Geological Quarterly, 2010, **54** (2): 143–158

# Petroleum geology of the Polish part of the Baltic region – an overview

Paweł H. KARNKOWSKI, Leszek PIKULSKI and Tadeusz WOLNOWSKI

Karnkowski P. H., Pikulski L. and Wolnowski T. (2010) – Petroleum geology of the Polish part of the Baltic region – an overview. Geol. Quart., **54** (2): 143–158. Warszawa.

The Polish part of the Baltic region is located within the contact zone between two large geological units: the Precambrian platform and the Paleozoic platform. It comprises the Polish sector of the southern Baltic Sea and the adjacent onshore part of Northern Poland (Western and Eastern Pomerania). The fundamental geological pattern is defined by the Teisseyre-Tornquist Zone, separating the East European Craton from the Paleozoic platform. As a result of exploration activity in the onshore Pomerania region, four oil fields in Cambrian sandstones, seven gas fields in Carboniferous sandstones, six gas fields in Rotliegend sandstones, and eleven oil fields within the Zechstein Main Dolomite horizon have been discovered. The petroleum play of the southern Baltic Sea region and adjacent areas must be considered separately for Eastern and Western Pomerania. In the Peribaltic Syneclise we can only take into consideration organic matter appearing in lower Paleozoic rocks but their geothermal history refers to the period from the Vendian up to the recent. The present extent of the "oil window" in the Upper Cambrian rocks is mainly restricted to the offshore area. Reservoir properties of the "gas window" Cambrian rocks are rather low due to intensive diagenetic processes. Acquisition of gas should be possible by processes of hydraulic stimulation (tight gas). Lower Paleozoic rocks rich in organic matter (Ordovician and Silurian), especially in the border zone of the EEC ($R_o$ >1.3%), could be an area of unconventional gas fields (shale gas). The Western Pomerania petroleum play shows two separate source rocks units. The older one embraces Carboniferous deposits with organic matter of terrestrial origin and generated gases accumulated in the Rotliegend and Carboniferous traps. The second petroleum system is located within the carbonates of the Zechstein Main Dolomite (Ca2). This is a closed system, meaning that the source rocks are at the same time the reservoirs sealed by Zechstein evaporates. Hitherto discovered hydrocarbon deposits in the Polish part of the Baltic region have confirmed good perspectives regarding oil and gas hydrocarbon zones. New, conventional and unconventional discoveries remain possible.

*Paweł H. Karnkowski, Institute of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland, e-mail: Karnkowski@uw.edu.pl; Polish Oil and Gas Company, Kasprzaka 25, PL-01-242 Warszawa, Poland, e-mail: Pawel.Karnkowski@pgnig.pl; Leszek Pikulski, Exploration and Exploitation Oil and Gas Company "Petrobaltic", Stary Dwór 9, PL-80-958 Gdańsk, Poland, e-mail: leszek.pikulski@petrobaltic.com.pl; Tadeusz Wolnowski, Polish Oil and Gas Company-Zielona Góra Branch, Staszica 9, PL-64-920 Piła, Poland, e-mail: Tadeusz.Wolnowski@pgnig.pl* *(received: January 20, 2010; accepted: May 17, 2010).*

Key words: Baltic region, petroleum geology, shale gas.

## INTRODUCTION

The Polish part of the Baltic region comprises the Polish sector of the southern Baltic Sea and the adjacent onshore part of Northern Poland (Western and Eastern Pomerania). It is located within the contact zone between two large regional geological units: the East European Craton (EEC) and the Paleozoic platform of Central and Western Europe (Fig. 1). The relativly shallow depth of the Baltic Sea favours geological prospection for hydrocarbon deposits (Brangulis *et al.*, 1993; Dobrova *et al.*, 2003; Zachowicz *et al.*, 2004). But prospecting and exploitation in the offshore area are also harmful for the natural environment so they need to be realized with special care to avoid polluting the Baltic Sea (Elmgren, 2001; Sanderson *et al.*, 2009; Szarejko and Namieśnik, 2009).

Results of geological studies in Northern Poland have been published systematically from the 1950s. A milestone, summarizing the first period of studies on the southern Baltic area, was the *Geological-structural Atlas of the Southern Part of Baltic Sea* edited by Witkowski (1989). Its was supplemented by a special issue of the *Geological Quarterly* in 1990, including detailed papers on selected geophysical-geological problems (Kiełt, 1990; Dadlez, 1990; Pokorski, 1990; Ryka, 1990; Wagner, 1990; Witkowski, 1990*a*, *b*). In next few years several important papers referring to this area were published by Lund *et al*. (1991), Dadlez (1993), Ryka (1993), Witkowski (1993) and Modliński *et al.* (1994). Publication of the *Geological Atlas of Southern Baltic Sea* edited by Mojski *et al*. (1995) and *Map of the Baltic Sea Bottom Without Quarternary Deposits* (Kramarska *et al.*, 1999) summarized numerous data obtained by the beginning of the 1990s. Geological research, other than

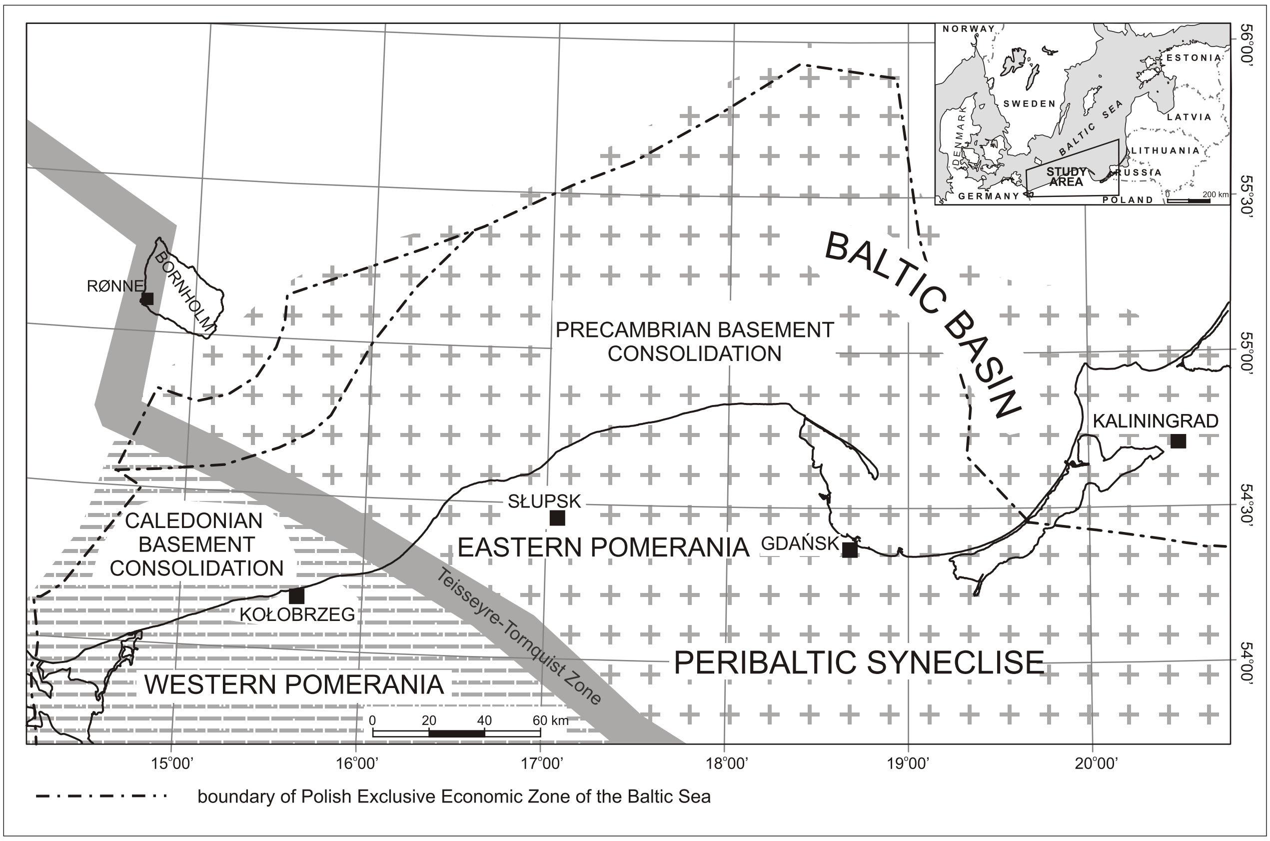


**Fig. 1. Location of study area with main geological and geographical units**

for prospecting for offshore hydrocarbons, has enabled detection of natural raw material deposits on the sea bottom (Kramarska, 1991; Masłowska, 1993, 2002). In this decade, regional geological prospecting applying the methodology of "Sedimentary Basin Analysis" with advanced computer geological modelling was initiated (Karnkowski, 1996, 2000, 2003; Kotarba *et al.*, 2003, 2004; Kosakowski *et al.*, 2003; Poprawa *et al*., 2010). Several papers (Karnkowski, 1993; Wolnowski, 2002, 2003; Domżalski *et al*., 2004; Pikulski, 2004; Kotarba *et al*., 2005), dedicated to solving petroleum geology problems.

The concession politics of Poland enables foreign investors to start studies in the difficult – from a geological point of view – area of Northern Poland. The deposits discovered, including these small ones, are easy for management because of the proximity of consumers and because of a dense pipeline infrastructure. The stability of political and economic conditions in Poland during the last 20 years favours such prospecting initiatives. Many sedimentary basins in the world have now been relatively well characterized and the framework of petroleum provinces defined. Lately, there has started a tendency to prospect in mature basins, where hydrocarbons deposits have been just discovered and where new findings are possible due to new ideas. The Baltic Sea and the adjacent areas is a good place to test concepts of exploration in mature basins. Geochemical studies (Kosakowski *et al.,* 2003; Kotarba *et al.,* 2003, 2004) and geological modelling (Karnkowski, 1996, 1999, 2000 2003; Kosakowski *et al.*, 2009; Wróbel *et al.,* 2009, 2010) are useful in such investigations.

## GEOLOGICAL SETTING

The Polish sector of the Baltic Sea and the adjacent onshore part of Northern Poland are the main object of this study. The fundamental geological pattern is defined by the Teissyre-Tornquist Zone (T-T Zone), separating the Precambrian platform (part of the East European Craton) from the Paleozoic (epi-Caledonian) platform. The northwestern region was often called Western Pomerania in regional geological literature but the area located eastwards from the T-T Zone is named the Peribaltic Syneclise (Fig. 1). The last term practically refers only to the preserved lower Paleozoic deposits, that presently form a giant syncline (depression). These deposits of northeastern Poland could be considered – in terms of sedimentary basin analysis – as a product of Baltic Basin evolution. This basin was initiated in the late Vendian in the area of present-day NE Poland, the Kaliningrad region, the Peribaltic countries and the southern part of the recent Baltic Sea. Its basement was the western part of East European Platform (Areń and Lendzion, 1978; Jaworowski, 1979, 1982; Dadlez, 1987; Linnemann *et al.,* 2008). The main stage of its development took place in the early Paleozoic (Modliński and Podhalańska, 2010).

## PALAEOGEOGRAPHIC DEVELOPMENT

Marine transgression, initiated at the beginning of the Cambrian, was registered in many basins worldwide, among them also in Poland (Geyer *et al*., 2008). During the Middle Cambrian a general regression took place due to uplift of the EE Craton. The next transgressive episode was in the Ordovician. Areal decrease of the Mid-Late Cambrian basin also caused enlargement of land areas supplying eroded clastic material (Lendzion, 1970; Szczepanik, 2000).

