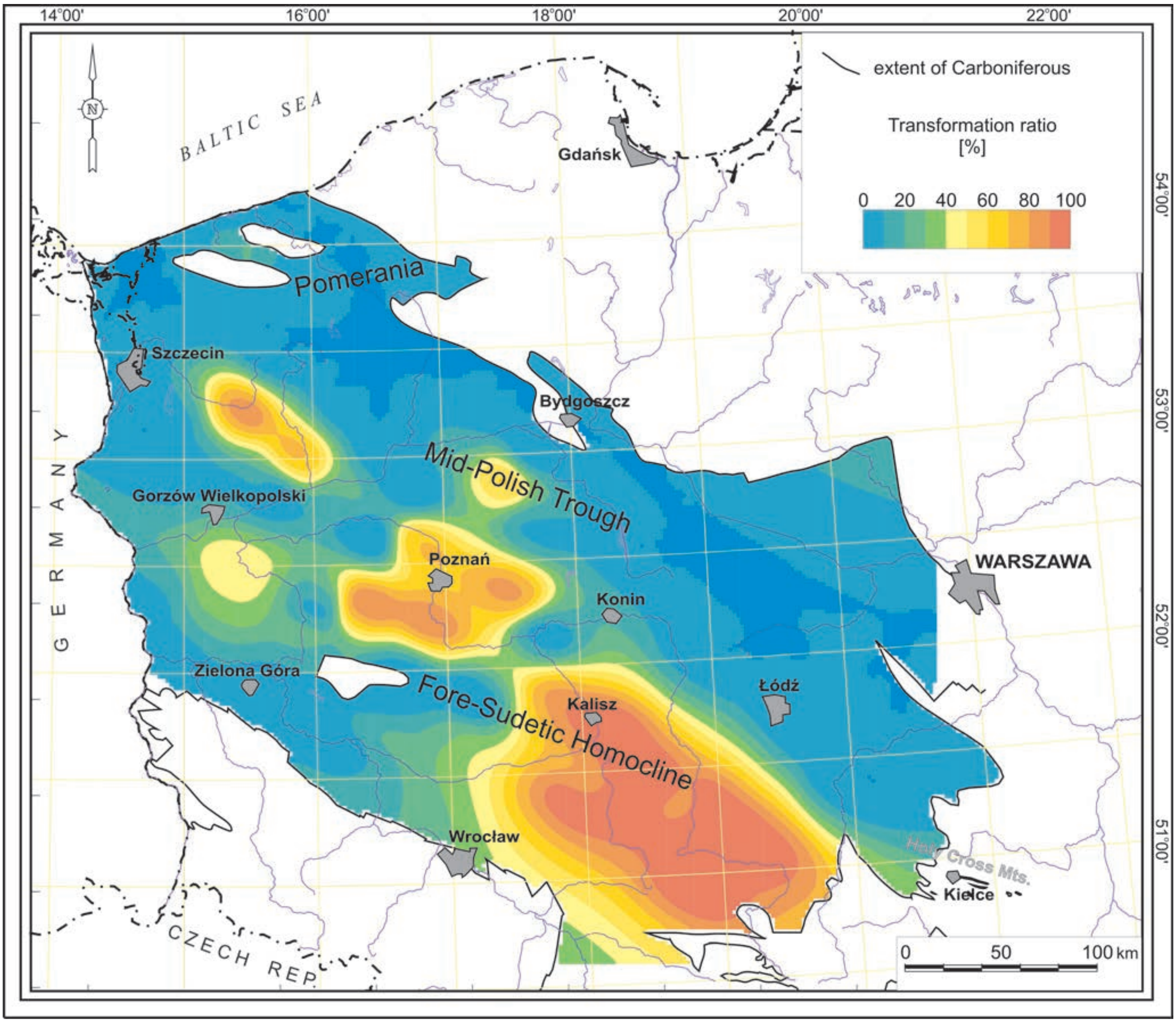

Fig. 12. Degree of kerogen transformation (TR%) in Carboniferous source rocks (referred to top of Carboniferous) calculated for end of Carboniferous

