Geological Quarterly, 2010, **54** (2): 103–108

Geology, ecology and petroleum of the lower Paleozoic strata in the Polish part of the Baltic region

INTRODUCTION

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The Baltic Basin is an oval depression on the East European Platform, covering the NE part of Poland, the southern part of the Baltic Sea, the Kaliningrad District of Russia, Lithuania, Latvia, Estonia, Sweden and Denmark (Ulmishek, 1991). In the Baltic region petroleum exploration started at the end of the 1950s in Lithuania, Latvia and the Kaliningrad District of the former Soviet Union. The first oil deposit (Kuldigskoye, Latvia) in Middle Cambrian sandstone reservoirs was discovered in 1964 (Vosylius, 1987). From 1964, more than 30 oil fields and a few gas fields have been discovered in the Russian (Kaliningrad District), Lithuanian and Latvian parts of the Baltic region. Oil and gas accumulations and shows occur in Middle Cambrian, Ordovician and Silurian strata (Vosylius, 1987; Zdanaviciute and Lazauskiene, 2004, 2007).

In the Polish onshore part of the Baltic region, the small Żarnowiec oil deposit was first discovered in 1970. Later in this area, two small oil accumulations in the Dębki in 1971 and Białogóra in 1991, and one gas-condensate accumulation at Żarnowiec-West in 1987 were discovered (Karnkowski, 1999; Domżalski *et al*., 2004; Karnkowski *et al*., 2010). In the Polish offshore part of the Baltic region, three oil accumulations in the B3 structure in 1981, B8 in 1983, and B34 in 1996, and four gas-condensate accumulations in B4 in 1991, B6 in 1982, B16 in 1985, and B21 in 1996 were discovered in Middle Cambrian sandstone reservoirs (Domżalski *et al*., 2004; Karnkowski *et al*., 2010). All discovered on- and offshore oil and gas accumulations are in the *Paradoxides paradoxissimus* Zone of the Middle Cambrian (Karnkowski *et al*., 2010).

Between 1976 and 1990 the "Petrobaltic" Joint Petroleum Exploration Organization of Poland, the former German Democratic Republic and the former Soviet Union explored oil and gas fields in the offshore part of the Polish part of the Baltic region. In 1990, this organization was transformed into the "Petrobaltic" S.A. Company (from 2010 named LOTOS Petrobaltic S.A.) as a Polish independent company performing petroleum exploration in the Polish Exclusive Economic Zone of the Baltic Sea. From the end of 1960s in the onshore part of the Polish Baltic region petroleum exploration was run by PGNiG S.A. (the Polish Oil and Gas Company) (Sikorski and Solak, 1991).

The main objective of the papers in this Thematic Issue of the *Geological Quarterly* is determination of the geological, geochemical and petrophysical conditions and their influence on the exploration prospectives of conventional and unconventional hydrocarbon resources within the lower Paleozoic succession in the Polish part of the Baltic region. Furthermore, the hazard of geogenic pollution of the Polish Baltic Sea is also discussed.

This Volume is a continuation of the Thematic Issue series, edited within the *Geological Quarterly* over the past few years. These are "Poland: junction of the main geological provinces of Europe" (2006, vol. 50, No. 1), "Stable isotope records of environmental change" (2005, vol. 49, No. 2) and "Multidisciplinary event approaches to the Devonian stratigraphic record" (2004, vol. 48, No. 3).

The studies, the results of which are presented in this Volume, were undertaken as part of two projects of the Ministry of the Environment entitled "Geology, ecology and petroleum of

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the lower Paleozoic strata of the Polish part of the Baltic region" (No. 182/2005/Wn-06/FG-sm-tx/D) and "Geochemical investigations of the Southern Baltic Sea to assess geogenic pollution and petroleum prospective" (No. 407/2005/Wn/-07/FG--sm-tx/D) carried out at the AGH University of Science and Technology in Kraków and the Polish Geological Institute – National Research Institute in Warsaw, respectively. These projects were financed by the National Fund for Environmental Protection and Water Management.

The authors of the papers contributing to this volume mainly come from the AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection in Kraków and the Polish Geological Institute – National Research Institute in Warsaw as well as in two cases the PGNiG S.A. (Polish Oil and Gas Company) in Warsaw and Zielona Góra, the LOTOS Petrobaltic S.A. Company in Gdańsk and the U.S. Geological Survey in Denver. As such, they represent large parts of the Polish geological and petroleum communities that jointly pursue their research efforts.