The Cambrian–Ordovician boundary is erosional over most of NE Poland but in Eastern Pomerania sedimentary continuity between both systems has been documented. Similar continuity was assumed for this contact in Western Pomerania, where the Tornquist Sea extended during the Cambrian (Fig. 2A). Transgression of the Ordovician sea flooded the whole area of Eastern Pomerania, accumulating mainly clay and marly deposits and subordinately carbonate (Modliński, 1982; Modliński and Szymański, 1997; Servais *et al*., 2008). Deep marine clay sedimentation continued in the Tornquist Sea during the entire Ordovician (Fig. 2B) and Silurian (Fig. 2C).

The Silurian rocks in the southern Baltic area are represented mainly by siltstones and claystones (Teller, 1974; Tomczykowa, 1988; Verniers *et al*., 2008) and they constitute regional seals for Cambrian reservoirs. In the upper part of the Silurian succession there are numerous limestone interbeds (Usaityte, 2000). At the end of the Silurian and beginning of the Devonian the entire area was uplifted and eroded (Fig. 2D). During the Devonian and the Carboniferous the Baltic Basin became eroded in part and the early Paleozoic subsidence rate significantly decreased (Narkiewicz *et al*., 1998). The Mazurian High – a significant and well-known palaeotectonic and palaeogeographic element – was then marked.

The basin frameworks are well documented by shallow water deposits of the shore zone, observed in surface outcrops or in shallow boreholes in the Baltic islands, in the Tallinn and Vilnius regions and in NE Poland (Poprawa *et al*., 1997, 1999). The thickness distribution of these deposits was controlled by the marginal zone of the East European Platform, where during the Silurian the passive basin margin was located and flexed due to loading by the overthrusted Caledonian orogen (Krawczyk *et al*., 2008). The thickness of lower Paleozoic deposits in this marginal zone is over several thousand metres but in the areas of the Peribaltic countries and in the middle Baltic Basin it is several hundred metres (Modliński *et al.*, 1999, 2006).

This uplifted area of the western part of the EEC influenced – in the Devonian and in the Carboniferous – the sedimentary evolution of the Western Pomerania basin (Świdrowska and Hakemberg, 1996; Lipiec and Matyja, 1998; Matyja, 2006). The depositional history began at the end of the Emsian (Fig. 2E) or at the beginning of the Eifelian (Lipiec and Matyja, 1998; Matyja, 2009) producing mainly shallow marine clastics with thin interbeds of carbonate and evaporate lithofacies (Fig. 2F). In the Middle and Late Devonian such shallow marine deposition continued while deeper open shelf sediments also accumulated (Fig. 2G). Transgressive-regressive events were common then but it is difficult to decide whether they resulted from global sea level changes or from local tectonic phenomena. At the end of the Devonian the extremely shallow water facies of the lower Frasnian (Fig. 2H) were replaced by open shelf marls or by coral-stromatoporoid carbonates in the proximal part of the basin (Matyja, 2006, 2009). In the middle Famennian shallow marine conditions returned and from the late Famennian until the early Tournaisian open shelf deposition prevailed (Fig. 2I). The southern Baltic area, adjoined from the north with Western and Eastern Pomerania, was defined palaeogeographically during the Devonian by the Mazurian High and the Fenno-Skania High (Usaityte, 2000). In that time deltaic and nearshore clastic facies with a transition to shallow marine carbonates and clastics prevailed there.

In early Carboniferous Eastern Pomerania probably became a land area and Western Pomerania was an area of deep (clastics) and shallow (carbonates) shelf (Fig. 2J; Żelichowski, 1987). Volcanic activity took place around the Devonian–Carboniferous boundary and marine deposition terminated in the early Namurian (Fig. 2K). During the whole of the Namurian and the early Westphalian the Devonian–Carboniferous deposits of Pomerania were eroded (Fig. 2L). Intense block tectonics locally caused erosional removal of up to 1000 m of strata. The mid Westphalian saw the onset of continental deposition but only in Western Pomerania and in the western part of the southern Baltic. Black and grey continental clastics with thin coal interbeds accumulated (Fig. 2M). In the late Westphalian red intercalations were deposited, indicating the tropical climate zone. The Stephanian deposits in Pomerania are frequently brownish-red in colour and they continue into the Autunian (lower Permian; Żelichowski, 1987; Pokorski, 1990). In the Polish part of the Baltic region area Devonian and Carboniferous deposits were preserved only in the Western Pomerania area (Bełka and Narkiewicz, 2008). The Mazurian and Fenno-Scania elevations significantly influenced deposition and erosion of these deposits. Closure of Iapetus Ocean and of Tornquist Sea as well as folding of the Devonian–lower Carboniferous flysch deposits into the Variscan orogen completely reorganized the palaeogeographic pattern in the southern Baltic region (Kroner *et al*., 2008). In the late Carboniferous almost the whole area was land but in Western Pomerania, probably within the foredeep, clastics from the eroded Variscides accumulated (Żelichowski, 1987; Ziegler, 1990; McCann, 1998; Narkiewicz *et al*., 1998; McCann *et al*., 2008).

The southern Baltic Sea area is mostly devoid of Rotliegend deposits. The Zechstein rocks, overstepping the Rotliegend basin boundaries (Fig. 3), are important for petroleum prospecting only in Western Pomerania. Development of significantly thick Mesozoic deposits was limited to the Polish Trough, part of which was located in Western Pomerania. In the area studied the Mesozoic deposits have not been prospected for oil but they play an important role as a component of subsidence history in the thermal evolution of the Polish Basin (Karnkowski, 1999).

The sedimentary history presented of the western part of the Baltic region (the Polish sector of the Baltic Sea and adjacent areas) and its Permian–Mesozoic period of evolution is illustrated by a typical profile of this region, in lower part of which occur lower Paleozoic rocks overlain by Permian–Mesozoic deposits. The synclinal (depression) form of the preserved rocks is a relict of the Baltic Basin but the final structural form of this region was a result of Variscan tectonic movements, which structurally rebuilt the western part of the basin into the

