Permian Basin as a main exploration target in Poland

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A b s t r a c t . The Polish Permian Basin (PPB) is a part of the Southern Permian Basin in the Western and the Central Europe. Results of burial and thermal analyses as well as a configuration of the Moho surface of the Polish Basin suggest the asymmetrical basin model. History of the Polish Basin reveals that the Late Permian and the Early Triassic periods represent the main rifting phase and its later development resulted from thermal relaxation. During the Late Triassic and the Jurassic time some cooling of rift heat field took place, but the turning point in thermal evolution of the Polish Basin was at the Jurassic/Cretaceous boundary when the south-western part of the Polish Basin was uplifted and intensively eroded.

The knowledge on the Permian Basin in Poland is chiefly connected with petroleum exploration. The gas fields are located mainly in the Rotliegend reservoirs. The Zechstein deposits, overlying the Rotliegend, are also in the area of economic interest: hydrocarbons occurring in carbonate deposits of the Werra (Zechstein Limestone — Ca1) and Stassfurt (Main Dolomite — Ca2) cyclothems.

Several tens gas fields have been hitherto discovered within the Rotliegend sandstones and the Zechstein limestones. Reservoirs are the clastic, terrestrial deposits of the Lower Permian and calcareous, biogenic carbonates of the Zechstein. Evaporates, mainly salts of the Werra cyclothem, are the regional sealing for the mentioned reservoirs. Natural gas accumulated in the Rotliegend sandstones and the Zechstein limestones is of the same origin: it was generated from organic matter occurred in the Carboniferous rocks and it migrated to higher places where it became concentrated within favourable structural or lithofacies conditions. High nitrogen content in the natural gas from the Polish Permian Basin is explained that nitrogen is generated from an organic matter within a sedimentary basin at higher temperatures than methane. Location of high helium concentration corresponds to the area of highest heat flow during the Late Permian, Triassic and Jurassic times, evidencing the Late Permian-Early Mesozoic rifting process.

Numerous oil gas fields discovered in the Main Dolomite (Ca2) unit constitute it as one of the most important exploration target in the Polish Basin. It composes the closed hydrodynamic system sealed from the top and the bottom by evaporates. Both the source rocks and reservoirs are characteristic for this unit. Influence of the burial and thermal history of the Polish Basin on a petroleum play generation within the Main Dolomite unit is clearly visible. The previous and the present petroleum discoveries in the Polish Permian Basin, comparing to the other petroleum provinces in Poland, indicate it as a main exploration target.

Key words: *Polish Permian Basin, oil and gas fields, petroleum play*

The Polish Permian Basin is a part of the great Permian sedimentary basin in Europe (about 1500 km long and 350 km wide), extending from England through Holland, Germany and Denmark up to Poland (Ziegler, 1982; Kiersnowski et al., 1995). This giant basin is called the Southern Permian Basin and its Polish part is distinguished as the Polish Permian Basin (Fig. 1). It began to develop in the latest Carboniferous. The Polish Permian Basin was located both within the Variscides and their foreland and it was limited from the north-east by the East European Craton. Its development continued during the whole Mesozoic up to the Cretaceous/Tertiary time when the general basin inversion occurred. Thus, the Polish Permian Basin was also situated in the area of the Permo-Mesozoic sedimentation termed as "the Polish Basin".

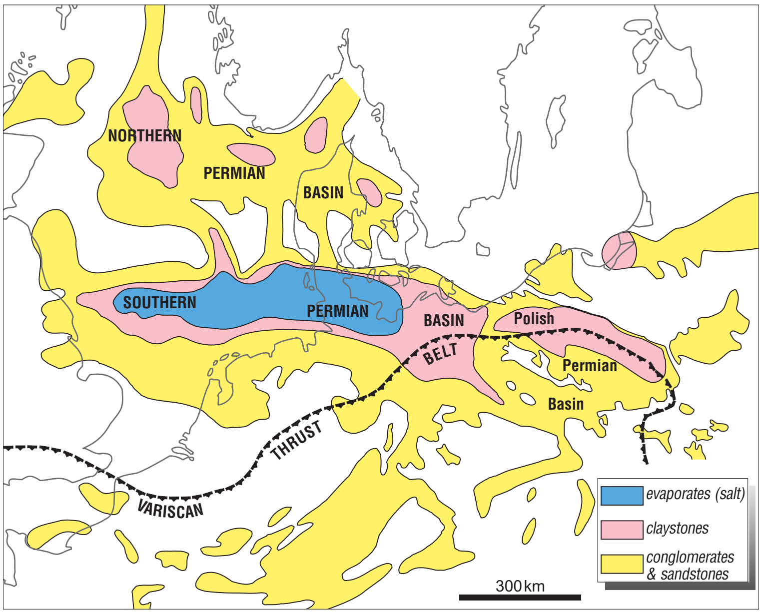

Fig. 1. Rotliegend basins in the Central and the Western Europe (main data after: Depowski, 1978; Karnkowski P.H., 1999; Ziegler, 1982)

Knowledge on the Permian in Poland is mainly the effect of petroleum explorations. Before the Second World War investigations for oil and gas fields were concentrated in the Carpathians, one of the oldest petroleum industry areas in the world. After the war, geological efforts were concentrated in the Carpathian Foredeep area, where rich and numerous gas fields were discovered within the Miocene deposits. Also the area situated north from the Carpathians and the Carpathian Foredeep was also in the scope of interest. In the 1930s a few papers emphasising interest of petroleum investigations in the Kujawy, Wielkopolska and Pomerania areas were published (Czarnocki, 1935; Bohdanowicz, 1930, 1936; Paszkiewicz, 1936). These authors had noticed an exploration possibility in the salt diapirs vicinity, by analogy with the oil fields pattern observed in Germany (Hannover region).

Drilling works in zones close to salt diapirs were without positive effects, so until now there were not found in

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Poland the oil fields of Hannover type, i.e. a petroleum play within the Mesozoic deposits situated nearby diapirs. In the 1950s, when the concept of large scale exploration in Poland was born, the validity of basin analysis has been appreciated (Olewicz, 1959).

In the 1950s the Polish Oil and Gas Company has began exploration of the Fore-Sudetic Monocline area. The first oil field discovery on the Polish Lowland (Rybaki near Krosno Odrzańskie), located within the Zechstein Main Dolomite deposits, was in 1961 and the first gas field discovery in the Rotliegend reservoirs (Karnkowski P. et al., 1966) was in 1964 (Bogdaj-Uciechów near Ostrów Wielkopolski).

Results of hydrocarbon exploration realized by the Polish Oil and Gas Company enabled documentation of

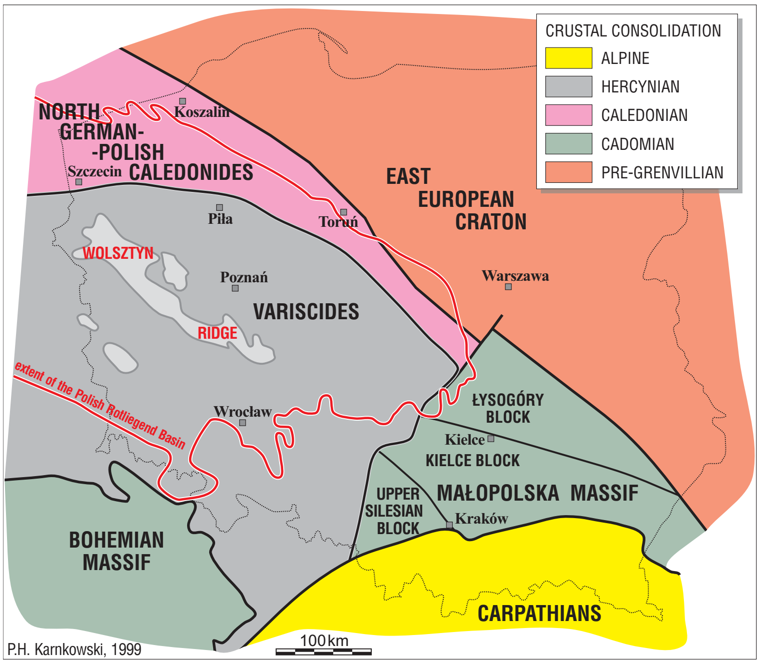

Fig. 2. Basement provinces of Poland and of the adjacent areas (after Karnkowski P.H., 1999)

more than 80 gas fields (mainly in the Rotliegend deposits) and more than 30 oil fields in the Zechstein carbonate rocks.