CONTENTS OF THE THEMATIC VOLUME

This paper is an introduction to this thematic volume of the *Geological Quarterly*. The volume contains 13 papers presenting the results of the geology, burial and thermal history, evaluation of hydrocarbon potential, content, genetic type and maturity of source rocks, petrophysical properties of reservoir rocks, origin of oil and natural gas, modelling of petroleum processes and ecological studies in the Polish offshore part of the Baltic region (Polish Exclusive Economic Zone of the Baltic Sea) and the adjacent onshore area.

Zdzisław Modliński and Teresa Podhalańska (2010) describe the lower Paleozoic strata in the Polish part of the Baltic region belonging to the Precambrian platform (East European Craton) as well as on the Paleozoic platform (Koszalin–Chojnice Zone) representing a presumed fragment of the Caledonian fold and thrust belt. The sedimentary strata have been well recognized in the Baltic Basin, and the entire succession has been penetrated in on- and offshore boreholes. The succession begins with deposits of the Żarnowiec Formation ascribed to uppermost Ediacaran and lowermost Cambrian, overlain by Middle and Upper Cambrian, Ordovician and Pridoli (Silurian) siltstones and shales, with subordinate calcareous intercalations in the upper part of the succession. In the Koszalin–Chojnice Zone only fragments of tectonically disturbed Ordovician and Silurian shales and siltstones have been recognized.

Jędrzej Pokorski (2010) presents the present-day structural pattern and division into tectonic blocks of the Polish parts of the East European Craton (Precambrian platform) and the East European Platform (Paleozoic platform) of the Baltic region. The platforms developed due to superimposition of three main deformation phases: syn-Caledonian (after the Silurian), syn-Variscan (end of Carboniferous and beginning of Permian) and syn-Alpine (latest Mesozoic or earliest Cenozoic). Generally, the boundary between these tectonic areas is considered to run along faults belonging to the Teisseyre-Tornquist Zone.

Paweł Poprawa *et al*. (2010) describes the burial history and thermal evolution of the Polish part of the Baltic region reconstructed for eight boreholes, both offshore A8-1/83, A23-1/88, B6-1/82 and B4-2A/02, and onshore Białogóra 3, Dębki 3, Łeba 8 and Żarnowiec IG 1, penetrating the lower Paleozoic succession. The burial history and thermal evolution are used for 1-D (Kosakowski *et al*., 2010*b*) and 2-D (Wróbel and Kosakowski, 2010) modelling of petroleum processes.

Paweł Karnkowski *et al*. (2010) review previous studies and reassess the palaeogeography and subsidence pattern, tectonic evolution, source, reservoir and seal rocks, heat flow and geothermal history, hydrocarbon generation and migration, hydrocarbon occurrence, history of petroleum exploration and nonconventional petroleum resources of the Polish part of the Baltic region.

Dariusz Więcław *et al*. (2010*a*) determine the content, genetic type and maturity of organic matter dispersed from the Lower Cambrian to the Pridoli (Silurian) sequence of the Polish part of the Baltic region based on the results of geochemical analyses of a total of a 1377 rock samples collected from 38 boreholes in the onshore and offshore areas. Four source rock horizons within the Middle Cambrian strata, Upper Cambrian–Tremadocian succession, Caradocian (Upper Ordovician) and Llandovery (Silurian) strata were selected. The best source rocks for conventional oil and natural gas were found in the Upper Cambrian–Tremadocian succession. Caradocian (Upper Ordovician) and Llandovery (Silurian) strata seem to be the best for unconventional shale gas resources.

Paweł Kosakowski *et al*. (2010*a*) describe the lower Paleozoic source rocks in the offshore parts of the Gryfice and Kołobrzeg blocks of the Paleozoic platform in terms of organic geochemical study and numerical modelling. The geochemical study revealed the presence of effective source rocks in Caradocian strata, but with low hydrocarbon potential. The remaining lower Paleozoic source rock horizons have not been documented by core samples. The timing of hydrocarbon generation and expulsion was modelled for the K1-1/86 and L2-1/87 boreholes located on the Gryfice and Kołobrzeg blocks, respectively. The lack of any discovered accumulations could be the result of hydrocarbon leaking caused by tectonic deformation and intensive vertical fault block movements.