Fore-Sudetic Homocline

Extremely high values of heat flow and burial in the SE part of the FSH can be attributed to the advective heat transport that was suggested by maturity modelling (Maćkowski, 2005; Poprawa *et al.*, 2005) and by 2-D fluid-flow modelling (Maćkowski *et al.*, 2008). In the FSH, calibration is usually very good for the Carboniferous section of profiles, but much worse for the Permian and Mesozoic overburden (Botor, 2011b, 2012b; Botor *et al.*, 2012). Generally, in the eastern FSH (Marcinki IG-1 well – Więcki IG-1 well), thermal maturity of the Carboniferous organic matter was reached before the Permian, as clearly evidenced by breaks in the Rr profiles in wells (Fig. 8; Maćkowski, 2005; Poprawa *et al.*, 2005; Maćkowski *et al.*, 2008; Botor, 2011b, 2012b; Botor *et al.*, 2012) and the distribution of Rr at the top of the Carboniferous (Fig. 11). In contrast, thermal maturity was achieved in the early Mesozoic in the central and western FSH (e.g., Siciny IG-1 well area, Fig. 8; Maćkowski *et al.*, 2008; Botor, 2011b, 2012b, Botor *et al.*, 2012), but an opposing view was preseted by Poprawa *et al.*, (2005) on the Variscan origin of organic maturity in that area. The burial history of the eastern FSH was also characterised by Early Cretaceous uplift and erosion. In the eastern FSH, the estimates for Carboniferous–Early Permian heat flow and Carboniferous overburden erosion were in the range of 87–140 mW/m^2 (Fig. 10A) and 2000 to 4000 m (Fig. 9A), respectively. In contrast, in the western FSH (e.g., Paproć–Siciny IG-1 wells area; Fig. 8E) relatively minor Variscan erosion was predicted (300–2000 m, Fig. 9A), whereas the heat flow value (80–110 mW/m^2; Fig. 10A) was typical for the Mid-European Variscides (Franke *et al.*, 2000). Sensitivity analysis of the models for the FSH area showed that they are consistent and allow for best-fit calibration (Botor, 2011b, 2012b; Botor *et al.*, 2012). Rr profiles (e.g., Siciny IG-1 well) did not reveal any characteristic breaks across the Carboniferous/Permian unconformity, as in the eastern FSH (east of the Marcinki IG1– Kalisz IG-1 line). Therefore, the conclusion can be drawn that thermal maturity of Carboniferous rocks in the central and western FSH was reached in the Mesozoic as evidenced also by the wide occurrence of gas fields in the Rotliegend. These fields were charged from Carboniferous source rocks. If the gas generation was developed and completed in the Late Carboniferous before the Zechstein sealing, all gas would have been lost, owing to erosion from the latest Carboniferous to the Early Permian.

In the eastern FSH, the main possible reason for high heat flow was probably volcanic and associated hydrothermal activity in that area (Karnkowski, 1999; Poprawa *et al.*, 2005; Maćkowski *et al.*, 2008). A very characteristic feature is the great thickness (2–4 km) of the eroded section, reconstructed from maturity modelling. This could have been related to the Late Carboniferous tectonic burial and resultant thermal doming, combined with a post-collisional isostatic reaction (Poprawa *et al.*, 2005). However, the extremely deep burial in the sections penetrated by some wells (above 4 km) reconstructed from maturity modelling, also can be interpreted as an artefact caused by convective heat transport, solely due to hydrothermal activity (Poprawa *et al.*, 2005; Maćkowski *et al.*, 2008). The current data do not solve this conundrum.

The Late Permian–Mesozoic and Cainozoic burial and the moderate heat flow (~50–60 mW/m2) did not change the maturity profile of the Carboniferous sediments (Speczik and Kozłowski, 1987; Maćkowski, 2005; Poprawa *et al.*, 2005). The calculated thickness of the eroded overburden (Fig. 9) can be deceptive, because it is greater than the amount of erosion, derived from trend analysis and palaeothicknesss of the Carboniferous strata (Papernik and Reicher, 1998). Additionally, if advective heat transport is assumed in the eastern FSH, the models can be calibrated, using the thickness of eroded overburden below 1000 m (Maćkowski *et al.*, 2008). However, Francu *et al.* (2002) postulated 4–8 km of Late Carboniferous overburden, with only moderately elevated heat flow (70 mW/m^2) for the Drahany Upland, in the Moravo-Sielsian Culm basin (the area south of the eastern FSH). The calculated thickness of eroded sediments ranges from 4–9 km for the Moravo-Silesian thrust-and-fold belt to 1.6 km farther east, in the marginal Variscan foreland basin. Francu *et al.* (2002) assumed that deep burial was achieved by deposition of a thick flysch succession, possibly followed by the emplacement of the Variscan orogenic wedge from the NW during the Viséan and Late Carboniferous. The accretion mechanism with compression and shortening would first increase the burial and later cause detachment, imbrication, and exhumation of the previously buried strata within the advancing orogenic wedge. The confidence in the estimates by Francu *et al.* (2002) is limited, since the reconstruction of the burial history and palaeogeothermal conditions is much more complex, when thrusting is involved and the sedimentary rocks are imbricated and stacked. Fast underthrusting of a cold crustal surface below an overriding nappe sheet causes lowering of the geothermal gradient in frontal orogenic belts. As a result, tectonic burial often is associated with a lower or equal, but not higher thermal overprint than that of a solely sedimentary cover of the same thickness (Angevine and Turcotte, 1983; Cermak and Bodri, 1996).