In the 1960s, numerous geological and geophysical data from the exploration and documentation works on hydrocarbons and copper-bearing deposits in the Southern Fore-Sudetic Monocline, were obtained, elaborated and published (Wyżykowski, 1964; Kłapciński, 1967; Sokołowski, 1967). Then, the extensive monograph of the Permian in the Fore-Sudetic Monocline prepared by Kłapciński (1971) emphasized main ideas on stratigraphy, facies and palaeogeography of the epoch. In the 1970s further recognition of the Rotliegend deposits was continued, especially in the Wielkopolska and Pomerania regions. It was expressed by numerous publications, e.g. Pokorski & Wagner (1972), Kuchciński (1973), Pokorski (1978) and Karnkowski P.H. (1977). This stage of geological investigations was summarised during the International Symposium on the Permian in Central Europe (Jabłonna, Poland, 1978). International meeting came to fruition in numerous papers (e.g. Karnkowski P. et al., 1978; Karnkowski P., 1981; Karnkowski P.H., 1981, 1987a, b; Maliszewska & Pokorski, 1978; Pokorski 1981a, b, 1989; Ryka, 1978a, b; Siemaszko, 1978; Roniewicz et al., 1981; Peryt, 1978).

The research state in the Polish Permian Basin in the last decade was summarized during the XIII International Congress on the Carboniferous and Permian (Hoffmann et al., 1997; Karnkowski P.H., 1997). The monograph titled *Orgin and evolution of the Rotliegend Basin in Poland* (Karnkowski P.H., 1999) was the paper summarised the forty years researches on the Lower Permian in Poland.

Geological setting

The tectonic position of the Polish Permian Basin and its relation to the main tectonic units in Poland is given by the Basement Province Map (Fig. 2). The main basement provinces are: the Precambrian East European Craton, the Cadomian blocks of the Upper Silesia and the Małopolska Massif, and the areas of Caledonian, Variscan and Alpine fold belts. During the long and complex evolution of the crystalline basement of Poland the mosaic of crustal elements became stepwise consolidated.

Position of the Polish Permian Basin with relation to the Variscides is shown in Fig. 3, clearly illustrating that a major part of the Rotliegend and the Zechstein Basins are superimposed onto the Variscan zone and its foredeep.

Rotliegend. The Rotliegend basins in Poland may be subdivided into two groups. The first one represents basins located in areas with a basement consolidated during the pre-Cambrian, such as the Słupsk Basin, Warmia Basin, Podlasie Basin and Silesian-Cracowian Basin. The second group comprises basins founded on a basement consolidated during the Caledonian or the Variscan orogenies. The Polish Rotlie-

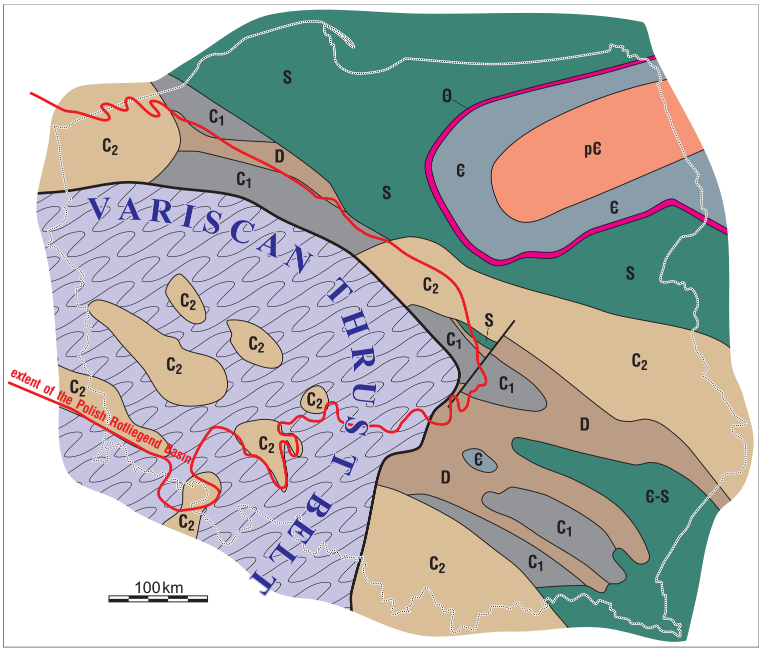

Fig. 3. Pre-Permian Geological Map of Poland (after Karnkowski P.H., 1999)

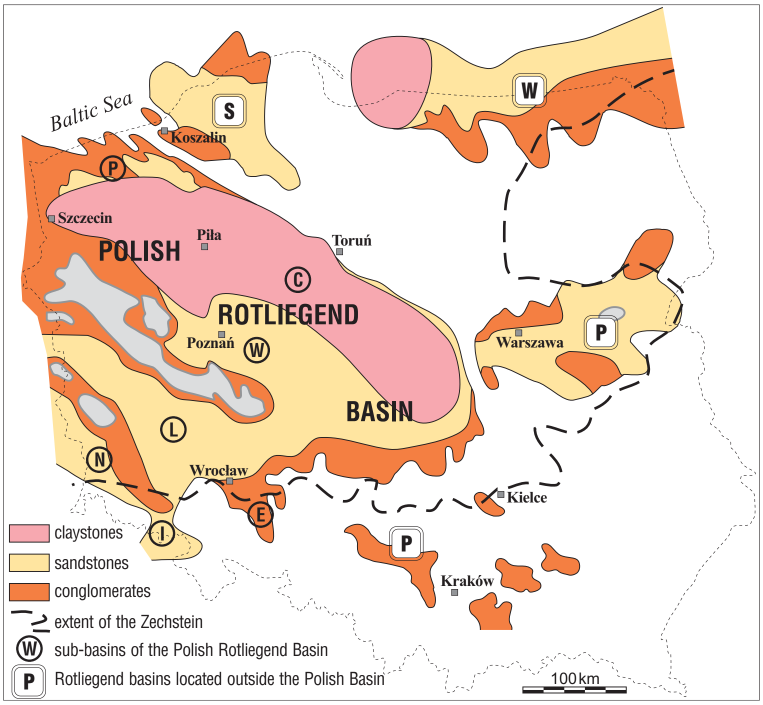

Fig. 4. Rotliegend Basins in Poland

gend Basin belongs there, with several subbasins such as: Intra-Sudetic Basin, North-Sudetic Basin and East-Sudetic Basin (the Laskowice Graben), Lower Silesia Basin, Wielkopolska Basin, Central Basin and Pomerania Basin (Fig. 4). The four last are important from a petroleum point of view. In all these regions, under volcanic rocks, there were found successions of grey and black clastics with gradually changing upward a colour into red and brown. Recently they occur very fragmentary but it is quite probable they primary occupied a larger area and they originated within local basins of scale comparable to the North-Sudetic Basin. The volcanic episode and the concurrent tectonic rebuilding have barely caused the Polish Basin creation, the first stage of which was reflected by deposition of the Wielkopolska Subgroup (Upper Rotliegend in age).

Because clastic, red deposits are almost devoid of index fossils, the stratigraphic subdivisions based on lithological criteria as the essential principle in establishing lithostratigraphic units (Fig. 5). Application of cyclic sedimentation and other geological processes (i.e. tectonics, climate) could be realized using the allostratigraphic units (Karnkowski P.H., 1987b) and the sequence stratigraphy units (Karnkowski P.H., 1999).

Since extended papers on the Rotliegend lithostratigraphy were published (Karnkowski P.H., 1987a, 1994) the Rotliegend formal lithostratigraphic units of the Polish Basin will be only shortly reviewed.

The oldest unit of the discussed Rotliegend subdivision is the **Dolsk Formation**, placed between the folded Variscan basement and volcanics (Fig. 5). It now occurs locally but primarily it could have extended over larger areas of the Rotliegend Basin. The lower part of the formation contains grey and black sandy deposits; upward red-brown siltstones prevail. The Dolsk Formation is overlain by volcanics and pyroclastics (Ryka, 1978a b; Jackowicz, 1994) of the Wyrzeka Formation. Occurrence of the volcanic rocks in the Polish Permian Basin is limited to its western part. Volcanics thickness exceeds occasionally one thousand meters and normally varies between 100–200 meters. Comparing this thickness with that of East Germany volcanics it is visible a great difference: in East Germany their maximum thickness exceeds 2500 m and the average value is 1000–1500 m while in the Polish Permian Basin it is ten times smaller. This difference could not be explain only by erosion of the lava covers and resulted from the was less developed Rotliegend volcanism in Western Poland than in East Germany. This volcanic event was related to the Saalian movements which in the first phase ceased sedimentation and later caused a great erosion of the Dolsk Fm. The main phase of these movements involved lava extrusion and eruption of pyroclastic rocks.

After such volcanic activity, the Saalian tectonic movements produced displacements of basement blocks covered by volcanics. Their erosion initiated sedimentation of coarse components of the Wielkopolska Subgroup (especially of Książ Wielkopolski Conglomerate Fm and Polwica Conglomerate Mb). Petrographic assemblages of these conglomerates provide often the only volcanism evidence and clasts quantification in the sequences informs about removed lava covers. The both discussed formations are joined into the Lower Silesia Subgroup due to their common co-occurrence, i.e. the Dolsk Formation is normally protected by the volcanic cover of the Wyrzeka Fm (Fig. 5).