Maciej Kotarba (2010) demonstrates the origin of hydrocarbon gases associated with oil and condensate accumulations within the Middle Cambrian sandstone reservoir in the Polish part of the Baltic region based on results of molecular analyses, stable carbon isotopes of methane, ethane and propane, and stable hydrogen isotopes of methane of four samples from the offshore B3-4/91 and B3-9/95 boreholes and two intervals in the B7-1/91 borehole, and four samples from the onshore Dębki 2, Dębki 5K, Malbork IG 1 and Żarnowiec 7 boreholes. The natural gases are compared to the gases generated from three rock samples of the Upper Cambrian–Tremadocian source rocks by hydrous pyrolysis at 330°C for 72 h, which enabled the author to differentiate and evaluate thermogenic and microbial components.

Dariusz Więcław *et al*. (2010*b*) describe the origin of oil from accumulations within the Middle Cambrian sandstone

reservoir from both offshore and onshore areas of the Polish part of the Baltic region based on the results of density, fraction, sulphur content, biomarker and stable carbon isotope analyses of 21 samples.

Dariusz Więcław *et al*. (2010*c*) estimate kinetic parameters for oil generation and expulsion from the Upper Cambrian–Tremadocian source rock succession of the Baltic region by two methods:

– organic sulfur content in kerogen,

– hydrous pyrolysis experiments conducted at 330 and 355°C for 72 h, then applying these estimated HP kinetic parameters at geological heating rates of 1 and 10°C/m.y.

Kinetic parameters of kerogen, as for the burial history and thermal evolution (Poprawa *et al*., 2010) are used for 1-D (Kosakowski *et al*., 2010*a*, *b*) and 2-D (Wróbel and Kosakowski, 2010) modelling of petroleum processes.

Roman Semyrka *et al*. (2010) assess the petrophysical properties of the lithostratigraphical successions of the lower Paleozoic strata, mainly the Middle Cambrian reservoir rock in the Polish part of the Baltic region between the Koszalin and Kuźnica fault zones by means of mercury porosimetry and well logging results. The porosimetric measurements allow one to determine critical rock parameters and to distinguish genetic types of reservoirs. Moreover, the well logs enable one to identify the Middle Cambrian rock in well sections and to distinguish several lithostratigraphic units.

Paweł Kosakowski *et al*. (2010*b*) present results of the 1-D modelling of hydrocarbon generation and expulsion processes as well as the timing of hydrocarbon generation in profiles of eight boreholes: A8-1/83, A23-1/88, B6-1/82, B4-2A/02, Białogóra 3, Dębki 3, Łeba 8 and Żarnowiec IG 1 for four source rock successions: the Middle Cambrian, the Upper Cambrian–Tremadocian, the Caradocian (Upper Ordovician), and the Llandovery and Wenlock (Silurian).

Magdalena Wróbel and Paweł Kosakowski (2010) present results of the 2-D modelling of hydrocarbon generation, expulsion, migration and accumulation processes for four Middle Cambrian, Upper Cambrian–Tremadocian, Caradocian and Llandovery source rock units along the 127.3 km long 236-M2-76 cross-section between the A8-1/83 and B6-1/82 boreholes located in the northern offshore part of the Darłowo, Słupsk and Łeba blocks and the 39.5 km long 83-01-93T cross-section located along the southern onshore part of the Słupsk and Łeba blocks.

Krzysztof Jaworowski *et al*. (2010) describe the modern migration of harmful geogenic substances into bottom sediments and bottom water in the Polish Exclusive Economic Zone of the Baltic Sea. A geogenic substance is a fluid (gas or liquid) whose formation, chemical composition and physical properties result from natural geological processes. The bedrock of the Baltic Sea contains rocks which are sources of geogenic pollutants migrating along fault zones and pinchouts of sedimentary formations. The pollutant source rocks include: oil- and gas-bearing reservoir rocks (Middle Cambrian, Rotliegend, Zechstein and Carboniferous); black shales (lower Paleozoic); effusive rocks (Rotliegend); salts (Zechstein), reservoir rocks for mineral and thermal waters (Paleozoic and Mesozoic).