The regional metamorphic and diagenetic pattern and the present basin modelling suggest that the diagenetic and very low-grade metamorphic grade could not have been attained merely by high geothermal gradients, without significant burial in the Variscan orogen. Similar relationships between the burial and thermal histories and the geometry of the Variscan belt and its foreland basin are observed in the Ruhr Basin, Rhenish Massif, and external Variscides of southwest England (Warr *et al.*, 1991; Littke *et al.*, 1994). However, Gayer *et al.* (1998) concluded that the thermal pattern suggests the development of coal maturity as a consequence of the Variscan hydrothermal flow in South Wales. In order to solve this problem definitively, it would be necessary to perform studies of compaction trends, as was done for Pomerania (Stefaniuk *et al.*, 1996). Whatever the reason for the elevated temperature in the FSH, organic matter achieved high maturity in the latest Carboniferous, whereas the Permian to Mesozoic organic matter shows only mild maturity.

Pomerania

In Pomerania, the reconstruction of a comprehensive and unique thermal history is difficult, owing to the inadequate number of thermal maturity measurments (e.g., Rr) in some parts of profiles and problems with the optimal calibration, using different heat-flow scenarios in the wells studied (Burzewski *et al.*, 1996, 1998; Kotarba *et al.*, 2004; Resak *et al.*, 2008).

Kujawy–Masovia area

The best-fit model calibration in the central part of the MPT was achieved using heat-flow values, lower than those presently observed (Botor, 2011a). This is supported by independent information on the lower geothermal palaeogradient, based on apatite fission-track dating (Poprawa and Andriessen, 2006). However, a very similar quality of model calibration can be also obtained (Botor, 2011a), assuming constant heat flow in the Mesozoic, as suggested by Karnkowski (1999).

On the flanks of the MPT, the maturity field was determined with reference to the Jurassic to Cretaceous burial, probably associated with an extensional tectonic regime (Kutek, 1994; Hakenberg and Świdrowska, 1997; Poprawa, 1997). Additionally, an increase in heat flow was assumed in the Masovia area (Korabiewice PIG1 – Mszczonów IG1 wells) in the Jurassic for consistency with the K-Ar ages of diagenetic illite in sandstones that according to Kozłowska and Poprawa (2004) imply a heat-flow anomaly.

GAS GENERATION

The results of modelling indicate that the Carboniferous sediments attained their thermal maturity between the Late Carboniferous and the Cretaceous. Several stages of thermogenic gas generation and expulsion could be distinguished (Karnkowski, 1996, 1999, 2007; Burzewski *et al.*, 1998; Kotarba *et al.*, 2004, 2005; Botor 2011a, b). How-