Volcanics are overlain by siliciclastics of the Upper Rotliegend, developed as conglomerates at the basin margins and around paleohighs but as siltstones and claystones in the basin centre. In the transitional zones the sandstones prevail (Fig. 5). These three lithofacies are classified as individual formations: the Książ Wielkopolski Conglomerate Formation, the Siekierki Sandstone Formation and the Piła Claystone Formation.

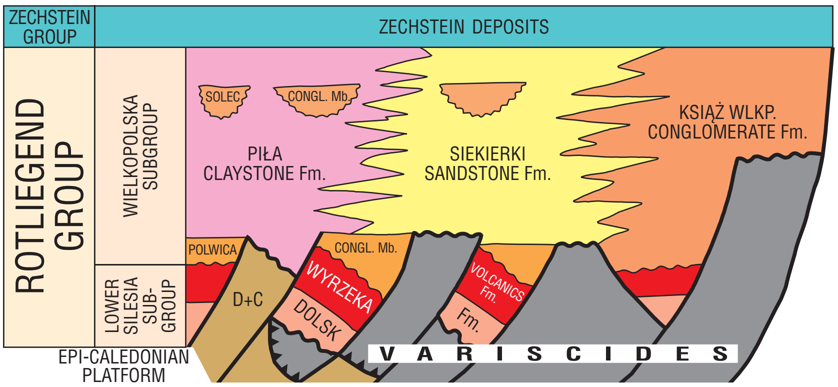

Fig. 5. Formal Rotliegend lithostratigraphic units in the Polish Basin (Karnkowski P.H., 1987a, 1994)

Sandstones of the Siekierki Fm are petrographically uniform but of various genesis. They lie directly on the Lower Carboniferous basement, the Dolsk Fm or on volcanics of the Wyrzeka Fm. Locally, within the profile of Siekierki Fm., especially in its lower and the middle parts, conglomerate intercalations are found. Such lowest coarse interbeds were distinguished as the Polwica Conglomerate Member and the upper one as the Solec Conglomerate Member. Both units of local extension could be included into marginal parts of lava-pyroclastic sheets or connected with activated tectonic zones, with an intensive subsidence and/or tectonic movements.

The Piła Fm is combined with the Siekierki Fm and the Książ Wlkp. Fm into the Wielkopolska Subgroup (Fig. 5). Thickness distribution of the Piła Fm and the joined formations indicates that the area predominated by claystones correlates well with the greatest depocenter of the Polish Rotliegend Basin, although in the Wielkopolska area some places of exclusively sandy facies are known, with profiles a few hundred metres thick.

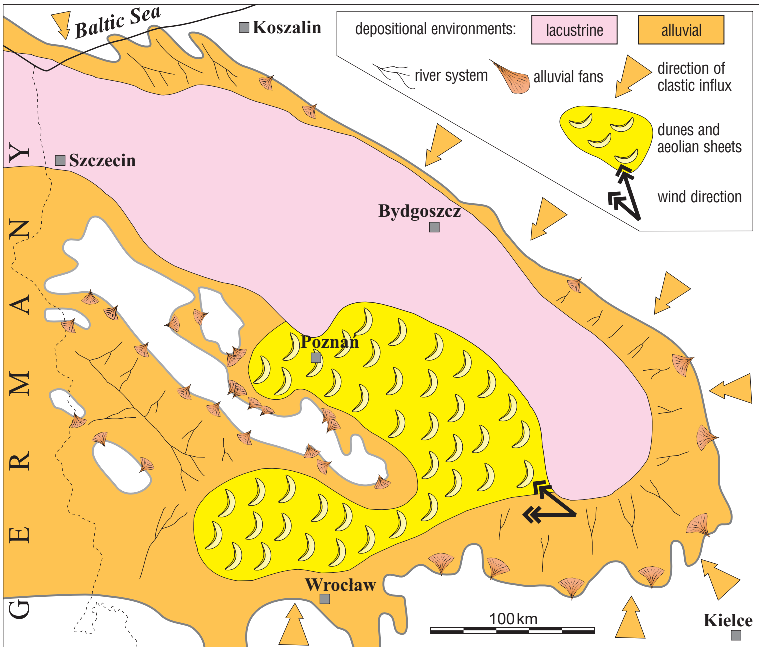

Fig. 6. Pre-Zechstein palaeogeography (sequence no VI, Karnkowski P.H., 1999)

The best recognized part of the Polish Rotliegend Basin is the Wielkopolska region (northern margin of the Wolsztyn Ridge). Main transport direction of coarse material during sedimentation of the Wielkopolska Subgroup evidences that from the beginning of Upper Rotliegend the Wolsztyn Ridge was the main supply area.

Aeolian transport was also present and in some areas it prevailed. The nature of the Uppermost Rotliegend Group is controversial. Undoubtedly, the clastic sediment below the Kupferschifer unit is locally partly reworked by the Zechstein sea transgressing, but from the lithostratigraphical point of view all clastics below the black marine shales are dated as the Rotliegend.

Reconstruction of evolution of the Polish Permian Basin in the Rotliegend time begins from pre-volcanic and volcanic periods, when the true Polish Basin has not yet existed. The Silesian Subgroup, comprising the Dolsk Fm and the Wyrzeka Volcanics Fm, originated directly before the creation of the Polish Basin frames. Analysis of individual formations and the changes occurring during their development enabled to define the transformation stages of Variscan pattern into the new Permo-Mesozoic basin. The Rotliegend time became a period when the main remodelling of Late Carboniferous pattern took place succeeded by development of epicontinental sedimentation within the Permian Basin.

Recently the author attempts to distinguish the sequences in the Rotliegend succession of Polish Permian Basin considering both climatic and tectonic factors (Karnkowski P.H., 1999). Sequences are more easily distinguished within the Wielkopolska Subgroup based on two tectonic and one climatic episodes (Karnkowski P.H., 1999, Fig. 15). From petroleum point of view the uppermost part of the Rotliegend is the most important one distinguished as a sequence VI. This sequence is connected with a period of final clastic sedimentation in the Polish Rotliegend Basin. It is bounded from the top by marine deposits — in this case, the continental sediments transformed by invading Zechstein sea. During this phase of basin development the paleogeography significantly changed: the aeolianites extent enlarged distinctly toward the Lower Silesia area (Fig. 6). After the author's opinion such change was involved by none extraordinary event (aeolian sedimentation continued from the beginning of main dry sequence in the Poznań region), but it resulted from an increased subsidence rate in the eastern part of Lower Silesia subbasin. This subsidence caused a favourable hydrological system of shallow subsurface groundwater level and it enabled preservation of former dune fields by their overburden.

Zechstein. The invaded Zechstein sea flooded various older deposits: clay sediments of the central lake, dune fields with dunes several tens meters high and fluvial deposits as well as areas devoid of Rotliegend accumulates, e.g. the Wolsztyn Ridge (Karnkowski P.H., 1986a). Quickly invading sea only partly destroyed the former relief, the remains of which are visible in copper mines in the Lower Silesia region, and it could be reconstructed in the Wielkopolska area with seismic and drill data (Karnkowski P.H. et al., 1997a, b).

The Zechstein deposits in Poland are mainly evaporates subdivided into four cyclothems — Fig. 7 (Antonowicz & Knieszner, 1984; Głowacki, 1986; Wagner, 1988). In the beginning of the first cyclothem (Werra, PZ1) the Zechstein Limestones unit (Ca1) has developed (Peryt, 1978; Peryt & Ważny, 1978). The second cyclothem (Stassfurt, PZ2) exhibited the similar sedimentological history but in a smaller extent. Carbonates (Main Dolomite unit, Ca2) were deposited in all basin but only carbonate platform facies and their surroundings are of the thickness, organic matter content and petrophysical properties sufficient they be considered as an exploration target (Fig. 7).

Numerous oil gas fields discovered in the Main Dolomite (Ca2) unit constituted this formation one of the most important exploration target in the Polish Basin. It composes the closed hydrodynamic system sealed from the top and the bottom by evaporates. The Main Dolomite (Ca2) unit is the set of carbonates occurred at the base of Zechstein cyclothem Stassfurt (Antonowicz & Knieszner, 1984; Głowacki, 1986; Depowski, 1978; Górecki et al., 1995;

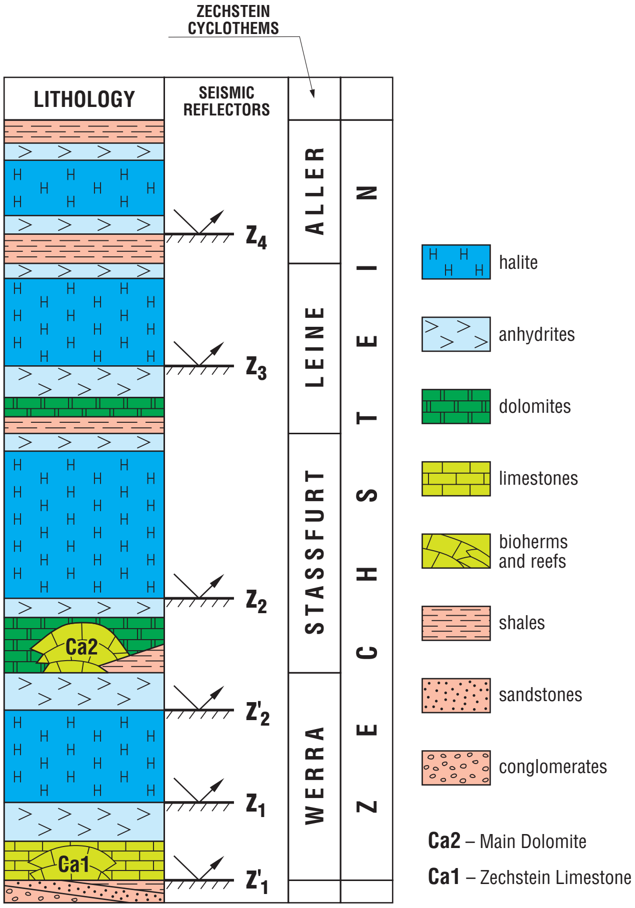

Fig. 7. Position of the Zechstein Limestone (Ca1) and the Main Dolomite (Ca2) units in the Zechstein cyclothem succession

Wagner, 1988, 1994). Both source rocks and reservoirs occur within this unit.