CONCLUSIONS AND OUTLOOK

The best source-rocks are in the Upper Cambrian–Tremadocian succession on the Precambrian platform. Other levels – Middle Cambrian, Caradocian and Llandovery – can be also considered as sources of hydrocarbons (Więcław *et al*., 2010*a*). The potential source rock horizons on the Paleozoic platform (Gryfice and Kołobrzeg blocks) were geochemically documented only within the Caradocian strata. The organic carbon content (TOC) is low, usually below 0.3%, and the hydrocarbon potential does not exceed 250 mg HC/g TOC (Kosakowski *et al*., 2010*a*). Oil, condensate and gas accumulated in Middle Cambrian sandstone reservoirs both in onshore and offshore deposits on the Łeba Block have a multi-stage origin. Methane, a thermogenic gas mainly also contains an insignificant microbial component which indicates that the traps within the Middle Cambrian sandstone reservoir had already been formed and sealed when migration of microbial methane took place. Succesively, the traps were supplied by new portions of thermogenic gaseous hydrocarbons as well as early condensate and oil (Kotarba, 2010). Oil and gas from both onshore and offshore accumulations were generated by oil-prone Type II kerogen (Kotarba, 2010; Więcław *et al*., 2010*b*). The problem of the petroleum system of the lower Paleozoic succession in the Polish part of the Baltic region was solved by accounting for the functional scheme of threshold parameters of the development of hydrocarbon generation, exploration, migration and accumulation processes (Magoon and Dow, 1994) and criteria of distribution of source potential index (SPI). Traps formed from the end of the Silurian to the end of the Carboniferous (Westphalian?). Moreover, in the southern zone of study area uplift movements have been inferred around the Cretaceous–Paleogene boundary, which may have resulted in the rebuilding of traps. Results of 1-D and 2-D modelling reveal (Kosakowski *et al*., 2010*b*; Wróbel and Kosakowski, 2010) that hydrocarbon generation, expulsion and migration processes took place in the Devonian and Carboniferous. Renewal of tectonics in the area and possible restructuring of the traps caused preservation of hydrocarbon accumulation to finally take place after post-Cretaceous inversion. The critical moment is attributed to the time of maximal subsidence of the basin, i.e. at the end of the Westphalian (Poprawa *et al*., 2010).

Based on source rock-oil-gas correlation (Kotarba, 2010; Więcław *et al*., 2010*a*, *b*), one- and two-dimensional modelling (Kosakowski *et al*., 2010*b*; Wróbel and Kosakowski, 2010) and analysis of the petroleum system (Kotarba *et al*., 2010) ranking of areas of prospectivity for conventional petroleum exploration were established on the Precambrian platform (Fig. 1): (II) good for oil and gas, (III) medium for oil and condensate and good for gas, (IV) low for gas, and (V) minimal for oil and gas. Moreover, a migration area (I) was established on the Precambrian platform where oil and gas accumulations (B3, B4 and B8) occur. The ranking also covers area (VI) of low prospectivity for oil and gas exploration for the Paleozoic platform.

In the last few years special attention has been paid to the Caradocian and Llandovery as well as the Upper Cambrian–Tremadocian claystone-siltstone successions for evalua-