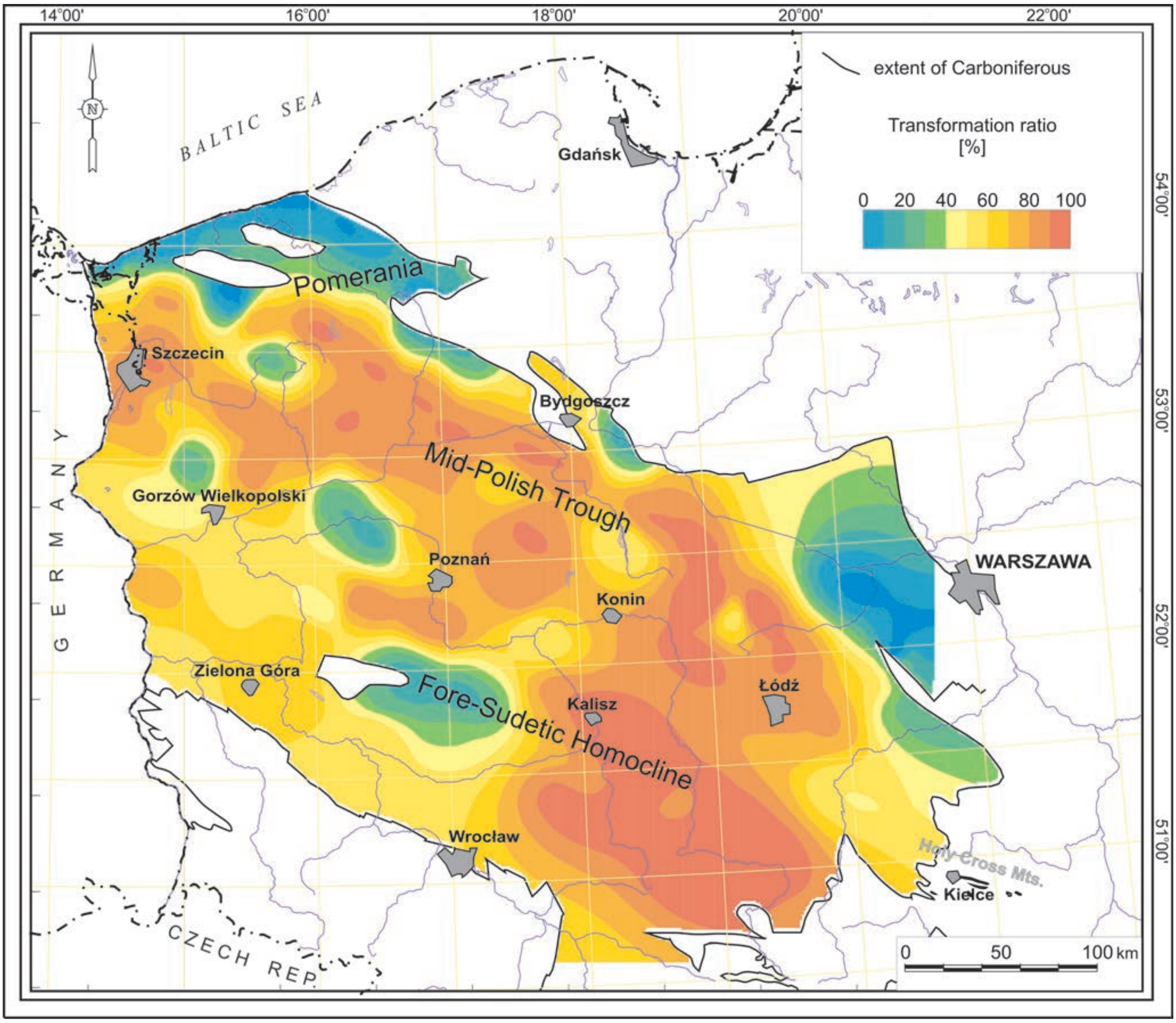

Fig. 13. Degree of kerogen transformation (TR%) in Carboniferous source rocks (referred to top of Carboniferous) calculated for the end of Triassic

ever, in contrast to previous published studies, the present account considers the entire Carboniferous substratum of the Rotliegend basin (Figs 12–14). The Lower Carboniferous source rocks generated gas in two phases: in the Late Carboniferous and later from the Early Triassic to the Late Cretaceous. In contrast the Upper Carboniferous source rocks generated gas only in the Mesozoic, owing to insufficient burial in the Variscan stage of development (Botor, 2011b, 2012b). As suggested for some parts of the German Basin (Pletsch *et al.*, 2010), Westphalian gases replaced and displaced older gases that had come from Lower Carboniferous source rocks. This caused the mixing of gases in the conventional gas fields (Pletsch *et al.*, 2010).

Taking into account the geological development of the study area, several different thermal models can be applied successfully to achieve very good calibration results. However, the timing and amount of hydrocarbons generated according to various models are not much different, at least in the central part of the MPT (Botor, 2011a). In addition, because of salt tectonics, organic maturation and gas generation can be significantly delayed in some Carboniferous source rocks below salt diapirs and pillows, as was the case in the German Basin (Schwarzer and Littke, 2007). In general, it can be concluded that the thermal maturity of the Carboniferous rocks, except for in the eastern FSH, was reached in the Mesozoic, which also is supported by the wide occurrence of gas fields in the Rotliegend. As stated above, gas that had accumulated in these fields and originated from the Carboniferous source rocks would have been lost during erosion near the Carboniferous–Permian boundary, if gas generation had been developed and completed before the Zechstein sealing.

The degree of transformation of Carboniferous kerogens corresponds with the initial and main phases of liquid hydrocarbon generation in Masovia and northern Pomerania. In the axial part of the MPT and in the FSH, Carbonif-