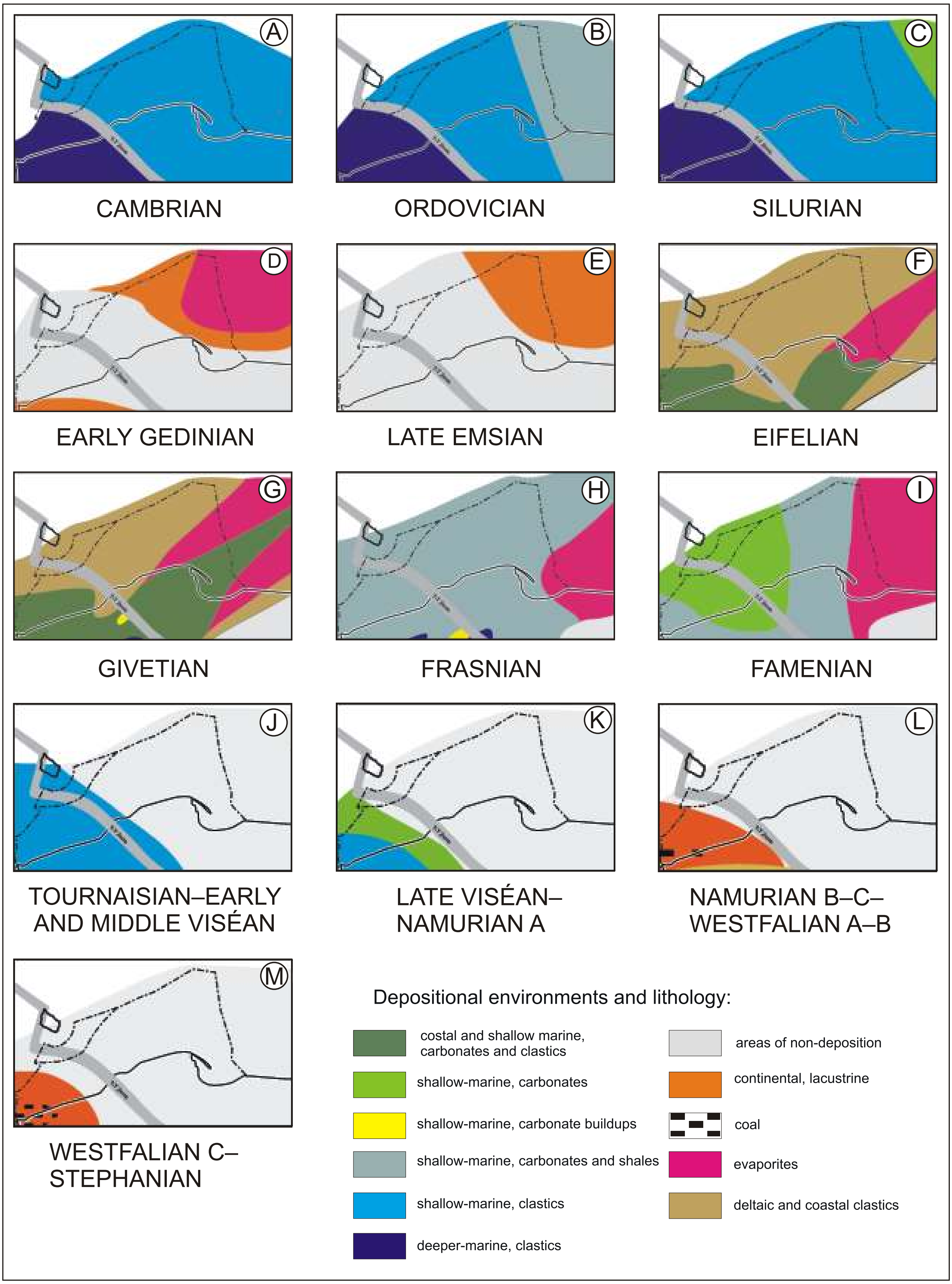


**Fig. 2. Cambrian to Carboniferous palaeogeographic maps (Karnkowski, 1999, extended and supplemented)**

Other explanations as in Figure 1

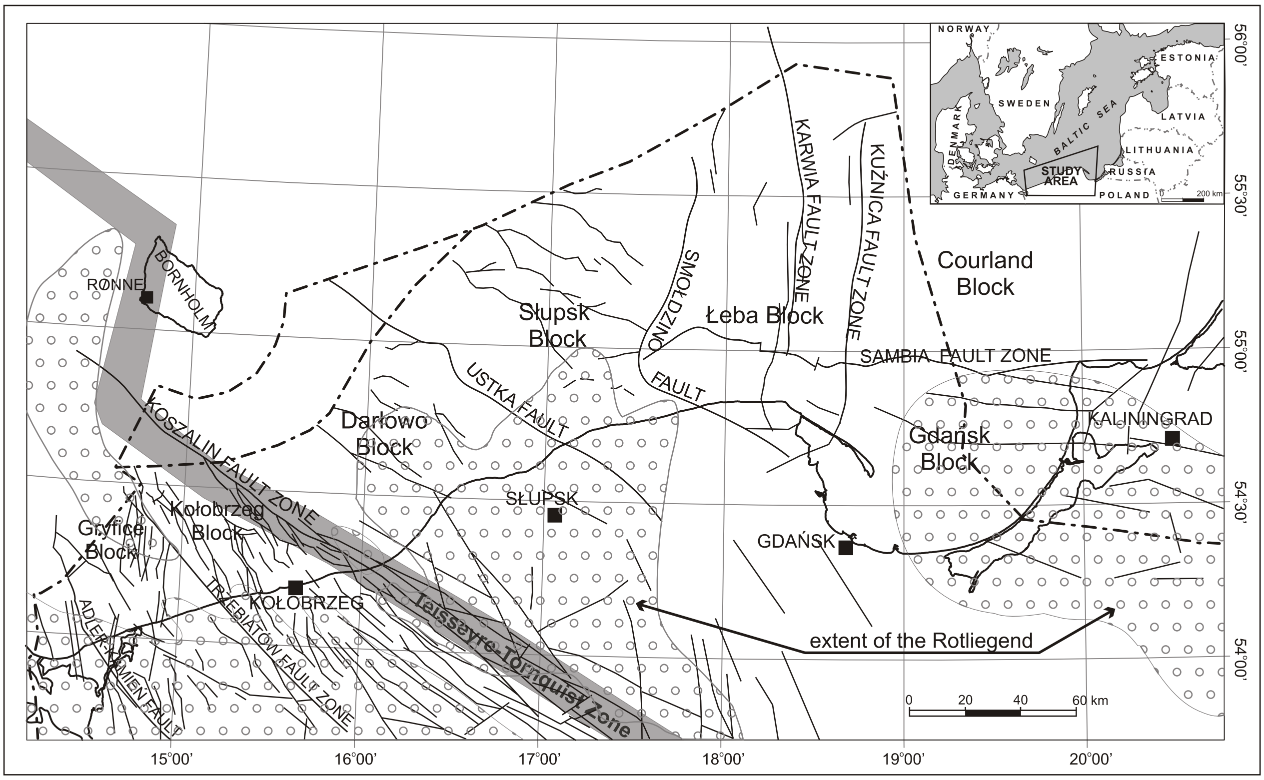


**Fig. 3. Sub-Permian tectonic map with extent of the Rotliegend strata (sources: Pożaryski, 1987; Witkowski, 1989; Dadlez, 1990; Lech, 1993; Mojski *et al*., 1995; Kramarska *et al*., 1999; Pokorski and Modliński, 2007; Polish Oil and Gas Company unpubl. data)**

Fault system according to Pokorski (2010); explanations as in Figure 1

Peribaltic Syneclise. The resultant structure is bounded to the west by the German-Polish Caledonides and to the east, by the Mazurian High, recently without Paleozoic cover.

## STRUCTURAL FEATURES

Westwards from the T-T Zone the older Paleozoic deposits, several thousand metres thick, intensively folded and tectonically deformed, have formed the German-Polish Caledonides belt (Franke, 1994; Maletz *et al*., 1997; Dadlez, 2000). They are documented in boreholes only near the marginal zone of the East European Platform. During the late Paleozoic this belt was covered by platform deposits of Devonian and Carboniferous age.

The main structural features of Western Pomerania are determined by the consolidated Caledonian basement. In vertical succession the following rock successions have been distinguished: the Caledonian (Silurian, Ordovician and Cambrian), the epi-Caledonian (Devonian, early Carboniferous), the Carboniferous–Permian (Westphalian–Rotliegend), the Zechstein–Mesozoic and the Cenozoic. Each of these successions plays an important role in the geological structure of Western Pomerania. The Caledonian succession consists of highly folded Silurian, Ordovician and Cambrian deposits. In boreholes Ordovician rocks are most common, Silurian ones are found rarely while Cambrian strata have not yet been found but their occurrence in the area is suspected from the developmental scheme of early Paleozoic basins. Clayey shales with sandstone interbeds are the main lithological components of the succession, which is highly deformed with beds of varied inclination, up to vertical and overturned, that caused an apparent thickness increase of the deposits although their original thickness may reach thousands of metres. The Caledonian succession is part of the German-Polish Caledonides (Dadlez, 1978, 1980, 1987). Above it, the Devonian and the lower Carboniferous deposits (the epi-Caledonian complex) occur, being commonly built of red sandstones and siltstones (Old Red) (Miłaczewski, 1987; Żelichowski, 1987). The following succession (Carboniferous–Permian in age) corresponds with the period of late Carboniferous and Rotliegend, continental deposition when prevailed, limited frequently to small basins controlled by fault zones (grabens and half-grabens). The Devonian–Carboniferous successions are weakly folded but intensively faulted (Karnkowski, 1979; Dadlez, 1980; Znosko, 1986; Pożaryski, 1987; Knieszner *et al*., 2000; Matyja, 2006). Such a block-fault type of tectonics determined the intense erosion of the Devonian–Carboniferous rocks so that various Devonian and Carboniferous formations are observed on the sub-Permian surface (Karnkowski, 1979; Lech, 1993).

From the beginning of research in Pomerania maps of the sub-Permian geology were made and updated as new geological and geophysical data were acquired (Witkowski, 1989; Lech, 1993; Pokorski and Modliński, 2007). The last-cited map is a compilation embracing not only the area of Poland, but also Russia (Kaliningrad district), Lithuania, Latvia, Denmark (Bornholm) and Sweden (Gotland). The fault systems dominantly have a N–S and E–W arrangement (Fig. 3). The main N–S fault field appears to the north of the Łeba–Gdańsk area (Smołdzino Fault, Karwia Fault, Kużnica Fault; Fig. 3). These faults change direction to E–W at the Polish coastline. The characteristic shape of the Sambia peninsula refers to the E–W trending Sambia Fault pattern. The extent of lower Paleozoic rocks along the Mazury High is concordant with the E–W fault system.

To the west from the T-T Zone the faulting pattern has a NW–SE direction. Huge dislocation zones such as the Koszalin Fault and Trzebiatów Fault limit blocks of basement which are internally strongly faulted. The results of this phenomenon are numerous tilted blocks with strongly eroded Carboniferous and Devonian covers. In Pomerania Bay the N–S trending faults are again present. The Kamień Pomorski Block limits the Polish Rotliegend Basin from the north. It seems that the NW–SE faulting pattern is dominant in the wide contact zone of the EEC and the Paleozoic Platform. N–S and E–W fault directions prevail in the remaining area (Fig. 3). The migration of hydrocarbons and trap formation were substantially dependent on the faulting pattern.

In Western Pomerania extended lava covers of Autunian age were preserved. Deposits and boundaries of the Polish Rotliegend Basin in Western Pomerania are well documented by the boreholes (Nowicka and Wolnowska-Ślemp, 2005). The influence of the T-T Zone, the strong influence of the Caledonides and of the Devonian–Carboniferous fault systems on the facies and thickness distribution of the Rotliegend deposits is very evident (Lech, 1993; Karnkowski, 1999; Kiersnowski and Buniak, 2006). The Zechstein transgression overstepped the extent of Rotliegend clastics in the Polish Basin and flooded its periphery to form local basins (e.g., Słupsk, Mazurian and Podlasie basins) as for as Lithuania. The Devonian–Carboniferous succession is overlain by Permian–Mesozoic with strata an almost horizontal arrangement and negligible deformation because the relatively small thickness of Zechstein deposits prevented intensive halotectonics. The Laramide tectonic movements eroded part of the Mesozoic rocks. The Cenozoic succession overlies the Mesozoic deposits discordantly (Jarosiński *et al*., 2009).

This review of the geological distribution of the areas studied indicates they are determined by the age of basement consolidation. The pre-Cambrian (pre-Grenvillian) age of consolidation for the basement of the Baltic region and the Caledonian age of the early Paleozoic shelf basin of Pomerania and of the northern part of the Polish Basin (located in the epi-Caledonian platform) define the limits for discussion of the geology and hydrocarbon prospectivity in the Polish sector of Baltic Sea and in adjacent areas (Fig. 1).

## DATA USED AND METHODS

The petroleum and regional geology of the Polish sector of the Baltic Sea and of adjacent areas has been discussed in numerous papers (Witkowski 1989, 1990*a*, *b*; Dadlez 1990, 1993; Kiełt, 1990; Pokorski, 1990; Ryka, 1990; Wagner, 1990; Mojski *et al*., 1995; Karnkowski, 1996, 1999, 2000, 2003; Karwasiecka and Bruszewska, 1997; Jaworowski, 2000*a*, *b*; Wolnowski, 2002, 2003; Kotarba *et al*., 2003, 2004; Pikulski, 2004; Fig. 4). The results discussed here are compiled from their published and non-published materials. The basic geological data come from numerous prospecting investigations of the Polish Gas and Oil Company and of “Petrobaltic” Company. These investigations enabled the realization of several geological projects, many of which were completed with the discovery of new hydrocarbon deposits (Karnkowski, 2003). It should be mentioned that at the beginning of “Petrobaltic” activity (years 1975–1990) much geological information was secret. During last 10–15 years the geological results of “Petrobaltic” studies were made more available (Domżalski and Mazurek, 2003). Data on deposits located onshore are accessible e.g., in the monograph on the petroleum geology of Poland (Karnkowski P., 1999). In spite of the discovery of relatively small hydrocarbon deposits in the Polish sector of the Baltic Sea and in the adjacent areas this region is still interesting as regards further prospecting.

In the Polish part of the Baltic region the evolution of the maturity of organic matter has been modelled by the first author (Karnkowski, 1996, 1999, 2000, 2003). The methodology and input data have been discussed in the papers cited. In the present compilation the results of previous research have been used. In the previous papers not all results were published and the cross-sections with organic matter maturity zones and map the “gas window” as the potential “shale gas” fields in the Silurian deposits are presented here for the first time.

## SOURCE ROCKS, RESERVOIRS AND SEAL ROCKS

Petroleum plays of the southern Baltic and adjacent areas must be considered separately for Eastern and Western Pomerania. In the Peribaltic Syneclise we can only take into consideration organic matter present within the lower Paleozoic rocks, particularly as it refers to the Middle and Upper Cambrian, Tremadocian, Caradocian and Llandovery. All these successions contain organic matter of marine origin (kerogen type II). The best source rocks are the Upper Cambrian and Tremadocian deposits where TOC content is 1–18% (Kanev *et al*., 1994). In the other successions organic matter is less than 1% (Kanev *et al*., 1994).

The Western Pomerania petroleum play shows two separate source rock units. The older one consists of Carboniferous deposits with organic matter of terrestrial origin (upper Carboniferous deposits with 1% TOC average and lower Carboniferous rocks with average 0.5% TOC).

The second petroleum system is related to the carbonates of the Zechstein Main Dolomite (Ca2). This is a closed system, i.e. source rocks and reservoirs are both sealed by Zechstein evaporates. This is a very profitable arrangement because the hydrocarbons generated did not need to migrate for long distances

The content of organic matter within the Main Dolomite is variable. The highest values of TOC are distinguished within the barrier zone and adjacent palaeogeographic elements. In the basin facies the average TOC content is 0.1–0.2% and in barrier facies it is higher though not impressive – 0.3–0.4% TOC (Kotarba *et al*., 2003, 2004).