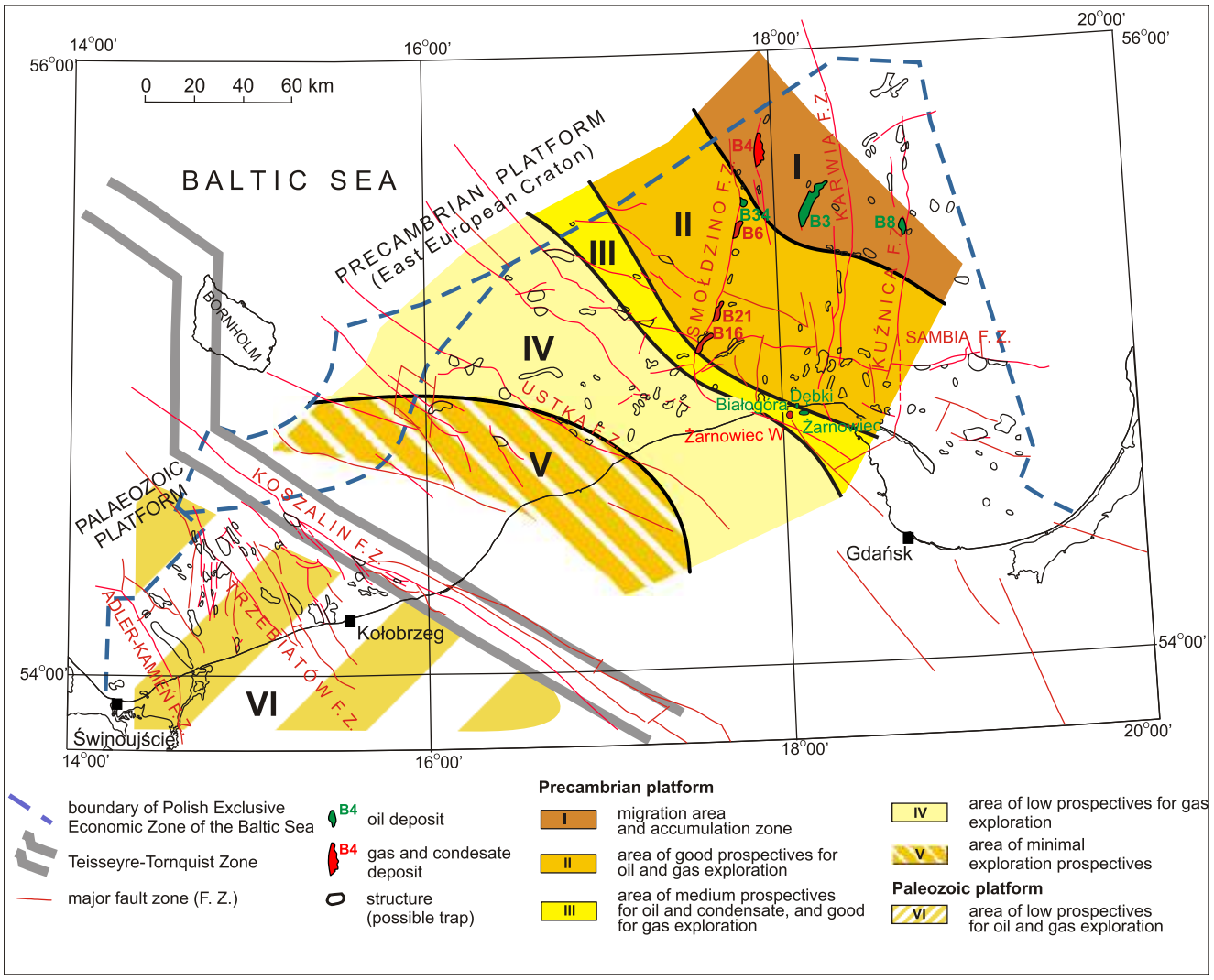

Fig. 1. Prospectivity petroleum exploration in the Polish part of the Baltic region (Kotarba *et al.*, 2010)

Fault system and location of possible traps after Pokorski (2010) and Domżalski and Mazurek (2003)

tion of resources of unconventional shale gas (Poprawa, 2010). The main criteria of the evaluation of shale gas resources are tectonic setting and thickness as well as geochemical characteristics of claystone-siltstone successions (Curtis, 2002). The content, genetic type and maturity of dispersed organic matter within these successions were by described Więcław *et al.* (2010). In the Polish part of the Baltic region there should occur considerable resources of shale gas.

Acknowledgements. My foremost gratitude is due to Henryk J. Jezierski Undersecretary of State and Chief State Geologist, and Ewa Zalewska, Director of the Department of Geology and Geological Concessions of the Ministry of the Environment, Paweł Siemek and Henryk Wronkowski, present and former Presidents of the LOTOS Petrobaltic S.A. Company and Dr. Tadeusz Wolnowski Director of Petroleum Exploration of the Zielona Góra Branch of the Polish Oil and Gas Company for their kind and patient support of research in the Baltic region.

My special thanks are expressed to Doc. Dr. Jerzy Nawrocki, Editor-in-Chief of the *Geological Quarterly* and Director of the Polish Geological Institute – National Research Institute in Warsaw for his help with the editorial work.

Thanks are due to all the reviewers of the manuscripts at various stages of preparation, who devoted time borrowed from their busy schedules in order to critically read the papers.

To Dr. Anna Becker from the Polish Geological Institute – National Research Institute in Warsaw heartiest thanks for editorial advice.

Many thanks are due to Ms. Ewa Dąbrowska-Jędrusik and Ms. Bogumiła Kwaśniewska from the Polish Geological Institute – National Research Institute in Warsaw and Ms. Joanna Gawęda-Skrok, Ms. Maria Fremel and Mr. Sebastian Ptak from the AGH University Science and Technology in Kraków for technical editorial work.

Last but not least, I want to express all my gratitude to my Loving Wife for her understanding and patience.

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