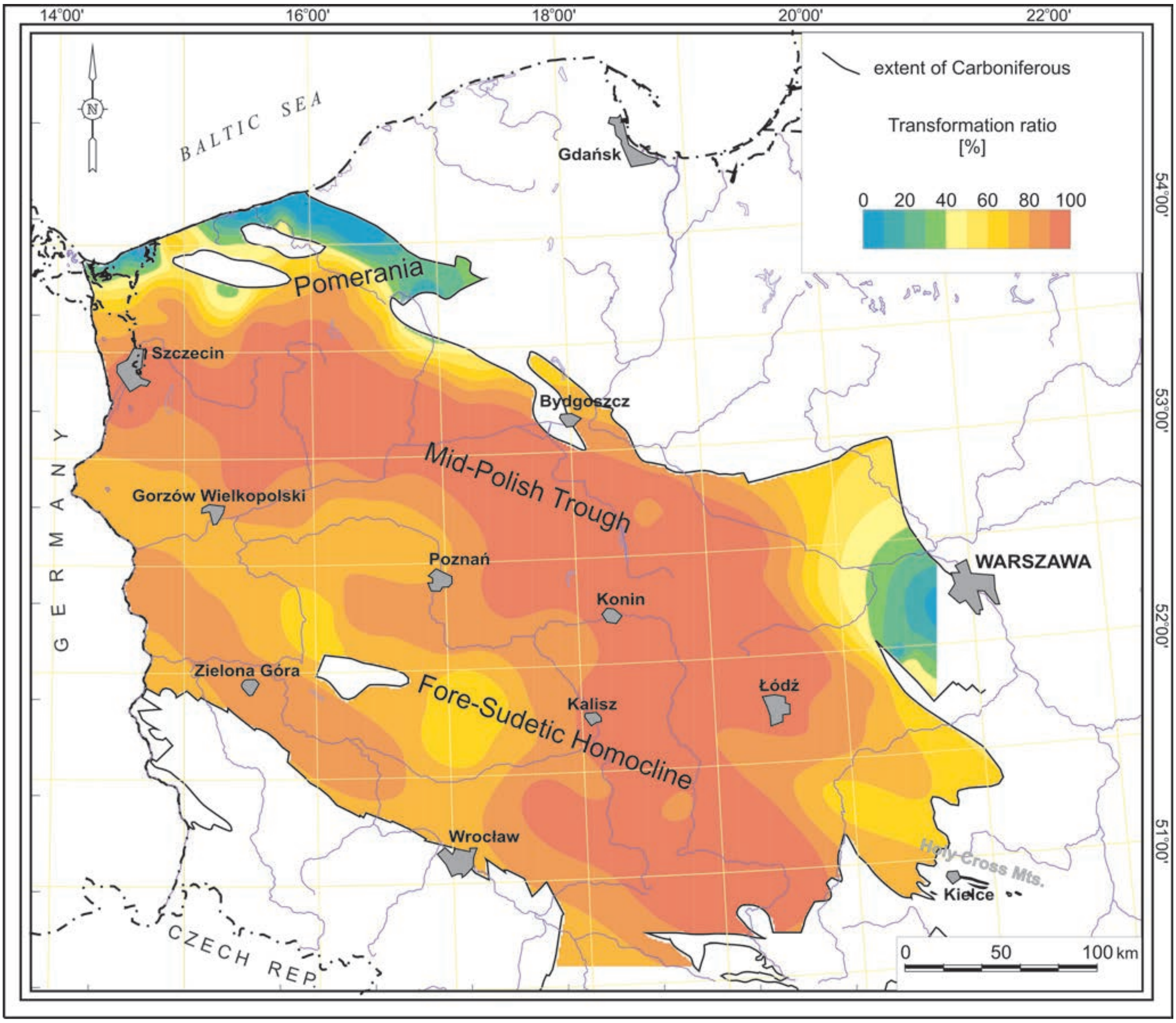

Fig. 14. Degree of kerogen transformation (TR%) in Carboniferous source rocks (referred to top of Carboniferous) calculated for the end of Cretaceous

erous kerogens are characterized by a degree of transformation that corresponds to the phase of gas condensate generation, but above all, the phase of thermogenic generation of dry gas.

GAS MIGRATION

The greatest amounts of gases were generated and expelled from the Carboniferous source rocks in the substratum of the Mogilno-Łódź Depression, the axial part of the MPT, and the Lower Silesian (Zielona Góra) Depression (Figs 12–15) (see also Maćkowski *et al.*, 2008; Górecki *et al.*, 2011). Taking into account the K-Ar age dating of authigenic illites, which can be used as a proxy for the closure of gas migration paths, this should have happened in the Mesozoic, mostly from the Early Jurassic to the Early Cretaceous (Lee *et al.*, 1985; Hamilton *et al.*, 1989; Liewig and Clauer, 2001; Michalik, 2002; Protas *et al.*, 2006; Maliszewska *et al.*, 2009, and references therein). Therefore, it seems reasonable that numerous reservoirs in the Rotliegend basin were filled by hydrocarbons before the end of the Late Jurassic. This also is strongly supported by gas-migration modelling (Fig. 15; Maćkowski *et al.*, 2008), which showed that migration had an episodic character and lasted from the Late Triassic to the Early/Late Jurassic.