Basin of the Main Dolomite unit was subdivided by a palaeogeographic criterion into three main sedimentary environments: a basin plain, slopes of carbonate platforms and carbonates platforms.

A basin plain occupied the area of the basin depocenter (Polish Trough). Its sediments are characterized by condensed series of low-energy sediments, accumulated below a wave level, with the thickness up to 10 meters, often less than 5 meters. Deposition took place at the depth of 300–400 meters at the redox conditions. Sometimes the carbonate microplatforms existed within the basin plain creating small the bottom palaeohighs/elevations. They were grouped mostly in the surroundings of the Gorzów Wielkopolski platform, in the Zielona Góra large gulf (Peryt & Dyjaczyński, 1991) and on the south-eastern edge the Pomerania platform (Wagner, 1994, 1998).Their surface areas varied from several to tens of square kilometers and lithofacies variability of the Main Dolomite unit was highly controlled by the microplatforms size.

Slopes of carbonate platforms were connected with the platforms but they represented two opposing sedimentary environments: a shallow, high-energy one outside the barrier edge and a relatively deep, low-energy one characteristic for the basin plain. Thickness and facies differentiation of slope sediments resulted mostly from the morphology of the carbonate platform edge, the slope angle and of sea currents flowing parallel to the slope. The slope deposits thickness is contrastingly diversified, from few metres up to the over 200 m depending on the barrier configuration and the slope pitch. In the Polish Basin of the Main Dolomite unit all kinds of tilting slopes appear: from the very inclined/steep ones, forming escarpments (e.g. the slope of Kamień Pomorski platform, the slope of the north part of Gorzów Wielkopolski platform) to the very flat ones (e.g. eastern slope of Wielkopolska platform or the fragment of north-western part of Pomeranian platform at its contact with the Rewal bay, where the borders between the slope and the basin flat are erased.

Carbonate platforms of the Main Dolomite unit in Poland composed terraces with dominant a shallow-water sedimentation, occurring in the whole border part of the sedimentary basin. (Wagner, 1988, 1994). The platforms width varied from a dozen up to 150 kilometres. The border line of platforms extent was very varied because of the basin plain cutting deeply — as the bays — into the platform margins, for example Rewal, Zielona Góra and Noteć bays. The morphology of individual platforms was irregular from a very flat one to a highly diversed one. It was influenced by geological structures and palaeorelief of the basin bottom surface. Average thickness of platform sediments is 30–40 meters and locally in culminations — 60–100 meters. Sedimentary environment of the Main Dolomite unit was generally a shallow-water one with increased salinity, determinating the fauna development. Majority of animal groups which lived in the sea of Zechstein Limestone unit, such as corals, echinoderms, brachiopods, bryozoans, cephalopods, fishes have disappeared in the Main Dolomite sediments. Instead them salt-tolerable bivalves and snails were found there. In such environment particularly algae and cyanosis have intensively developed forming the huge amounts of biomass being an important source for hydrocarbons deposits. Higher salinity influenced also the possibility of local occurrence of the reducing environment, at periods of the intense development of cyanosis even in shallow-water, lagoon environments. In many areas such anoxic conditions could protect the matter from destruction and let it buried and transforming into hydrocarbons.

Four main facial zones could be distinguishing on the carbonate platform realm: a barrier zone, a platform plain, a salina and a subaeral part of the platform.

Barrier zones expanded outside the platforms edges towards an open sea. Most often they existed in the proximity of steeply inclined platform slope, e.g. the Gorzów Platform or the northern part of Wielkopolska Platform. Barrier zones evolved both outside the platform as well as onto its internal slope. The main building materials of barriers were peri- and sublitoral calcareous sands with horizontal and cross bedding orgined in the shallows system, above a wave base.

The platform plain extended the barrier zone. It occupied a very vast area creating the biggest individual palaeogeographic unit within the carbonate platform environ. Morphological differences were not so large, but in a relatively shallow-water environment the little bathymetric differences resulted in changes of sedimentary regimes. Within the platform plain two principal zones were distinguished: widespread high-energy zones, especially on the Wielkopolska and Pomerania Platform and low-energy ones occurring behind barriers or in the depressions of vast platform plain.

Salinas were the shallow-water parts of the platform plain which were limited by barriers of calcareous sands. They were the shallow separated subbasins, medimum in size, with a high water salinity periodically resulted in a sulphates precipitation. Depending on the isolation degree from the rest of the basin the high- or low-energy sedimentary conditions could prevail in salinas. In the low-energy environment remarkably beneficial conditions prevailed for the development of organic mats and buildings. In these places the huge biomass amounts could be concentrated, buried and later transformed into hydrocarbons. The best case of such environ could be the paleosalina of Kamień Pomorski.

The subaeral platform part was development in the costal basin zone as sebkha facies. Very shallow-water sedimentary environment, high salinity and hot and extremely dry climate were the main factors responsible this zone was without petroleum features.

Reservoirs in the Main Dolomite unit are well recognised and there are no problems with their identification. Quite different problem is with the source rocks. For years of hydrocarbon exploration it was opinion that such source were dark-grey, laminate mudstones occurring in the basin centre. Last geological and geochemical studies (Kotarba, 2000) demonstrated, that these series, somehow having the features of source rocks, could not be considered as a main sources for hydrocarbon accumulation, because they were not subjected to expulsion for the greater scale as well as because of a small distance of hydrocarbon migration within the Main Dolomite deposits. So the microbial and algae originated rocks were regarded as an organic matter source there. Cyanosis could provide large amounts of organic matter and in periods of their bloom they could create locally the reducing conditions also in shallow-water zones protecting the organic matter from destruction. Evaporate conditions during deposition of the Main Dolomite unit both supported the development of cyanosis by eliminating their consumers and became very favourable for the organic matter preservation. Also green and red algae have flourished that time, producing calcareous deposits with organic matter and playing also a rock-building role.

For many years the role of cyanosis and algae has been undervalued by petroleum geology, mainly because of the low total content of organic coal in the rocks (TOC) of the Main Dolomite unit (average — 0.3%), placing these deposits as the lowest one in the source rocks ranking. This index was defined after determination of the 3rd type kerogene and it is applied for all types of source rocks. But it was not considered that the organic matter produced by cyanosis and algae created kerogene of 2nd and 1st types which almost completely was converted into hydrocarbons leaving on site a very low TOC value. Only last results (Kotarba, 2000) demonstrated the increased TOC content in microbial carbonates (average — 0.75%). Summarizing, the source rocks of the Main Dolomite unit in the Polish Basin are microbial and algae in origin and they can be subdivided into two groups: 1) source rocks of shallow-water zones for which the first source of organic matter were benthonic cyanobacteria and algae, 2) source rocks of relatively deep-water zones producing organic matter by planktonic cyanobacteria and algae.

Post-permian burial history

The Permian Basin, which started in the early Permian, continued its geological history up to the present. Reconstruction of its burial and the thermal history enabled to recognize better the mechanisms responsible for the Polish Basin development.

The first stage of Polish Basin evolution took place in the Rotliegend time. The volcanic period then could be considered as the earliest stage of Polish Basin development. The post-volcanic Rotliegend sediments had already a distinct facies and thickness pattern within the whole basin (over 1000 m thick in the depocenter).

The Zechstein transgression invaded the Rotliegend Basin of a clearly defined pattern, with deposit thickness exceeding 1500 m in the depocenter. The whole area of former Rotliegend deposition was flooded and the transgression extended wider, especially onto the East-European Platform. Such extensive marine expansion resulted from a very low position — beneath a sea level — of the Rotliegend basin bottom. This also enabled a rapid transgression (Karnkowski P.H., 1986b) onto the highly peneplenized area of East-European Platform. The epicontinental Zechstein sea was shallow, with a limited connection with the Late Permian marine basin, extending in the area of recent Arctic. Dry and hot climate favoured evaporate sedimentation. Predominantly, the Zechstein deposits are overlain by the Lower Buntsandstein ones, under which the original extents of the Zechstein cyclothems were preserved.