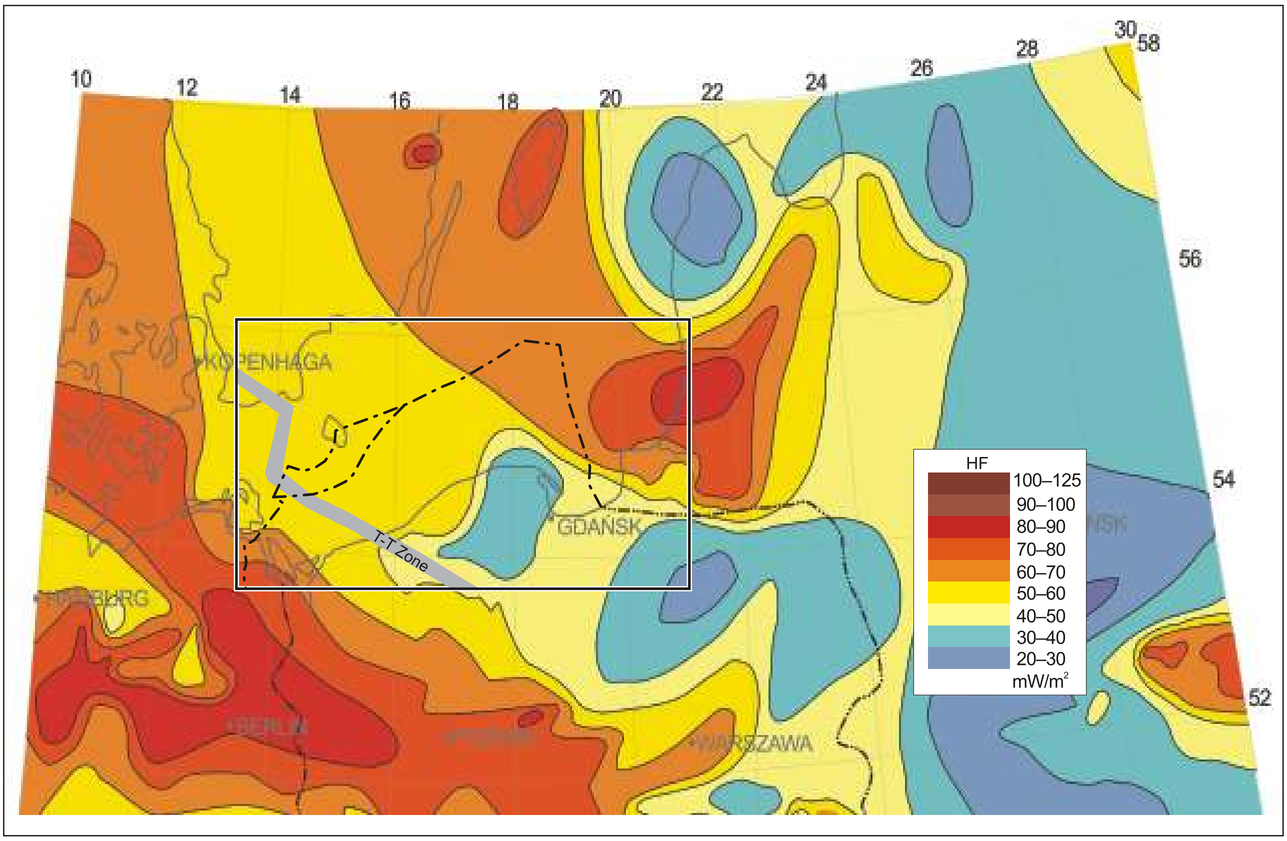


**Fig. 4. Map of the recent heat flow in the study area (rectangle) and adjacent regions (after Karwasiecka and Bruszewska, 1997)**

The Cambrian quartzitic sandstones are reservoirs in Eastern Pomerania and in the adjacent offshore area (Schleicher *et al*., 1998). Their thickness varies between 120 metres in the Baltic Sea region up to 60 metres in the onshore. The porosity is strongly variable and depends first of all on the depth. Generally the porosity is less than 5% below 3000 metres depth (Weil, 1990; Semyrka *et al*., 2010). It is influenced by diagenetic, temperature-dependent processes transforming siliceous quartz-sandstones into quartzites. In zones characterized by good petrophysical parameters porosity reaches 14% but permeability has 24 mD maximum (Weil, 1990). Regional sealing is provided by Upper Cambrian and Ordovician claystones and shales. The Silurian claystones give an additional seal (Zdanaviciute and Lazauskiene, 2004).

In Western Pomerania Carboniferous or the Rotliegend clastics are gas reservoirs sealed by Zechstein evaporates: if the Rotliegend rocks are missing the role of reservoirs belongs to the porous Carboniferous clastics (Kozłowska, 2005). The porosity and permeability of clastic rocks are strongly variable. This is particularly so for the Rotliegend conglomerates characterized by very low porosity/permeability values (Rusek *et al*., 2005). Reservoirs within the Main Dolomite unit are grainstones and packstones connected to the barrier and lagoonal facies. The present good porosity/permeability parameters are the effects of complex diagenesis processes. As a result fractures have been formed and were later filled with oil (Karnkowski, 1993). The Main Dolomite deposits are very well sealed by the Stassfurt evaporates.

## GENERATION AND MIGRATION OF HYDROCARBONS

The problems of hydrocarbon generation regard first of all the reconstruction of time, place (space) and the extent of processes leading to the transformation of organic matter into liquid or gaseous hydrocarbons. In the onshore part of the Baltic Basin the results of computer-aided modelling show that the main phase of hydrocarbon generation was not later than at the end of Carboniferous time (Karnkowski, 2003; Wróbel *et al*., 2009). The same conclusions are valid for the offshore area north of the Łeba–Gdańsk coastal line. Permian–Mesozoic palaeotectonic events in the area discussed have contributed mainly to the migration and accumulation of hydrocarbons. The best reservoir properties are in the Middle Cambrian sandstones (Sikorska and Pacześna, 1997) and consequently they constitute primary exploration targets. On the basis of modelling in Eastern Pomerania (Karnkowski, 2003) and analysis of the Gdańsk offshore area a map of hydrocarbon zones at the top of Cambrian was prepared (Fig. 5A): the "oil window" at the top of the Upper Cambrian is relatively narrow in the onshore area and considerably wider in the Gdańsk Bay and adjacent offshore region. The "gas window" dominates in the onshore area and continues offshore within the Słupsk Block (Fig. 3). The marginal part of the EEC is located in the overmature zone ($R_o$ >2%), so within the Upper Cambrian rocks only dry gas may be expected (Fig. 5A).

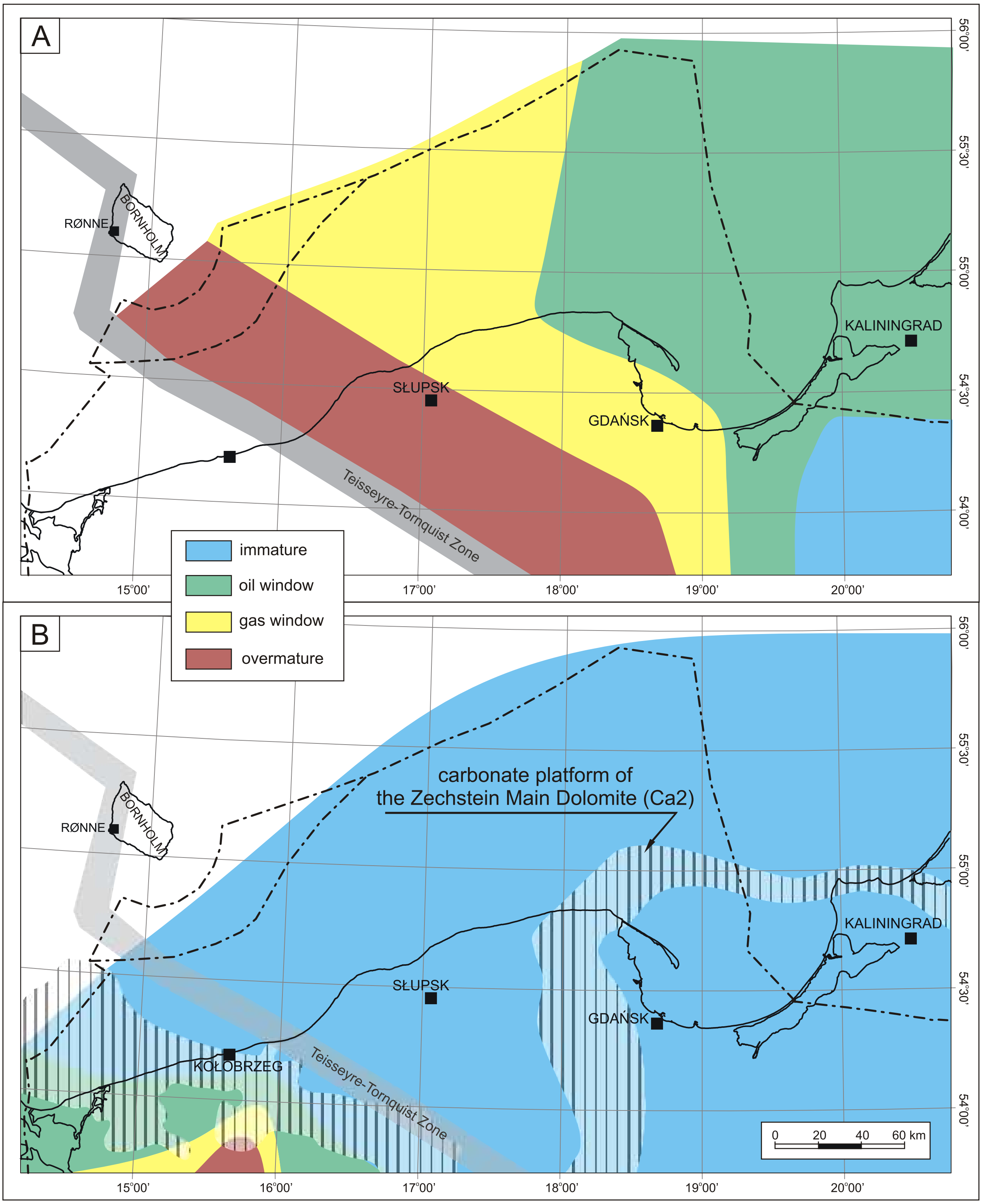


**Fig. 5. Extent of hydrocarbon zones in the main exploration targets**

**A** – at the top of Cambrian (Eastern Pomerania; Karnkowski, 2003, extended and supplemented); **B** – in the Zechstein Main Dolomite (Karnkowski, 1999, 2000, extended and supplemented); other explanations as in Figure 1

A very important element in the analysis of hydrocarbon generation here are oil fields discovered in the Kaliningrad District. Also, the lack of significant petroleum discoveries in the onshore Gdańsk region demands additional explanation. It seems that the preliminary answer for the above paradox regards the present heat flow distribution in the Central Europe (Fig. 4), including the Kaliningrad District (Plewa *et al.*, 1992; Karwasiecka and Bruszewska, 1997). North to the Polish state border (north to the Mazury and Warmia region) a high and distinct geothermal anomaly is marked which embraces not only the Kaliningrad District but also all of Lithuania (*cf.*, Karnkowski, 2003). This phenomenon, a relatively high value of the organic matter maturity in the Lithuanian part of the Baltic region that Lazauskiene and Marshall (2002) recently analysed. In Poland, within the Mazury High area, a large negative heat flow anomaly can be observed. The geothermal field of the northern slope of the Mazury High is characterized by rapid change from a low to a high value of heat flow (Fig. 4). The presence of the Lithuanian geothermal anomaly, with a prolongation to the Kaliningrad District, can explain the good palaeogeothermal conditions for hydrocarbon generation in the Paleozoic source rocks despite their shallow burial.

In the last few years a couple of papers referring to hydrocarbon generation in the Peribaltic Syneclise were published (Nehring-Lefeld *et al.*, 1997; Swadowska and Sikorska, 1998; Grotek, 1999). For geological analysis, vitrinite reflectance diversity was used. The results of the analysis suggest that the Paleozoic palaeogeothermal gradient was higher than the present one, and the main factor controlling the transformation of organic matter into hydrocarbons was the depth of burial. Hence in the border zone of the EEC the $R_o$ within the lower Paleozoic rocks is relatively high.