The very high kerogen transformation probably caused nitrogen generation, particularly in the deepest part of the basin (e.g., the Kujawy–Kutno area) from the Triassic to the Early Jurassic. Natural gas, recovered in the North German Basin, adjacent to the Pomeranian segment of the Polish Basin, is dominated by nitrogen (over 90% – Gerling *et al.*, 1997). Such an extremely high nitrogen content must have been related to the fact that nitrogen is generated from organic matter within a sedimentary basin at higher temperatures than methane. Nitrogen-rich gases are mainly formed

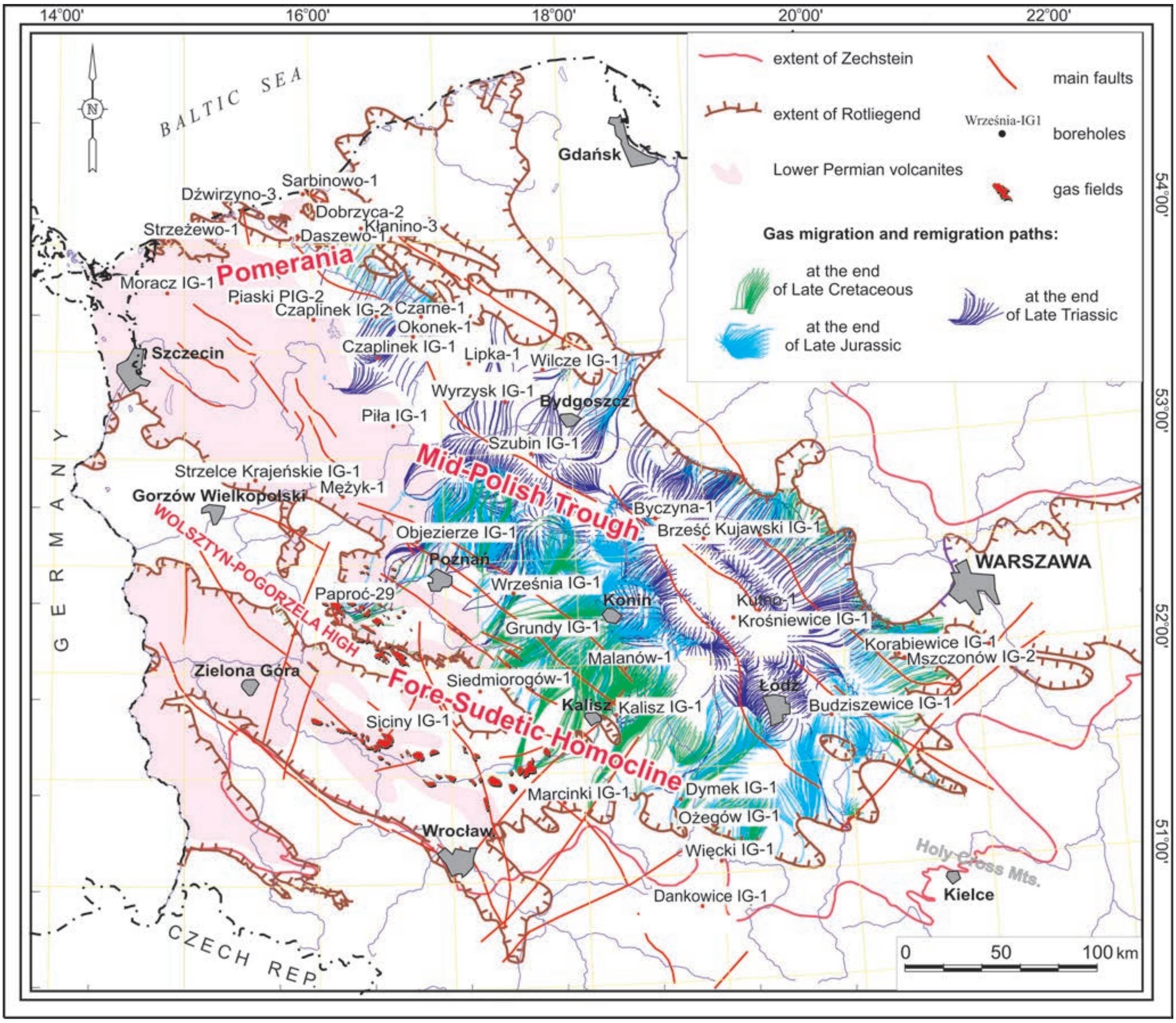

Fig. 15. Gas migration paths at top of Upper Rotliegend reservoir rocks (modified after Maćkowski *et al.*, 2008)

during the final stage of gas generation, when sedimentary rocks are transformed into metamorphic rocks (e.g., Littke *et al.*, 1995).