The main areas of subsidence during the Zechstein were the same as in the Late Rotliegend but they were of wider extend. This initial phase of Polish Basin evolution was characterized with the extremely high tectonic subsidence. The Buntsandstein Basin inherited the main palaeotectonic pattern of the Zechstein Basin: initially as shallow-marine one, later a periodically drying inland basin of low salinity, subjected to sedimentation of fine clastic deposits of a clayey and silty type, locally calcareous, with infrequent inserts of oolitic limestones and/or silty limestones, sometimes with concentrations of anhydrites (Szyperko-Teller & Moryc, 1988). The zones of maximum subsidence, mostly repeated the former structures, characterized with thickness values over 1500 m in the Polish Trough depocenter.

The Muschelkalk sedimentary basin was a continuity of the former Late Buntsandstein basin. Than the environment of a shallow epicontinental open sea has dominated with marine carbonate lithofacies, predominantly limestones (Gajewska, 1988a). At the turn of the Muschelkalk and the Keuper periods the sea retreated from this area (Deczkowski & Franczyk, 1988a; Gajewska, 1988b). During the Early Keuper; only a shallow inland basin existed in which the deltaic-lagoonal-fluvial sediments were deposited. Thickness of the Muschelkalk, Keuper and Rhaetian units also exceeded 1400 meters in the Polish Basin depocenter.

The Lower Jurassic epicontinental sediments in the Polish Lowlands developed in a vast inland basin which several times became affected by short-lasted marine ingressions (Deczkowski & Franczyk, 1988b). The Lower Jurassic sequences developed as a platform association of sands and clays, accumulated within a variety of sedimentary conditions from fresh-water ones to brackish and marine environments. Tectonic movements at the turn of the Roetian and the Lower Jurassic defined the new frames of sedimentary basin, which at the end of the Sinemurian has distinctly differed from the Uppermost Triassic Basin. The Mid-Polish Trough was distinguished as a group of depocenters, located directly along the East-European Platform margin. Such a situation was partially stimulated by formation of the Wielkopolska Swell.

The Middle Jurassic sedimentary basin became remarkably expansive so the next transgressions occupied a wider area of the Polish Basin. The Middle Jurassic sediments consist mainly of claystones and sandstones and their average thickness is of 150–400 m and only in the Kutno region — up to 1100 m (Dayczak-Calikowska & Moryc, 1988). The palaeotectonic pattern of the Middle Jurassic shows transitional features between the Early and the Late Jurassic ones.

During the Late Jurassic almost the entire area of the Polish Basin was covered by the epicontinental sea. There was a good communication with the Tethyan Ocean to the south and with a boreal sea to the north as well as with marine basins in both the western and the eastern directions. Subsidence variability was significantly dynamic within the basin. Its northern part was characterized by a very low subsidence rate (200–500 m). Tectonic activity renewed in the basin southern part was expressed as an extended area of increased subsidence. Such extension of the Polish Basin has developed during the Late Jurassic mainly in subhorizontal transtensional conditions in the NNE-SSW direction (Hakenberg & Świdrowska, 1997).

At the turn of the Jurassic and the Cretaceous the southwestern margin of Polish Basin was uplifted and eroded. During the Early Cretaceous continuous deposition took place only within the Mid-Polish Trough (maximum thickness — 500 meters). This basin was connected with two palaeogeographic provinces: the boreal province in the northwest and the Tethys in the south and the southeast (Marek, 1988). In the Fore-Sudetic area all the Jurassic and the part of Triassic deposits were eroded so the Upper Cretaceous transgressive sediments overlie there the Buntsandstein or the Muschelkalk series.

During the Albian age a new transgression took place and a marine sedimentation continued in the vast area of Polish Basin during the whole Late Cretaceous (Jaskowiak-Schoeneichowa & Krassowska, 1988). In the depocenter carbonate facies prevailed replaced by marly and sandy deposits in the basin margins. Maximum subsidence rate (deposits thickness over 2500 meters) was within the Mid-Polish Trough (Pożaryski & Brochwicz-Lewiński, 1979). At the turn of the Cretaceous and the Tertiary this area was subjected to a tectonic inversion and the Mid-Polish Anticlinory was developed. Its uplift was accompanied by a significant erosion, which removed mainly the Cretaceous and the part of Jurassic sediments/rocks. The southwestern basin part was also emerged and most of the Upper Cretaceous series, located there, became eroded. Calculated maximum subsidence shows that top of the Rotliegend deposits within the Mid-Polish Trough in the Late Jurassic time was located at the average depth of 7 km beneath the contemporaneous sea level but at the end of the Cretaceous period it locally reached a depth of 8–10 km.

Thermal history of the Polish Basin

Thermal history of the Polish Basin was reconstructed using a computer simulation (Karnkowski P.H., 1999) and it is presented on the two maps of heat flow distribution.

The first one refers to a time interval from the Recent to the Jurassic-Cretaceous boundary (Fig. 8A) and it may be approximately considered as the recent HF distribution. The second map illustrates heat flow values for the Rotliegend-Late Jurassic period (Fig. 8B).

The image of heat flow distribution for the Rotliegend-Late Jurassic period (Fig. 8B) coincides with the former map only in the area of Polish Trough. Then in the south-eastern part of Polish Basin the higher heat flow values during the Permian-Jurassic period was observed. The large anomaly is especially visible between Poznań and Wrocław cities.

The thermal history of Polish Basin-Fill evidenced that at the beginning of its development (especially in the Permian-Triassic time interval) the high geothermal anomalies occurred in the western part of Polish Basin. It was related to the syn-rift stage of sedimentary basin development. During the Late Triassic and the Jurassic times took place some cooling of rift heat field, but the turning point in thermal evolution of Polish Basin was at the Jurassic/Cretaceous boundary when the south-western basin part was uplifted and intensively eroded. Then a heat flow supply into the basin decreased and distinct features of former epoch were obliterated in the heat flow field image.

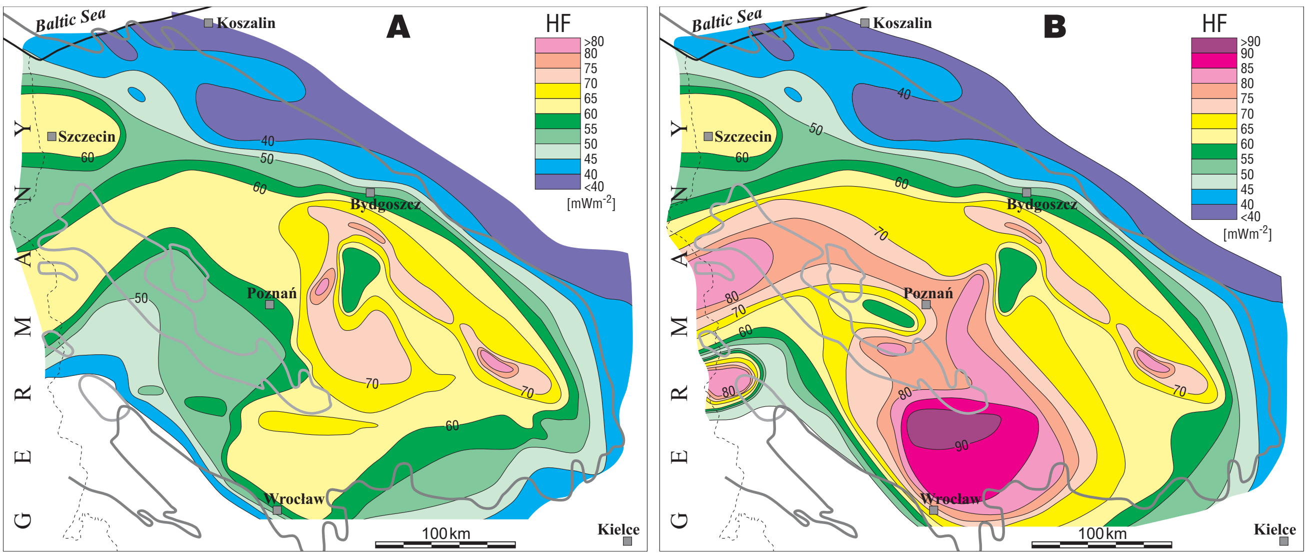

Fig. 8. Map of average heat flow values in the area of Polish Permian Basin obtained from the computer simulations: A — from the Cretaceous to the Recent present time; B — the Late Permian to the Late Jurassic period