Western Pomerania, in the last few years, has been intensively studied and geologically modelled to establish the conditions of hydrocarbon generation for the Carboniferous–Rotliegend and the Zechstein deposits (Karnkowski, 1996, 1999, 2000; Kosakowski *et al.*, 2009). The results of geological modelling of the early Paleozoic generation conditions (Karnkowski, 1996) here indicate high heat flow values. High palaeoheat flow in the late Paleozoic degraded cellulose into nitrogen. In northwestern Poland the methane content in the Carboniferous and the Rotliegend reservoirs varies between 50–15%. A higher nitrogen content is known in the western part of Pomerania, close to the Odra River. In Eastern Germany the content of nitrogen exceeds 90%.

In the late Zechstein heat flow values significantly decreased in relation to the previous period (Karnkowski, 1996). The heat flow pattern in Western Pomerania during the period from the late Permian to the present has not changed fundamentally (Karnkowski, 1996). These palaegeothermal conditions caused that the Main Dolomite deposits entered very late into the phase of petroleum generation, in the early Cretaceous, and in a way this process continues until today (Karnkowski, 2000). Differentiation of thermal field and burial history caused that the "oil window" zone in Western Pomerania is limited to a narrow belt, 5–30 km in width (Fig. 5B). All oil fields in the Main Dolomite unit discovered within the area discussed are in the modelled "oil window" (Karnkowski, 1999, 2000, 2007*a*). This reason restrict the area of exploration to a narrow belt, but it enables concentrating of exploration targets in better specified regions. Unfortunately, the offshore area of the Main Dolomite occurrence in the area of Pomerania Bay is located in the transition (oil-gas) zone of hydrocarbon generation. The chances of oil or gas discoveries are limited to the southern part of Pomerania Bay.

## HISTORY OF PETROLEUM EXPLORATION

Petroleum exploration in Northern Poland began in the 1950s. At first the East European Platform was investigated, but small oil fields were discovered only in the onshore peribaltic zone (Table 1). As a result of exploration activity (1955–2001) in the onshore Pomerania region four oil fields in Cambrian sandstones and seven gas fields in Carboniferous sandstones, six gas fields in Rotliegend sandstones and eleven oil fields within the Zechstein Main Dolomite horizon were discovered. The occurrence of oil fields in Eastern Pomerania is limited mainly to the coast and offshore Baltic area in the Polish economic sector (Figs. 6 and 7; Table 1).

The foundation of the "Petrobaltic" Joint Venture (1975) gave a new impulse to exploration in the economic zones of Poland, the former Soviet Union, and the former German Democratic Republic. To date in the Polish economic sector offshore hydrocarbon fields have been discovered only in the Cambrian deposits north of Gdańsk Bay (Figs. 6 and 7A). Political and economic changes in Eastern Europe at the end of the 1980's transformed the International "Petrobaltic" Company into the solely Polish "Petrobaltic". The main activity of the present "Petrobaltic" has focused on exploitation of the fields discovered. New boreholes were drilled and field B4 started production in 1996. The next oil field B3 was ready for exploitation in 2006. From 2003 "Petrobaltic" started to transform as a private company and now the LOTOS Group (a petrochemical company) is almost the sole owner of it.

The significant increase in resources in the Western Pomerania region was in the years 1970–1980 due to numerous boreholes (about 100). Oil fields were quickly developed and almost all oil reserves were exploited. Gas in this region contains 50–60% methane and sometimes less (Table 1). Not all gas fields were developed and only half of the resources were exploited. The last 25 years of exploration in this area did not yield significant successes.

## NON-CONVENTIONAL PETROLEUM RESOURCES

A general overview of the prospective exploration area with regard to conventional elements of petroleum play was provided by Karnkowski (2007*b*) in the paper concerning petroleum provinces in Poland. For the Cambrian deposits – in the area of Peribaltic Syneclise – the oil production horizons are the

Table 1

**Oil and gas fields in the Polish part of the Baltic region: history of discoveries and resources**

| Field name | Discovery | Reservoir stratigraphy | Main fluid type | Discovered resources | Remarks |
|---|---|---|---|---|---|
| WESTERN POMERANIA | | | | | |
| Międzyzdroje E | 1970 | Rotliegend (P1) | Gas | 0.41 Bcm | 20–22% HC |
| Międzyzdroje W | 1971 | Rotliegend (P1) | Gas | 0.40 Bcm | 20–22% HC |
| Międzyzdroje | 1971 | Main Dolomite (Pz2) | Oil | 0.118 MMt | |
| Przytór | 1971 | Rotliegend (P1) | Gas | 0.48 Bcm | 20–22% HC |
| Wierzchowo | 1971 | Carboniferous (C1) | Gas | 0.55 Bcm | 70% HC |
| Kamień Pomorski | 1972 | Main Dolomite (Pz2) | Oil | 4.7 MMt | associated gas: 12% $H_2S$, 80 HC |
| Petrykozy | 1974 | Main Dolomite (Pz2) | Oil | 0.027 MMt | |
| Rekowo | 1975 | Main Dolomite (Pz2) | Oil | 0.096 MMt | associated gas: 5% $H_2S$ |
| Wrzosowo | 1975 | Carboniferous (C2) | Gas | 0.73 Bcm | 40% HC |
| Gorzysław N | 1976 | Carboniferous (C2) | Gas | 1.68 Bcm | 40–45% HC |
| Gorzysław S | 1976 | Carboniferous (C2) | Gas | 0.59 Bcm | 40–45% HC |
| Trzebusz | 1978 | Carboniferous (C2) | Gas | 0.14 Bcm | 40–45% HC |
| Wysoka Kamieńska | 1978 | Main Dolomite (Pz2) | Oil | 1.4 MMt | associated gas: 91% HC |
| Błotno | 1980 | Main Dolomite (Pz2) | Oil | 0.165 MMt | associated gas: 5% $H_2S$ |
| Daszewo | 1980 | Main Dolomite (Pz2) | Oil | 0.567 MMt | |
| Daszewo N | 1980 | Carboniferous (C2) | Gas | 1.79 Bcm | 65% HC |
| Daszewo N ropa | 1980 | Main Dolomite (Pz2) | Oil | 0.1 MMt | |
| Ciechnowo | 1981 | Rotliegend (P1) | Gas | 0.83 Bcm | 45–47% HC |
| Białogard | 1982 | Rotliegend (P1) | Gas | 0.74 Bcm | 52% HC |
| Brzozówka | 1989 | Main Dolomite (Pz2) | Oil | 0.124 MMt | |
| Tychowo | 1989 | Main Dolomite (Pz2) | Oil | 0.042 MMT | |
| Sławoborze | 2001 | Main Dolomite (Pz2) | Oil | 0.155 MMt | 0.475 Bcm of gas |
| EASTERN POMERANIA | | | | | |
| Dębki | 1972 | Cambrian | Oil | 0.43 MMt | associated gas: 95% HC |
| Żarmowiec | 1972 | Cambrian | Oil | 0.5 MMt | associated gas: 95% HC |
| Żarnowiec W | 1973 | Cambrian | Oil | 0.055 MMt | |
| Białogóra E | 1990 | Cambrian | Oil | 0.0145 MMt | |
| OFFSHORE (Polish part of the Balic Sea) | | | | | |
| B3 | 1981 | Cambrian | Oil | 5.3 MMt | water depth: 80 m |
| B4 | 1981 | Cambrian | Gas | 2.0 Bcm | water depth: 60 m |
| B6 | 1982 | Cambrian | Gas | 1.8 Bcm | water depth: 70 m |
| B8 | 1983 | Cambrian | Oil | 3.7 MMt | water depth: 80 m |

Middle Cambrian sandstones. The oil and gas fields discovered up to now (especially in the offshore Baltic area and Kaliningrad District) show that main type of trap is a close-to-fault anticline. Reservoir properties decrease with increased depth. Considering the large occurrence of Cambrian rocks it was stated that almost in whole area of the Polish part of the EEC these deposits have exploration perspectives. There is a problem of reservoir rocks with low petrophysical parameters such as the Cambrian sandstones lying deeper on the slope of the Peribaltic Syneclise (tight gas sandstone type).

A general review of the tight gas and shale gas potential in Poland is given in paper of Poprawa and Kiersnowski (2008). For the shale gas perspectives the Upper Ordovician and the lower Silurian shales in the Polish part of the EEC are indicated (Grotek, 2009; Klimuszko, 2009). The results of geological modelling (Karnkowski, 2003) suggest the possible occurrence of such gas deposits in the Peribaltic Syneclise. The modelled geological as well as economic conditions will be a positive factor if the petrophysical-geochemical parameters of these rocks enable realization of the "shale gas" projects.

The present world exploration tendencies indicate increasingly more possibilities for gas from unconventional (tight gas and shale gas) deposits. Specification of exploitation of unconventional petroleum resources does not prefer (at least presently) offshore areas for exploration of this type of deposit in the southern Baltic region. Rather good perspectives, however, exist within the onshore Peribaltic area (Fig. 8). It seems most reasonable was to concentrate on conventional gas structures with low porosity/permeability values. The objects are known and only a stimulation process is necessary. To prepare such stimulation a large amount of geological information is required concerning:

– technology of stimulation,
– content of gas in reservoir rocks and possibilities of its exploitation,

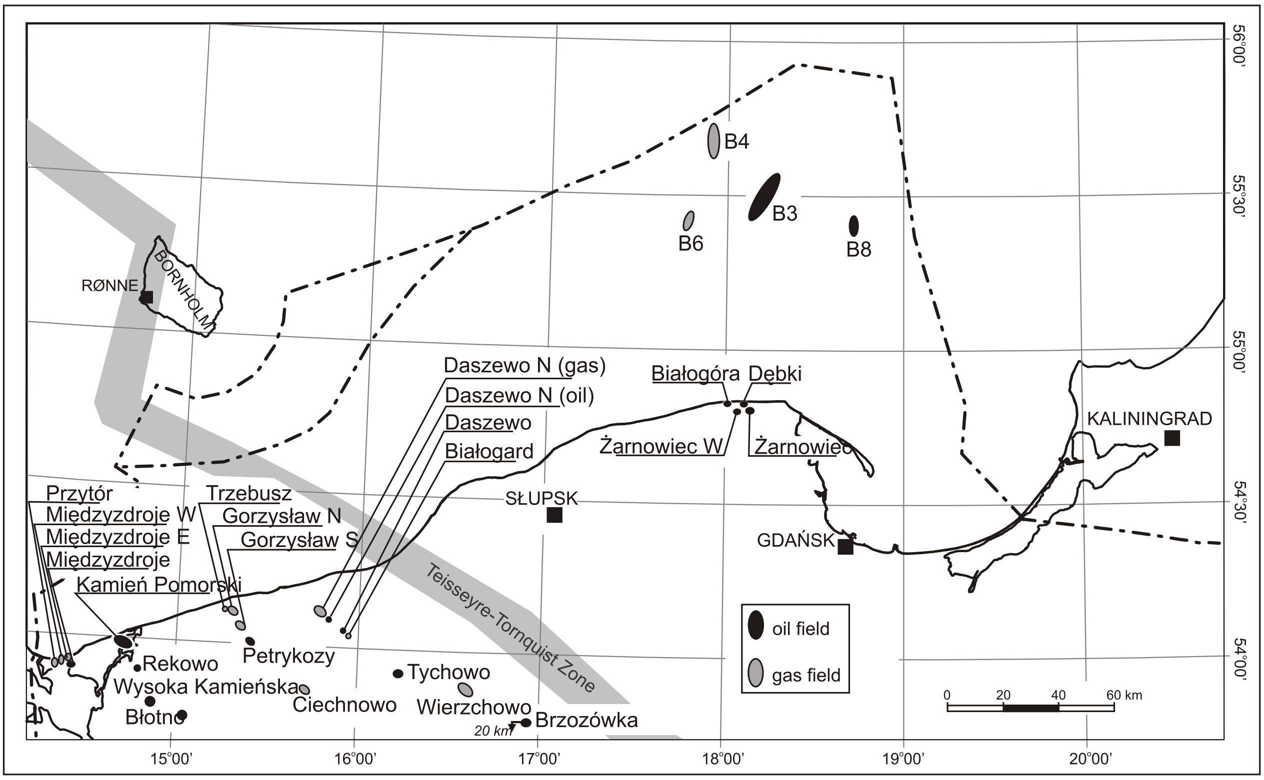


**Fig. 6. Oil and gas fields in the Pomerania region and adjacent offshore area (after Karnkowski, 1993 and "Petrobaltic" data)**

Explanations as in Figure 1

- geochemical and petrophysical properties of source and reservoir rocks,
- petrology of the rocks in terms of their sedimentary environment, lithofacies, mineralogy, pore structure and types of matrix,
- pattern of joints (both existing and future – those which have to arise as result of the stimulation process),
- geomechanical properties of the rocks,
- comparative study on similar conditions and technology in other petroleum provinces.