The distribution and content of nitrogen and helium within natural gas, found in the Polish Rotliegend basin (Karnkowski, 1993, 1999; Lokhorst, 1997), demonstrate the relatively high nitrogen content (45–80%) in Pomerania and the erra- tic occurrences of helium, found in only a few wells. It seems that the presence of helium is connected with deep faults or fracture zones, along which it could have migrated upward (Karnkowski, 1999). The variability of the nitrogen content in the natural gas decreases from the German Basin towards the East European Platform (Lokhorst, 1997). Since the generation of nitrogen, due to the high-temperature transformation of organic matter, is widely accepted in Germany, a similar explanation might be considered for the Pomerania region. This might be the case, even if the temperatures experienced by the Carboniferous source rocks were lower in NW Poland than in the German Basin and they decreased from west to the east. Although gas generation in Pomerania was initiated in the Late Carboniferous the second and main phase of this process occurred in the Mesozoic. The Carboniferous source rocks, which were subjected to a lower thermal regime, could mature slowly and release both nitrogen and methane.

The different distribution patterns of helium and nitrogen content are visible in the southern part of the Polish Basin: nitrogen content increases towards the basin margins, but helium is concentrated in one distinct area (NE part of the FSH). This is the case, not only for single wells, but also for entire gas plays (Kotarba *et al.*, 1992; Karnkowski, 1999). The northeastern FSH is one of the few places in the world, where condensed gas provides industrial amounts of helium, both due to the high content in natural gas plays and the significantly large volume. The nitrogen content is also high, from 40 to 75% (Pletsch *et al.*, 2010). The methane content increases towards the basin centre and the characteristic locations of higher methane amounts within a nitro-