Burial and thermal factors versus hydrocarbon generation in the Polish Basin

Knowledge of heat flow value variation and distribution is applied to modelling of hydrocarbons generation. The Rotliegend series contain gas fields and the Zechstein carbonates — both gas and oil deposits. A fundamental question of current exploration works is the occurrence of "an oil window" that means zones with potentially preserved liquid hydrocarbons. The answer to this question permits also to qualify zones of gas occurrence or zones in which the hydrocarbons generation not yet began. Images of zones with hydrocarbon generation created by computer simulations were plotted on the geochemical cross-sections and the data from these sections served for constructions of organic matter maturity maps for individual stratigraphic surfaces. In the case of the Zechstein Basin the Main Dolomite deposits are the most perspective exploration formation and just for this unit the map of organic matter maturity was first constructed (Fig. 9). On this map oil and gas fields discovered in the carbonates of the Main Dolomite unit are presented. In most cases the type of hydrocarbons are agreed with the simulated zones although there are some defections resulting probably from the influence of local palaeothermal conditions. Realization of this map, together with marking the range of most profitable source and reservoir rocks, permits to predict better the most prospective zones to research. Co-occurrence of favourable petrophysical and geochemical parameters within the Main Dolomite deposits reduce the exploration risk. The regionalization of hydrocarbon types is clearly visible after analysing the map of oil and gas fields in the Main Dolomite deposits. In the Western Pomerania area no gas fields exit but in the south-eastern part of Fore-Sudetic Monocline only gas fields occur. However in the south-western part of Fore-Sudetic Monocline oil fields prevail and only sporadic gas fields occur irregularly. Thermal history is highly responsible for such state of hydrocarbon types distribution in the Main Dolomite Basin. The purpose of computer simulations is also to check on an evolution of these zones in the geological time. It is a basic fundamental in analysis of hydrocarbon migration depending on changes in structural arrangements in the sedimentary basin. On Fig. 10 few images of extent changes of hydrocarbon zones were illustrated for the uppermost and the near-bottom parts of Zechstein succession during the late Triassic, late Jurassic and at present times. Presentation of hydrocarbon zones evolution in the bottom and the top of the Zechstein evidenced well a dynamics of these zones not only as the time function but also the depth factor. At the end of the Triassic considerable part of the Main Dolomite unit developed as barrier and lagoonal facies in the Wielkopolska area has entered the phase of "an oil window". Particularly it refers to the Leszno and Rawicz regions. Completely different situation was in the Western Pomerania area. Unlike two areas previously discussed where the main phase of "an oil window" was attributed to the turn of the Triassic and the Jurassic, in the north-western Poland only in the late Jurassic such process of oil generation was initated. Its main phase occurred in the Cretaceous period Fig. 10).

Gas fields and gas composition characteristics within the Rotliegend deposits and the Zechstein carbonates

In European, as well as in Polish petroleum geology, a notion of gas-bearing of the Rotliegend sandstones and Zechstein limestones is already widespread and unquestioned. It is widely known that the reservoirs are the clastic, terrestrial deposits of the Lower Permian and marine calcareous, biogenic carbonates of the Zechstein of maximum sea extents in the early transgression phases. Evaporates, mainly salts of the Werra cyclothem are the regional sealing for these reservoirs. Natural gas accumulated in the Rotliegend sandstones and the Zechstein limestones has the same origin: it was generated from the Carboniferous organic matter and migrated to higher lying series where it was concentrated within favourable structural or lithofacies traps. Economically cost-effective gas accumulations are the objects of exploration in the whole European Permian basins, also in the Polish Basin (Fig. 11).

First gas field discovering within the Polish Basin (Bogdaj-Uciechów gas field) was in 1964 (Karnkowski P. et al., 1966). Reservoirs are here the uppermost Rotliegend sandstones and the Zechstein limestones. The first exploration successes in the Rotliegend in the Polish Lowland (the southern part of Fore-Sudetic Monocline) extended the works front to the north. Large structural unit, the Wolsztyn Ridge — the area devoid of the upper, sedimentary part of the Rotliegend succession — was discovered and contoured. North to the Wolsztyn Ridge the first gas field discovery (Kaleje) was in the 1971. In beginning of seventies the next findings were in the area of the Western Pomerania (Górecki et al., 1995).

From the today's perspective, after over forty years of prospecting of the Rotliegend in the Polish Basin, it is possible to classify the recognized gas fields and to describe the gas-bearing regions. Gas fields could be subdivided into the following types: structural, palaeogeomorphological-structural (palaeodunes) and stratigraphic (lithofacial) ones. Detailed characteristic of

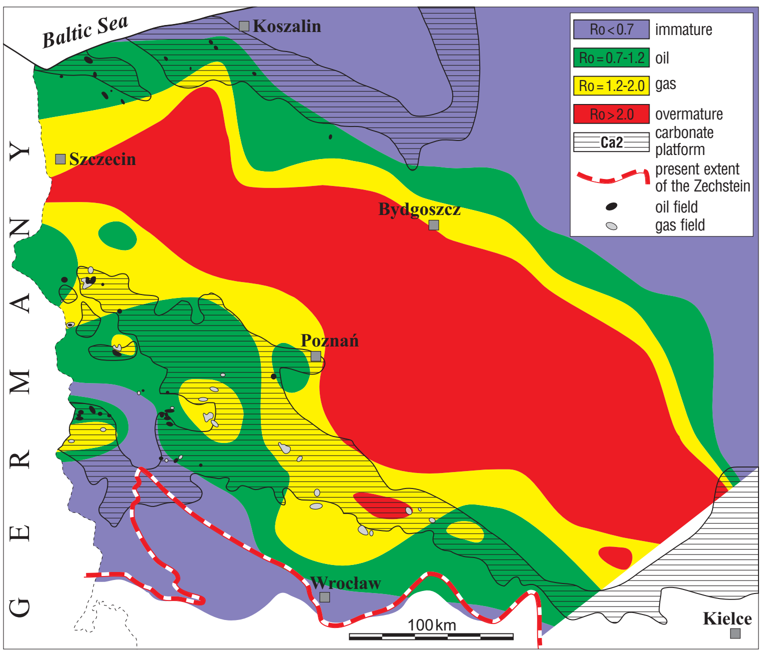

Fig. 9. Hydrocarbon zones the Main Dolomite (Ca2) unit

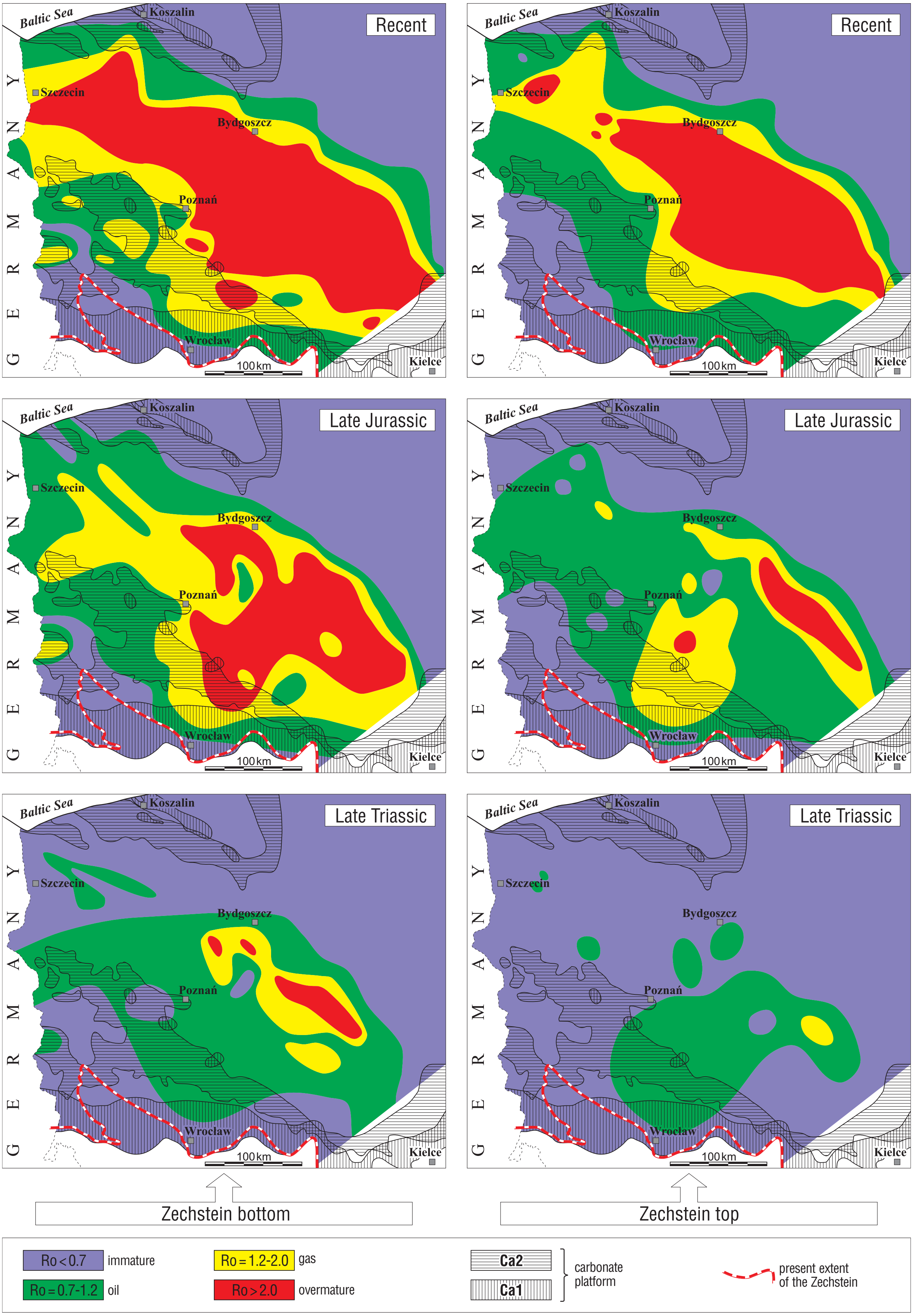

Fig. 10. Evolution of the hydrocarbon zones in the Polish Basin: from the Permian to the Recent present time