In the author's opinion the Cambrian rocks of the EEC should be the first object of interest: a petroleum system is proved by the existence of oil and gas fields in the Cambrian deposits, seismic acquisition and processing gives good results in structural investigation and the present state of and successes in hydraulic stimulation of tight gas reservoirs in Poland guarantees a reasonable level of exploration economy. Further activity should be to explore the Upper Ordovician and the lower Silurian shales located in the marginal zone of the EEC.

## CONCLUSIONS

1. The analysis of burial and thermal history of the Paleozoic successions in the southern Baltic area (western part of the Baltic Basin) shows a vast area within the oil window. It is much greater than in the onshore area, explaining the occurrence of oil fields in the offshore Baltic.

2. Cambrian traps for oil have a structural form and they are associated with faults along which migration of hydrocarbons occurred.

3. In the area of the "gas window" and of "dry gas" ($R_o$ >2%) reservoir properties of the Cambrian rocks are rather low due to intense diagenetic processes (tight gas). Acquisition of gas should be possible by processes of hydraulic intensification of exploitation.

4. Lower Paleozoic rocks rich in organic matter, especially in the border zone of the EEC ($R_o$ >1.3%), could be an area of unconventional gas fields (shale gas). The most prospective area is onshore located, and may be profitable as regards the economy of future shale gas.

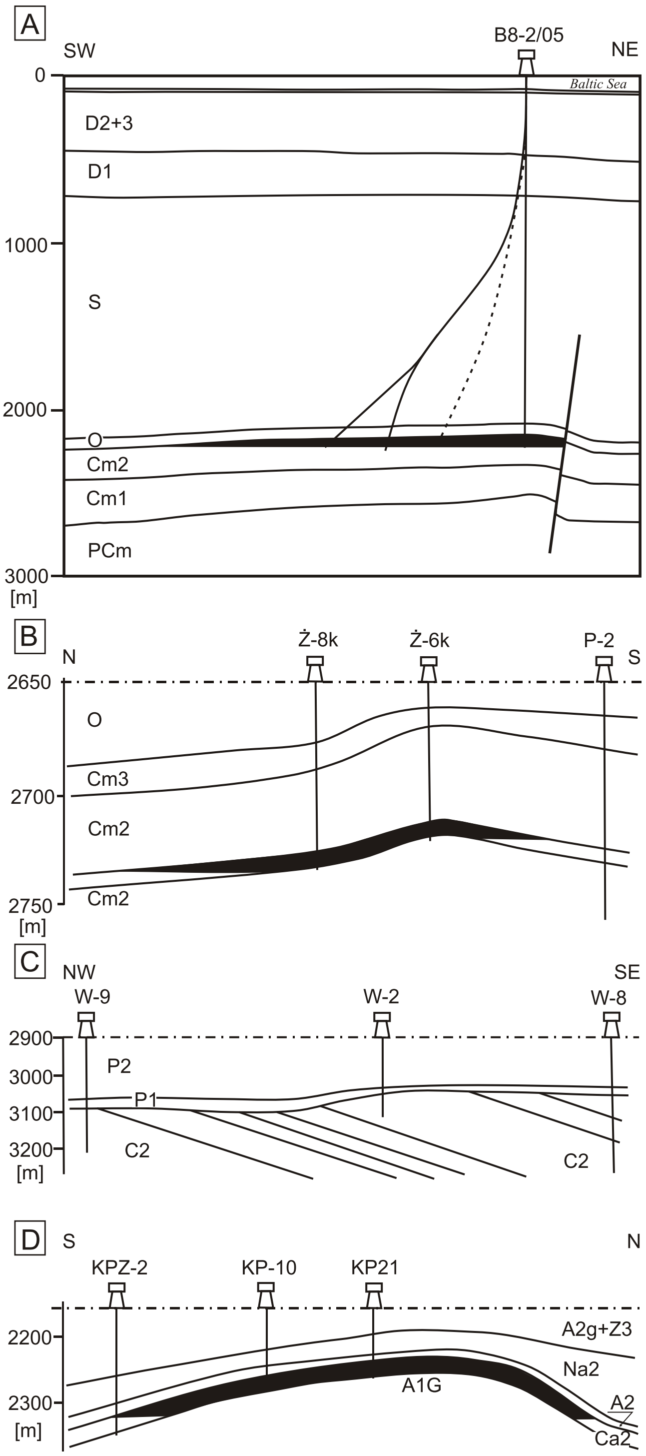


**Fig. 7. Selected examples of the oil and gas fields in the Pomerania region and adjacent offshore area**

**A** – B8-2/05 (oil field); **B** – Żarnowiec W (oil field); **C** – Wrzosowo (gas field); **D** – Kamień Pomorski (oil field; after Karnkowski, 1993 and "Petrobaltic" unpubl. data); PCm –Precambrian, Cm1 – Lower Cambrian, Cm2 – Middle Cambrian, Cm3 – Upper Cambrian, O – Ordovician, S – Silurian, D1 – Lower Dewonian, D2+3 – Middle and Upper Devonian, C2 – upper Carboniferous, P1 – Rotliegend, P2 – Zechstein, A1G – Upper Anhydrite, Ca2 – Main Dolomite, A2 – Basal Anhydrite, Na2 – Older Halite, A2G+Z3 – Screening Anhydrite and Leine cyclothem

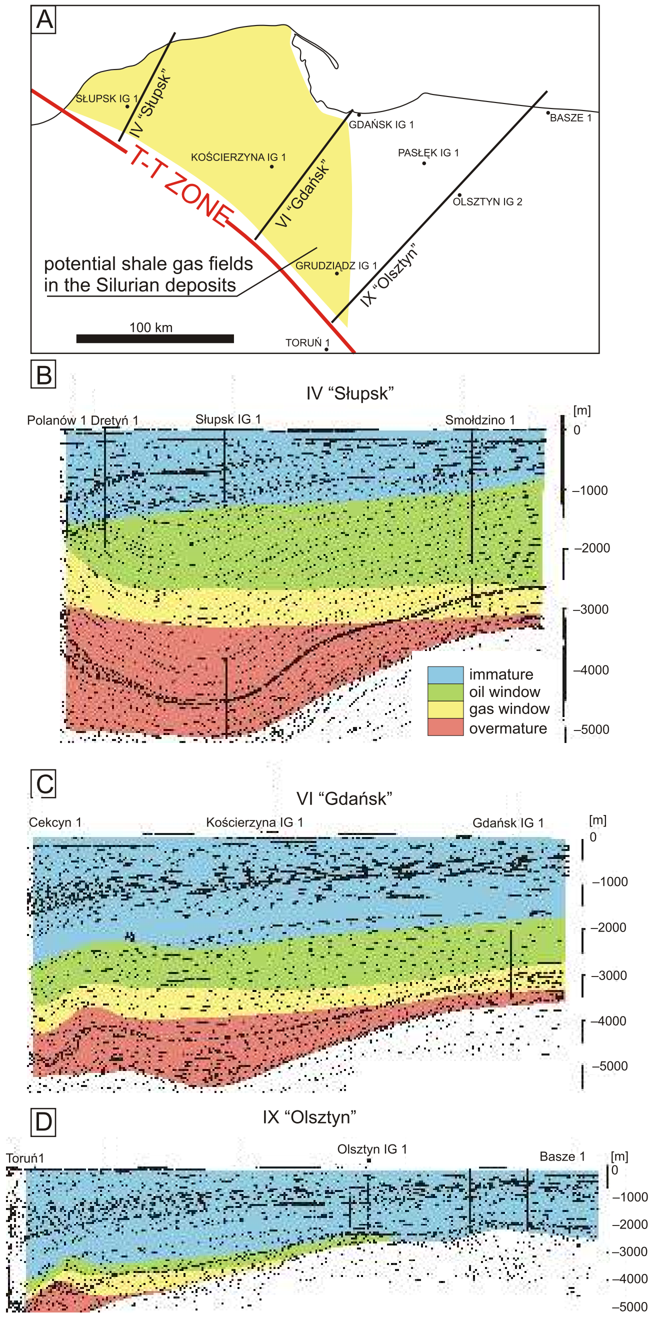


**Fig. 8. Potential "shale gas" fields in the Pomerania area**

**A** – extent of the "gas window" in the Silurian deposits; **B–D** – cross-sections showing extent of hydrocarbon zones (after Karnkowski, 2003, supplemented)

5. The southern Baltic lying on the west to the T-T line has petroleum systems: the upper Paleozoic (Carboniferous–Rotliegend) and the Zechstein (Main Dolomite carbonates) ones. This latter one is marked as a prospective area only in Pomerania Bay.

6. The Carboniferous–Rotliegend petroleum system in the southern Baltic is weakly explored. Partly the Rotliegend clastic rocks there are eroded or non-deposited. The Carboniferous rocks of Pomerania are strongly dislocated which make exploration of gas fields difficult. A content of gas with more than 50% of methane could be a positive element in evaluation of prospects. Shale gas exploration is not out of the question.

7. Hitherto discovered hydrocarbon deposits in Cambrian rocks, especially within the offshore zone, confirmed the good perspectives of the Gdańsk Petroleum Province.

8. To the west of the T-T Zone extends the Pomerania Petroleum Province the perspectives of which are only partly proved by boreholes. Offshore in the Pomerania Bay is an exploration challenge.

**Acknowledgments**. The authors wish to express their gratitude to Dr. Hilmar Rempel and the second anonymous reviewer who gave their time and energy ensuring the quality of the published paper. We are extremely grateful for their commitment and dedication to the peer review process.

## REFERENCES

AREŃ B. and LENDZION K. (1978) – Charakterystyka stratygraficzno-litologiczna wendu i kambru dolnego In: Wybrane problemy stratygrafii i litologii wendu oraz dolnego kambru na platformie prekambryjskiej w Polsce (ed. B. Areń). Pr. Inst. Geol., **90**: 1–49.

BEŁKA Z. and NARKIEWICZ M. (2008) – Devonian. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 383–410. Geol. Soc., London.

BRANGULIS A. P., KANEV S. V., MARGULIS L. S. and POMERANTSEVA R. A. (1993) – Geology and hydrocarbon prospects of the Paleozoic in the Baltic region. In: Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference (ed. J. R. Parker): 651–656. Geol. Soc., London.

DADLEZ R. (1978) – Sub-Permian Rock Complexes in the Koszalin-Chojnice Zone (in Polish with English summary). Kwart. Geol., **22** (2): 269–301.

DADLEZ R. (1980) – Tectonics of the Pomeranian Swell (NW Poland) (in Polish with English summary). Kwart. Geol., **24** (4): 741–768.