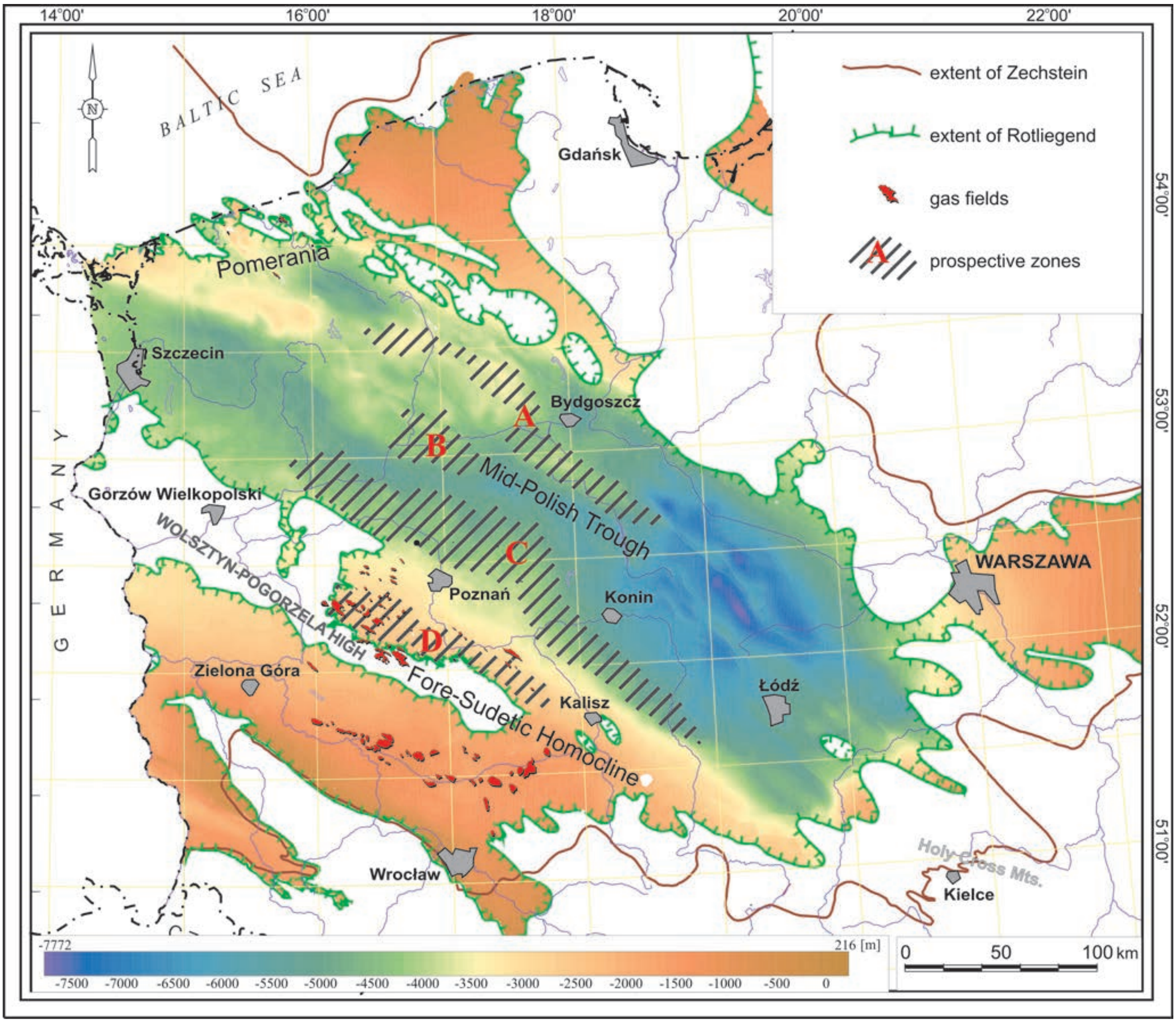

Fig. 16. Location map of prospective zones at top of Rotliegend (modified after Burzewski *et al.*, 2009; Górecki *et al.*, 2011)

gen-helium field indicate migration of it from the basin centre towards the south. The area with a high helium concentration corresponds to the part of the Polish Basin, affected by the highest heat flow during the Permian through the Mesozoic.

CONCLUSIONS

The most important results of the maturity modelling are summarised below:

1. The hydrocarbon potential of the Polish Rotliegend Basin significantly exceeds the reserves of gas fields discovered to date.

2. Carboniferous organic matter constituted the main source of the hydrocarbons, accumulated in the Rotliegend reservoirs. The results of the geochemical and petrographic research, carried out so far on the organic matter from the Carboniferous strata in Poland, have shown that the dispersed organic matter is mostly of a humic nature (gas-prone, Type III kerogen). Subordinately, only in the Tournaisian and Viséan deposits, kerogen of algal-marine origin (oil-prone, Type II kerogen) and mixed Type II/III kerogen occur. However, these have a low hydrogen content, which accentuates their rather gas-prone character. The predominating humic kerogen determined the character of the Carboniferous organic matter as a source of gaseous hydrocarbons. The quantity of dispersed organic matter is variable, sometimes quite large with averages oscillating around values in the order of 1–2% TOC.

3. In the Carboniferous section, a progressive increase in maturity of organic matter with burial depth can be observed from approximately 0.5% Rr at the top of the Westphalian (margins of the MPT) to over 5.0% Rr in the bottom parts of the Lower Carboniferous (eastern FSH). The majority of hydrocarbon fields occur in the zones, where the top of the pre-Permian basement attained a thermal maturity in the order of 1.0–2.0% in the vitrinite reflectance scale. The

presence of effective source rocks is restricted to the zones with maturity exceeding 1.0% Rr.

4. The thermogenic generation of hydrocarbons from the Carboniferous sources took place from the late Westphalian and throughout the Mesozoic, up to the Late Cretaceous. Its timing and advancement reveal considerable variability across the Carboniferous basin, reaching a kerogen transformation of approximately up to 100% in the zones of maximum maturity of organic matter. In the eastern FSH, gas generation was completed in Variscan time before the covering of it by the Zechstein and most gases were dispersed in the atmosphere. In other parts of the FSH, gas generation continued in the Mesozoic, with the highest rate in the Late Triassic to Early Jurassic. In the axial part of the MPT, gas generation commenced in the Early Triassic (the Kutno–Łódź area) and gradually increased up to the latest Jurassic, which was generally related to high burial and conductive heat flow. However, in the remaining parts of the MPT, gas generation began in the Late Triassic and reached a maximum in the Early Jurassic, also in the FSH. In the Konin–Kalisz area, gas generation continued until the Late Cretaceous.

5. Hydrocarbon migration proceeded in pulses of variable intensity. The main phases of gas migration took place in the Late Triassic, Early Jurassic, and Late Jurassic. Migration ceased in the Cretaceous. In the light of the results of hydrocarbon migration modelling, the most prospective areas for exploration are represented by the Konin–Malanów and Szubin–Byczyna–Kutno zones, and the Mężyk–Objezierze–Września zone. The area near the NE margin of the Wolsztyn-Pogorzela High remains prospective. The modelling has shown that the greatest amount of gas was dispersed in the marginal parts of the basin: (a) along the Teisseyre–Tornquist Zone, between the Late Triassic and the end of Early Jurassic, and (b) at the northern margin of the Holy Cross Mts., from the Middle to Late Jurassic. In the marginal zone of the Wolsztyn-Pogorzela High, the gas experienced less dispersion.

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