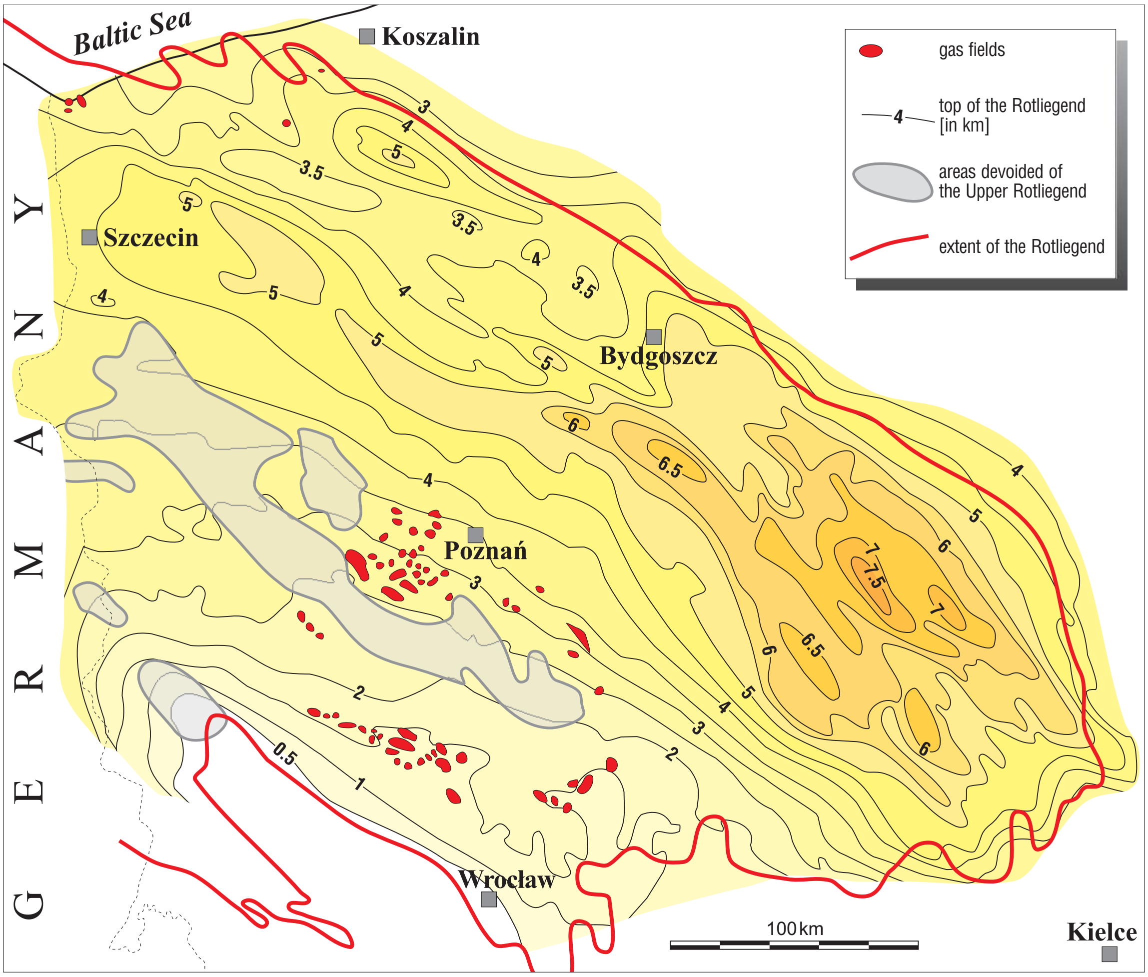

Fig. 11. Gas fields in the uppermost Rotliegend deposits on the background of the Lower Permian top

individual gas fields was presented in the monography by P. Karnkowski (1993).

Several dozen gas fields hitherto discovered within the Rotliegend sandstones and the Zechstein limestones and the general geological recognizing of the Polish Lowland structure enabled to distinguish the four exploration regions within the Polish Basin: 1) Zielona Góra–Rawicz–Ostrzeszów region (south of the Wolsztyn Ridge), 2) Wolsztyn Ridge and its borders, 3) Poznań region (north of Wolsztyn Ridge) and 4) Western Pomerania Region.

Most of discussed gas fields represent structural traps but some of them occur within the buried paleodunes so they should be classified to a stratigraphic trap category. Also gas plays adjacent to the Wolsztyn Ridge, where rapid facial transitions between aeolianites and fluvial sediments are observed, could be defined as lithofacial traps (Wolnowski, 1983; Gliniak et al., 1999). In Western Pomerania only few gas fields have been found within the Rotliegend succession. Current exploration works are organized to discover gas fields also within lithofacial traps (Karnkowski P.H. et al., 1996, 1997a, b). Such possibilities as: progressively improved seismic images of geology beneath the Zechstein horizon, application of 3D seismics, better procedures of seismic data processing and detailed studies on architecture of deposit systems in the Rotliegend Basin decide that such investigations seem to be very promising (Karnkowski P.H. et al., 1997a, b). Discovery of stratigraphic traps is quite difficult because the Zechstein-Mesozoic cover is characterized by frequent lithological and thickness variations complicating construction of a proper velocity model, enabling suitable conversion of the time/depth section. But these problems are successively solved and new discoveries seem very probable. More intensive exploration of Rotliegend series is limited due to occurrence of its significant part at the large depth. The Rotliegend top, located at a depth of about 3000 m below a recent sea level, occupies the dominant basin part so any geological prospecting there is very expensive and risky. But such situation does not indispose the foreign investors for further exploration and recently the most of Polish Rotliegend Basin area is subdivided into numerous concessionary plots; they are managed both by Polish and foreign investments. The basin central part is the most prospective area because there may occur large structures or stratigraphic (lithofacial) traps. Also the gas composition from this area, dominated by hydrocarbons (over 75% of volume) suggests further prospecting in the basin center (Poznań region — Fig. 12). Gas samples from Western Pomerania (the northern basin part) contain less than 25% of methane but nitrogen content is over 75 vol.%.

Origin of gas within the rotliegend deposits in the Polish Basin

Natural gas, recovered in the North-German Basin, adjacent to the Pomerania segment of the Polish Basin, is dominated by nitrogen (over 90% — Gerling et al., 1997). Such extremely high content is differently explained but the main reason is that nitrogen is generated from organic matter within a sedimentary basin at higher temperatures than methane. Nitrogen-rich gases are mainly formed during the final stage of gas generation, when sedimentary rocks are transformed into metamorphic rocks (Everlien & Hoffmann, 1991; Littke et al., 1995; Neunzert et al., 1996). The Westphalian coals, in the North-German Basin, actually deeply buried and highly mature (Gerling et al., 1997), are indicated as a source of organic matter.

Distribution and content of nitrogen and helium within natural gas found in the Polish Rotliegend series were constructed basing on elaborations of the Geological Bureau GEONAFTA (Kopczyńska, 1994) although data on such problem are also enclosed in the monography on hydrocarbons deposits in Poland (Karnkowski P., 1993). In the Pomerania area, with a relatively high nitrogen content (45–80%), helium is found sporadically, only in single wells drilled in few gas plays and it is without any industrial value. It seems that helium occurrence is connected with deep faults or fracture zones along which it could easily migrate upward. Content variability of nitrogen in natural gas decreases from the west to the east, from the German Basin toward the East-European Platform. Because in Germany the hypothesis on a high-temperature transformation of organic matter as a nitrogen source is accepted the analogous suspicion could be considered in the Pomerania region. The temperatures affected the Carboniferous source rocks in the north-western Poland were lower than in the German Basin and they decreased from the west to the east. Thermal modellings of this area (Karnkowski P.H., 1999) indicated that high HF values dominated up to the Zechstein. This heating produced so intensive organic matter maturity, that during the successive 300 mln years the Carboniferous source rocks, subjected to a lower thermal regime, could slowly mature and release both nitrogen and methane. It seems that the region from Szczecin to Koszalin is comparable — in a genetic sense — to the German Basin.