DADLEZ R. (1987) — Phanerozoic basinal evolution along the Teisseyre-Tornquist Zone (in Polish with English summary). Kwart. Geol., **31** (2–3): 263–278.

DADLEZ R. (1990) – Tectonics of the southern Baltic (in Polish with English summary). Kwart. Geol., **34** (1): 1–20.

DADLEZ R. (1993) – Pre-Cainozoic tectonics of the Southern Baltic Sea. Geol. Quart., **37** (3): 431–450.

DADLEZ R. (2000) – Pomerania Caledonides (NW Poland), fifty years of controversies: a review and a new concept. Geol. Quart., **44** (3): 221–236.

DOBROVA H., KOLLY E. and SCHMITZ U. (2003) – E & P Ventures in the Eastern-Central Europe Transformation States after 1989 – a review of Expectations and Results. OIL GAS European Magazine, **29** (4): OG 1–8.

DOMŻALSKI J., GÓRECKI W., MAZUREK A., MYŚKO A., STRZETELSKI W. and SZAMAŁEK K. (2004) – The prospects for petroleum exploration in the eastern sector of Southern Baltic as revealed by sea bottom geochemical survey correlated with seismic data. Prz. Geol., **52** (8/2): 792–799.

DOMŻALSKI J. and MAZUREK A. (2003) — Petrobaltic – dzisiaj. Prz. Geol., **51** (9): 791–793.

ELMGREN R. (2001) – Understanding human impact on the Baltic ecosystem: changing views in recent decades. Ambio, **30**: 222–231.

FRANKE D. (1994) – The deformational history of the Caledonian terranes at Baltica's southwestern margin. Z. Geol. Wiss., **22** (1\2): 67–80.

GEYER G., ELICKI O., FATKA O. and ŻYLIŃSKA A. (2008) – Cambrian. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 155–202. Geol. Soc., London.

GROTEK I. (1999) – Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland). Geol. Quart., **43** (3): 297–308.

GROTEK I. (2009) – Charakterystyka petrograficzna i dojrzałość termiczna materii organicznej z utworów syluru na obszarze kratonu wschodnioeuropejskiego. Prz. Geol., **57** (4): 300–301.

JAROSIŃSKI M., PORAWA P. and ZIEGLER P. A. (2009) – Cenozoic dynamic evolution of the Polish Platform. Geol. Quart., **53** (1): 3–26.

JAWOROWSKI K. (1979) – Transgresja morza kambryjskiego w północnej Polsce. Pr. Inst. Geol., **94**: 5–80.

JAWOROWSKI K. (1982) – Warunki sedymentacji osadów prekambru i kambru w północnej Polsce. Prz. Geol., **30** (5): 220–224.

JAWOROWSKI K. (2000*a*) – Facies variability in the Cambrian deposits from the Kościerzyna and Gdańsk sections (Pomeranian Caledonides foreland, northern Poland): a comparative study. Geol. Quart., **44** (3): 249–260.

JAWOROWSKI K. (2000*b*) – Facies analysis of the Silurian shale-siltstone succession in Pomerania (northern Poland). Geol. Quart., **44** (3): 297–315.

KANEV S., MARGULIS L., BOJESEN-KOEFOED J. A., WEIL W. A., MERTA H. and ZDANAVICIUTE O. (1994) – Oils and hydrocarbon source rocks of the Baltic syneclise. Oil and Gas J., **92** (28): 69–73.

KARNKOWSKI P. (1979) – Wgłębne przekroje geologiczne przez Niż Polski. Wyd. Geol., Warszawa.

KARNKOWSKI P. (1993) – Złoża gazu ziemnego i ropy naftowej w Polsce. Niż Polski, **1**. Tow. Geosynoptyków "Geos", AGH, Kraków.

KARNKOWSKI P. (1999) – Oil and gas deposits in Poland. The Geosynoptics Soc. "Geos", Kraków.

KARNKOWSKI P. H. (1996) – Historia termiczna a generacja węglowodorów w rejonie struktury Dobrzycy (Pomorze Zachodnie). Prz. Geol., **44** (4): 349–357.

KARNKOWSKI P. H. (1999) – Origin and evolution of the Polish Rotliegend Basin. Pol. Geol. Inst. Spec. Pap., **3**.

KARNKOWSKI P. H. (2000) – Thermal history and modelling of hydrocarbon generation and expulsion in the area of Western Pomerania (NW Poland) (in Polish with English summary). Nafta-Gaz, **56** (5): 271–287.

KARNKOWSKI P. (2003) – Modelling of hydrocarbon generating conditions within Lower Palaeozoic strata in the western part of Baltic Basin (in Polish with English summary). Prz. Geol., **51** (9): 756–763.

KARNKOWSKI P. H. (2007*a*) – Permian Basin as a main exploration target in Poland. Prz. Geol., **55** (12\1): 1003–1015.

KARNKOWSKI P. H. (2007*b*) – Petroleum provinces in Poland. Prz. Geol., **55** (12\1): 1061–1067.

KARWASIECKA M. and BRUSZEWSKA B. (1997) – Gęstość powierzchniowego strumienia cieplnego ziemi na obszarze Polski. Unpubl. Rep., Centr. Arch. Geol., Państw. Inst. Geol., Warszawa.

KIEŁT M. (1990) – Solution to the selected geological problems of the Southern Baltic area with the use of dip logging. Kwart. Geol., **34** (1): 113–136.

KIERSNOWSKI H. and BUNIAK A. (2006) – Evolution of the Rotliegend Basin of northwestern Poland. Geol. Quart., **50** (1): 119–138.

KLIMUSZKO E. (2009) – Ocena utworów syluru polskiej części kratonu wschodnioeuropejskiego w aspekcie możliwości generacji węglowodorów. Prz. Geol., **57** (4): 303.

KNIESZNER L., KALISZ T. and POLESZAK E. (2000) – Możliwości odkrycia złóż węglowodorów w rejonie Dobrzycy na Pomorzu Zachodnim. Prz. Geol., **48** (5): 455–561.

KOSAKOWSKI P., BURZEWSKI W. and KOTARBA M. J. (2003) – Petroleum potential of the Main Dolomite strata of the Kamień Pomorski area (northern Poland). Part 2 – Petroleum generation and expulsion processes (in Polish with English summary). Prz. Geol., **51** (8): 663–672.

KOSAKOWSKI P., KOTARBA M. J. and WRÓBEL M. (2009) – Zechstein Petroleum System in the Western Pomerania, NW Poland. Abstracts of the 71th EAGE Conference and Exhibition, Amsterdam, The Netherlands: P173.

KOTARBA M. J., KOSAKOWSKI P., WIĘCŁAW D., GRELOWSKI C., KOWALSKI A., LECH S. and MERTA H. (2004) – Hydrocarbon potential of Carboniferous source rocks on the Baltic part of Pomeranian Segment of the Middle Polish Trough (in Polish with English summary). Prz. Geol., **52** (12): 1156–1165.

KOTARBA M. J., KOSAKOWSKI P., WIĘCŁAW D. and KOWALSKI A. (2003) – Petroleum potential of the Main Dolomite strata of the Kamień Pomorski area (northern Poland). Part 1 – Source rock (in Polish with English summary). Prz. Geol., **51** (7): 587–594.

KOTARBA M. J., POKORSKI J., GRELOWSKI C. and KOSAKOWSKI P. (2005) – Origin of natural gases accumulated in Carboniferous and Rotliegend strata on the Baltic part of the Western Pomerania (in Polish with English summary). Prz. Geol., **53** (5): 425–433.

KOZŁOWSKA A. (2005) – Wpływ kompakcji i cementacji na porowatość piaskowców karbonu górnego w strefie Kołobrzeg-Międzyzdroje. Prz. Geol., **53** (3): 259.

KRAMARSKA R. (1991) – Warunki geologiczne występowania żwirów w obszarze południowobałtyckim. Inż. Mor., **3**: 98–100.

KRAMARSKA R., KRZYWIEC P., DADLEZ R., JEGLIŃSKI W., PAPIERNIK B., PRZEZDZIECKI P. and ZIENTARA P. (1999) – Geological Map of the Baltic Sea Bottom Without Quaternary Deposits (in Polish with English summary). Państw. Inst. Geol., Gdańsk–Warszawa.

KRAWCZYK C. M., McCANN T., COCKS L. R. M., ENGLAND R., McBRIDE J. and WYBRANIEC S. (2008) – Caledonian tectonics. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 303–382. Geol. Soc., London.

KRONER U., MANSY J.-L., MAZUR S., ALEKSANDROWSKI P., HANN H. P., HUCKRIEDE H., LACQUEMENT F., LAMARCHE J., LEDRU P., PHARAOH T. C., ZEDLER H., ZEH A. and ZULAUF G. (2008) – Variscan tectonics. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 599–664. Geol. Soc., London.

LAZAUSKIENE J. and MARSHALL J. (2002) – Chitinozoan reflectance and the thermal history of the Lower Palaeozoic sediments of the Baltic Basin. The Fifth Baltic Stratigraphic Conference, Wilno: 93–97.

LECH S. (1993) – Mapa geologiczna podłoża permu Pomorza Zachodniego, 1:200 000. Unpubl. Rep., Arch. B. G. “Geonafta”, Warszawa.

LENDZION K. (1970) – The Cambrian North-East Poland. In: Geology of Poland, **1**: 157–166. Inst. Geol.

LINNEMANN U., ROMER R. L., PIN C., ALEKSANDROWSKI P., BUŁA Z., GEISLER T., KACHLIK V., KRZEMIŃSKA E., MAZUR S., MOTUZA G., MURPHY J. B., NANCE R. D., PISAREVSKY S. A., SCHULZ B., ULRICH J., WISZNIEWSKA I., ŻABA J. and ZEH A. (2008) – Precambrian. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 21–101. Geol. Soc., London.

LIPIEC M. and MATYJA H. (1998) — Architektura depozycyjna basenu dolnokarbońskiego na obszarze pomorskim. Pr. Państw. Inst. Geol., **165**: 101–112.

LUND C.-E., GRAD M. and GUTERCH A. (1991) — Seismic structure of the Earth’s crust and lower lithosphere beneath the southern part of the Baltic Sea. Publ. Inst. Geoph. Pol. Acad. Sc., **A-19** (236): 63–83.

MALETZ J., BEIER H., KATZUNG G. and NIEDŹWIEDŹ A. (1997) – A Lower Palaeozoic (Ordovician-Silurian) foreland basin at the south-western rim of Baltica. Terra Nostra, **11**: 81–84.

MASŁOWSKA M. (1993) – Gravel accumulations in the southern Baltic – methods and results of exploration. Mar. Geores. Geotechnol., **11**: 175–180.

MASŁOWSKA M. (2002) – Natural aggregates deposits on the south Baltic bottom and problems with their accessibility (in Polish with English summary). Gór. Odkryw., **44** (2–3): 113–119.

MATYJA H. (2006) – Stratigraphy and facies development of Devonian and Carboniferous deposits in the Pomeranian Basin and in the western part of the Baltic Basin and palaeogeography of the northern TESZ during Late Palaeozoic times (in Polish with English summary). Pr. Państw. Inst. Geol., **186**: 79–122.

MATYJA H. (2009) – Depositional history of the Devonian succession in the Pomeranian Basin, NW Poland. Geol. Quart., **53** (1): 63–92.

McCANN T. (1998) – Lower Palaeozoic evolution of the northeast German Basin/Baltica borderland. Geol. Mag., **135**: 129–142.

McCANN T., SKOMPSKI S., POTY E., DUSAR M., VOZAROVA A., SCHNEIDER J., WETZEL A., KRAMER K., KOMPIHL K., SCHAFER A., KRINGS M., SOPLUSTIL S. and TAIT I. (2008) – Carboniferous. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 411–530. Geol. Soc., London.