A quite different distribution of helium and nitrogen content and their relationship are visible in the southern part of Polish Basin: nitrogen content increases there toward the basin margins but helium concentration belongs only to a one distinct area (north-east to Wrocław) and it is noticed not only in single wells but also within whole gas plays (Kotarba et al., 1992). This is one of few places in the world, from which a condensed gas supplies an industrial helium amount both due to its high content in natural gas plays and significantly large volume. Nitrogen content is also high, from 40 to 75 vol.%. Methane content increases toward the basin centre and the characteristic spots of higher methane amount within a nitrogen-helium field suggest its migration from a basin centre toward the south.

Location of high helium concentration corresponds to the area of highest heat flow during the Late Permian, the Triassic and the Jurassic in the whole Polish Basin. Deep seismic sections enabled construction of structural map of the Moho surface in Poland (Fig. 4). It illustrates that the region with recently highest helium amount and in which, during the Permian-Mesozoic period, existed the area with a highest heat flow, the Earth crust is thinned to less than 30 km. It may be accepted that the described paleothermal-geochemical-tectonic anomaly, located about 60 km north-eastward from Wrocław, evidences the effect of the Late Permian–Early Mesozoic rifting process.

Results of analysis of burial and thermal history of the Polish Basin as well as configuration of the Moho surface in Poland, where its uppermost position is accompanied with a very high helium concentration, suggest the asymmetrical basin model (Karnkowski P.H., 1999).

Further exploration in the rotliegend sandstones and the zechstein limestones in the Polish Basin

Most promising for further exploration is the Poznań region. Here the gas composition is of the best quality and possible location of relatively big structures. A positive example is the gas field Środa Wielkpolska discovered in the 2005. It is the first field in the eastern Wielkopolska area outside of the Poznań–Kalisz dislocation zone where all previous discoveries were plotted. Eolianites from the eastern Wielkopolska area probably extended to the north what is a good prognostic for exploration in the Poznań region (Karnkowski P.H., 1996).

The Wolsztyn Ridge and its borders still are in the exploration interests. Searching of lithofacial traps both in the Rotliegendes as well as in the Zechstein deposits, certainly becomes the priority in further works.

Zielona Góra–Rawicz–Ostrzeszów region, in spite of discoveries of many significant gas fields, also should be included in the future exploration. Exploitation infrastructure existing already here will reduce costs of developing even not very rich, new-open gas fields. Increase of gas price in the last years on the world markets is certainly responsible for the renewed interest of the Polish and foreign companies with the area located to the south of Fore-Sudetic Monocline.

The Western Pomerania region is the most difficult area for prospecting of gas in the Rotliegend sandstones. The main factor making the research difficult is the economic estimation of undertakings as a result of low methane content in gas composition. Low quality of the natural gas and increased expenses of drillings (a higher depth of search ranges than in the southern region of Polish Basin and more dispersed gas fields hitherto uncovered in the Rotliegend deposits) cause that decisions about new geological-geophysical works there will be taken extremely carefully.

Within the Polish Basin other challenges still remain. First of all is the explanation of structural traps occurrence under halotectonic structures (under salt diapirs and pillows). In order to deal with these problems it is necessary to take prospecting works at the depth below 4000 metres. Additionally it is required to clarify the possibility of natural gas accumulation in the middle-lower part of the Rotliegend succession. Sealing for such traps would be claystones and mudstones occurring in the upper part of the Rotliegend profile in the central part of Polish Basin.

Finally the most difficult challenge: Kutno anticline. This huge structure located in the centre of Poland and in the centre of the Mid-Polish Anticlinorium, was mapped in the Permian-Mesozoic deposits. It is not excluded that the lower part of Rotliegend succession building this anticline has good reservoir properties and it contacts with the Carboniferous source rocks. Its size, if it was filled up with gas, guarantees the gas accumulation estimated for several dozen billion cubic metres. In this case the exploration costs remain the main problem: the planned drilling should exceed the depth of 8000 metres.

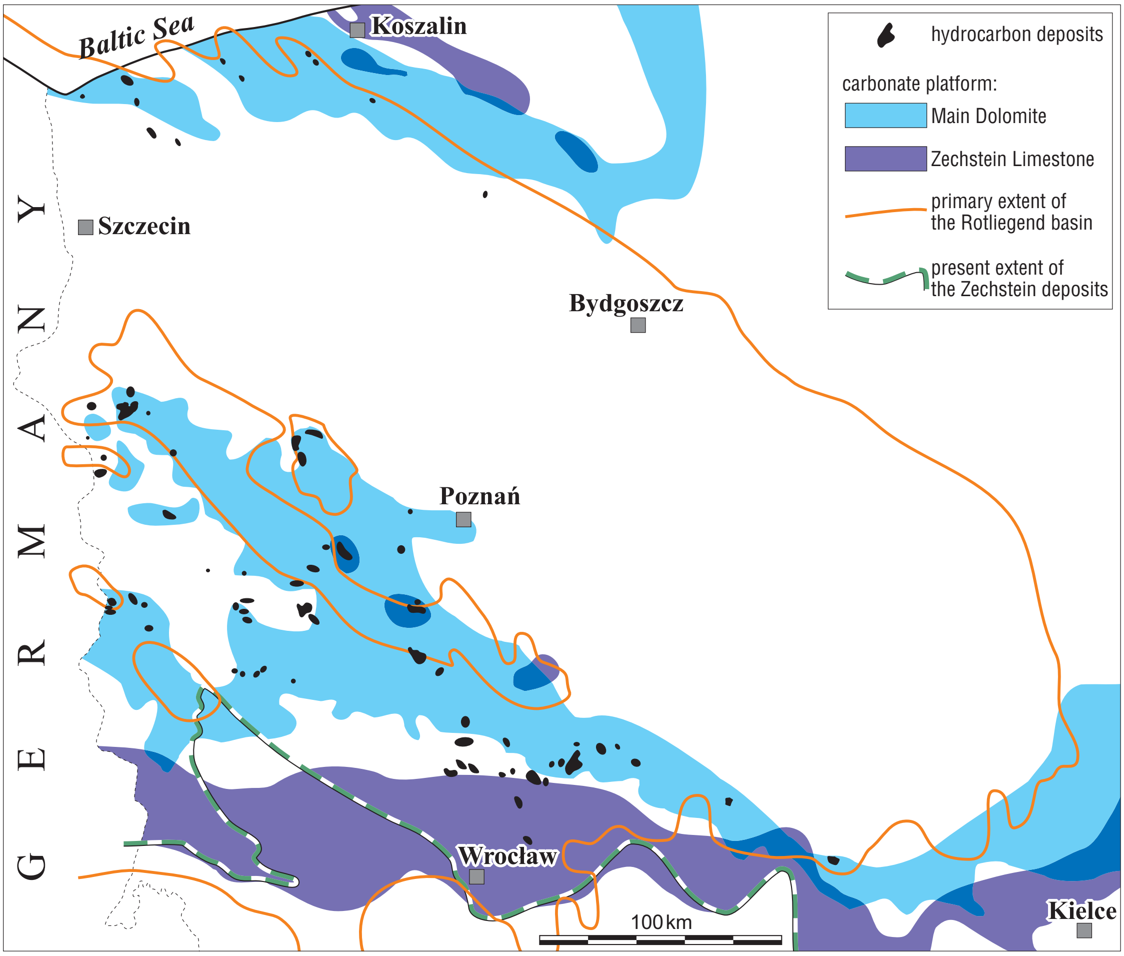

Fig. 12. Oil and gas fields in the Zechstein carbonate (Ca1, Ca2) deposits

Discoveries in the main dolomite deposits and the future works

From the first oil field discovery (Rybaki, 1961) numerous oil and gas field were documented in the Main Dolomite deposits in the Polish Basin (Fig. 12). In the 90's of the past century in the border zone of Fore-Sudetic Monocline and the Szczecin Synclinorium new oil and gas discoveries were achieved: Barnówko–Mostno–Buszewo (Mamczur & Radecki, 1997), Zielin, Lubiszyn, Różańsko, Stanowice, Dzieduszyce. These findings showed that in spite of many years exploration realized on the Main Dolomite unit in the Polish Basin there left many unrecognized objects worth of research. 3D seismic was the one of best tools to recognize the Main Dolomite deposits, its structures and properties. Its effectiveness confirmed in the BMB area resulted also in discovering new gas-condensate fields in the area of Gorzów Wielkopolski (Ciecierzyce, Racław, Baczyna). In the Pomerania region the Sławoborze field also was documented, but the largest one in the last time was placed in the area of Międzychód. The above described discoveries induced Polish petroleum geologists for the new look on prospections in the Main Dolomite unit and to verify reserves. Comparing studies of earlier results evidenced that if more we discover and we have better patterns to the evaluation, the better one can plan the exploration works and predict the new discovery. The most recent reserve estimation for the Main Dolomite unit in the Polish Basin calculated the total geologic resources of hydrocarbons at 307 ml tons and at 138 ml tons recoverable ones (Kotarba, 2000).

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