MIŁACZEWSKI L. (1987) – Dewon. Straygrafia i charakterystyka litologiczna. In: Budowa geologiczna wału pomorskiego i jego podłoża (ed. A. Raczyńska). Pr. Inst. Geol., **119**: 16–21.

MODLIŃSKI Z. (1982) – The development of Ordovician lithofacies and palaetectonics in the area of the Precambrian platform in Poland (in Polish with English summary). Pr. Inst. Geol., **102**.

MODLIŃSKI Z., JACYNA J., KANEV S., KHUBLIDIKOV A., LASKOWA L., LASKOVAS J., LENDZION K., MIKAZANE I. and POMERANCEVA R. (1999) – Paleotectonic evolution of the Baltic Syneclise during Early Palaeozoic as documented by palaeothickness maps. Geol. Quart., **43** (3): 285–296.

MODLIŃSKI Z., NEHRING-LEFELD M. and RYBA J. (1994) – The Early Palaeozoic complex in the Polish part of the Baltic Sea. Z. Geol. Wiss., **22** (1/2): 227–234.

MODLIŃSKI Z. and PODHALAŃSKA T. (2010) – Outline of the lithology and depositional features of the lower Paleozoic strata in the Polish part of the Baltic region. Geol. Quart., **54** (2): 109–121.

MODLIŃSKI Z. and SZYMAŃSKI B. (1997) – The Ordovician lithostratigraphy of the Peribaltic Depression (NE Poland). Geol. Quart., **41** (3): 273–288.

MODLIŃSKI Z., SZYMAŃSKI B. and TELLER L. (2006) – The Silurian lithostratigraphy of the Polish part of the Peri-baltic Depression (N Poland). Prz. Geol., **54** (9): 787–796.

MOJSKI J. E., DADLEZ R., KENIG K., KRAMARSKA R., KRZYMIŃSKA J., MAKOWSKA A., MASŁOWSKA M., MICHAŁOWSKA M., PIKIES R., POKORSKI J., PRZEZDZIECKI P., RYKA W., SZCZEPAŃSKA T., TOMCZAK A., UŚCINOWICZ S., WAGNER R. and ZACHOWICZ J. (1995) – Atlas Geologiczny Południowego Bałtyku, 1:500 000. Państw. Inst. Geol., Warszawa.

NARKIEWICZ M., POPRAWA P., LIPIEC M., MATYJA H. and MIŁACZEWSKI L. (1998) – Pozycja paleogeograficzna i tektoniczna a rozwój subsydencji dewońsko-karbońskiej obszaru pomorskiego i radomsko-lubelskiego. Pr. Państw. Inst. Geol., **165**: 31–46.

NEHRING-LEFELD M., MODLIŃSKI Z. and SWADOWSKA E. (1997) – Thermal evolution of the Ordovician in the western margin of the East-European Platform: CAI and $R_o$ data. Geol. Quart., **41** (2): 129–138.

NOWICKA A. and WOLNOWSKA-ŚLEMP M. (2005) – The characteristics of upper Rotliegendes sediments in Western Pomerania and its potential reserves. Nafta-Gaz, **61** (4):145–149.

PIKULSKI M. (2004) – Analiza paleogeograficzna utworów dolomitu głównego (Ca2) zachodniej Polski w aspekcie poszukiwania złóż węglowodorów. Pr. Inst. Górn. Naft. i Gaz., **130**.

PLEWA M., PLEWA S., POPRAWA D. and TOMAŚ A. (1992) – Poland. In: Geothermal Atlas of Europe. Gotha.

POKORSKI J. (1990) – Rotliegendes in the northwesternmost Pomerania and the adjacent Batic Basin (in Polish with English summary). Kwart. Geol., **34** (1): 79–92.

POKORSKI J. (2010) – Geological section through the lower Paleozoic strata of the Polish part of the Baltic region. Geol. Quart., **54** (2): 123–130.

POKORSKI J. and MODLIŃSKI Z., eds. (2007) – Geological Map of the Western and Central Part of the Baltic Depression without Permian and Younger Deposits (in Polish with English summary). Państw. Inst. Geol., Warszawa.

POPRAWA P. and KIERSNOWSKI H. (2008) – Potential for shale gas and tight gas exploration in Poland (in Polish with English summary). Biul. Państw. Inst. Geol., **429**: 145–152.

POPRAWA P., KOSAKOWSKI P. and WRÓBEL M. (2010)– Burial and thermal history of the Polish part of the Baltic region. Geol. Quart., **54** (2):131–142.

POPRAWA P., NARKIEWICZ M., ŠLIAUPA S., STEPHENSON R. A. and LAZAUSKIENĖ J. (1997) – Caledonian accretion along the TESZ (Baltic region to SE Poland). Terra Nostra, **11**: 110–117.

POPRAWA P., ŠLIAUPA S., STEPHENSON R. A. and LAZAUSKIENĖ J. (1999) – Late Vendian-Early Paleozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis. Tectonophysics, **314** (1–3): 219–239.

POŻARYSKI W. (1987) – Paleozoik podpermski. In: Budowa geologiczna wału pomorskiego i jego podłoża (ed. A. Raczynska). Pr. Inst. Geol., **119**: 174–185.

RUSEK M., BUNIAK A., SOLARSKA A., KOWALCZAK M. and GAUPP R. (2005) – Piaskowce czerwonego spągowca i ich diageneza na obszarze Wału Pomorskiego (złoże Ciechnowo). Prz. Geol., **53** (4): 340–341.

RYKA W. (1990) – The crystalline basement of the Polish part of the southern Baltic (in Polish with English summary). Kwart. Geol., **34** (1): 21–36.

RYKA W. (1993) – Crystalline basement of the Polish part of the Baltic Sea. Geol. Quart., **37** (3): 329–344.

SANDERSON H., FAUSER P., THOMSEN M. and SØRENSEN P. B. (2009) – Human health risk screening due to consumption of fish contaminated with chemical warfare agents in the Baltic Sea. J. Hazardous Materials, **162** (1): 416–422.

SCHLEICHER M., KÖSTER J., KULKE H. and WEIL W. (1998) – Reservoir and source-rock characterisation of the early Palaeozoic interval in the peribaltic syneclise, northern Poland. J. Petrol. Geol., **21**: 33–56.

SEMYRKA R., JARZYNA J., SEMYRKA G., KAŹMIERCZUK M. and PIKULSKI L. (2010) – Reservoir parameters of lithostratigraphic successions of the lower Paleozoic strata in the Polish part of the Baltic region based on laboratory studies and well logs. Geol. Quart., **54** (2): 227–240.

SERVAIS T., DZIK J., FATKA O., HEUSE T., VECOLI M. and VERNIERS J. (2008) – Ordovician. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 203–248. Geol. Soc., London.

SIKORSKA M. and PACZEŚNA J. (1997) – Quartz cementation in Cambrian sandstones on the background of their burial history (Polish part of the East European Craton). Geol. Quart., **41** (3): 265–272.

SWADOWSKA E. and SIKORSKA M. (1998) – Historia pogrzebania skał kambru na podstawie refleksyjności macerałów witrynitopodobnych w polskiej części platformy wschodnioeuropejskiej. Prz. Geol., **46** (8/1): 699–706.

SZAREJKO A. and NAMIEŚNIK J. (2009) – The Baltic Sea as a dumping site of chemical munitions and chemical warfare agents. Chemistry and Ecology, **25**: 13–26.

SZCZEPANIK Z. (2000) – The Cambrian of the western part of the Pomeranian Caledonides foreland, Peribaltic Syneclise: microfloral evidence. Geol. Quart., **44** (3): 261–273.

ŚWIDROWSKA J. and HAKENBERG M. (1996) – Paleotectonic evolution of the Koszalin-Chojnice Late Devonian basin (Western Pomerania, Northern Poland). Bull. Pol. Acad. Sc. Earth Sc., **44** (1): 17–36.

TELLER L. (1974) – The Silurian of the margin of the East European platform in the region of Miastko-Chojnice (NW Poland). Acta Geol. Pol., **24** (4): 563–579.

TOMCZYKOWA E. (1988) – Silurian and Lower Devonian biostratigraphy and palaeoecology in Poland. Biul. Inst. Geol., **359**: 21–41.

USAITYTE D. (2000) – The geology of the southeastern Baltic Sea: a review. Earth Sc. Rev., **50**: 137–225.

VERNIERS J., MALETZ J., KRIZ J., ZIGAITE Z., PARIS F., SCHONLAUB H. P. and WRONA R. (2008) – Silurian. In: The Geology of Central Europe (ed. T. McCann), **1**: Precambrian and Palaeozoic: 249–302. Geol. Soc., London.

WAGNER R. (1990) — Zechstein in the western part of the Polish Baltic area. Kwart. Geol., **34** (1): 93–112.

WEIL W. (1990) – The reservoir properties of the Middle Cambrian sandstone deposits in the Łeba-Żarnowiec area in the light of the statistic analysis (in Polish with English summary). Kwart. Geol., **34** (1): 37–50.

WITKOWSKI A. (1989) — Atlas geologiczno-strukturalny południowej części Morza Bałtyckiego. Wyd. Geol., Warszawa.

WITKOWSKI J. (1990*a*) – Evolution and tectonics of the Lower Palaeozoic structural complex in the Southern Baltic (in Polish with English summary). Kwart. Geol., **34** (1): 51–66.

WITKOWSKI J. (1990*b*) – Geodynamical and geothermic conditions of oil and gas bearing in the Southern Baltic (in Polish with English summary). Kwart. Geol., **34** (1): 67–78.

WITKOWSKI J. (1993) – Geology and oil-gas bearing of the Lower Paleozoic formations of the Pomerania and Southern Baltic Sea. Biul. Państw. Inst. Geol., **366**: 39–55.

WOLNOWSKI T. (2002) – Perspectives of hydrocarbons explorations in NW Poland in light of Pila's experience (in Polish with English summary). Nafta-Gaz, **58** (1):11–20.

WOLNOWSKI T. (2003) – Forecasting of supply potential of the main dolomite in the Perm basin (in Polish with English summary). Nafta-Gaz, **59** (11): 536–546.

WRÓBEL M., KOTARBA M. J. and KOSAKOWSKI P. (2009) – Timing and Extent of Petroleum Processes in Lower Palaeozoic Petroleum System in Western Part of the Balic Basin. Abstracts of the 71th EAGE Conference and Exhibition, Amsterdam, The Netherlands: P177.

WRÓBEL M. and KOSAKOWSKI P. (2010) – 2-D modelling of petroleum processes of the lower Paleozoic strata in the Polish part of the Baltic region. Geol. Quart., **54** (2): 257–266.

ZACHOWICZ J., KRAMARSKA R. and UŚCINOWICZ S. (2004) – The Southern Baltic Sea – test field for international co-operation. Prz. Geol., **52** (8/2): 738–743.

ZDANAVICIUTE O. and LAZAUSKIENE J. (2004) – Hydrocarbon migration and entrapment in the Baltic Syneclise. Org. Geochem., **35** (4): 517–527.

ZIEGLER P. A. (1990) – Geological Atlas of Western and Central Europe. Shell Internat. Petrol. Maatschappij BV. Geol. Soc. Publ. House, Bath.

ZNOSKO J. (1986) – Polish Caledonides and their relation to the other European Caledonides. Ann. Soc. Geol. Pol., **56** (1): 33–52.

ŻELICHOWSKI A. M. (1987) – Development of the Carboniferous of the SW margin of East European Platform in Poland. Prz. Geol., **35** (5): 230–237.