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THE OCCURRENCE AND CHARACTERISTICS OF RESERVOIR WATERS FROM THE SILESIAN SEGMENT OF THE ROTLIEGEND BASIN (SW POLAND)

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Abstract: The paper considers the potential for new discoveries of gas accumulations in the Rotliegend Basin on the basis of the analysis of reservoir and hydrochemical tests and the results of reservoir simulations. Several reservoir simulations carried out in the study area (history of production and history matching) demonstrate the regional migration of reservoir waters. The integration of the simulations with mathematical calculations (in consistency with Hubbert's theory) and with hydrochemical results permits recognition of the regional hydrodynamics and the potential localization of gas fields. In an analysis of the current hydrodynamic and hydrochemical conditions of reservoir waters in the Rotliegend (Lower Permian) strata, attention was focused on part of the sedimentary Rotliegend Basin, located south of the Wolsztyn-Pogorzela High, utilizing materials available from drilling and noting the differences between this area and the northern sub-basin. The current hydrogeological conditions and the dynamics of fluid transfer in the Rotliegend Basin are an effect of structural rearrangement during the Laramide orogeny. The basin hypsometry, resulting from the Laramide movements, became the decisive factor that controlled the filtration of groundwater. The recent hydrodynamic characteristics of migrating reservoir waters are reflected in the P-T (fluid pressure and temperature gradient) distribution pattern. Hence, the analysis of this distribution may reveal reactions that have taken place over time. It must be emphasized that clusters of gas fields are located in the zones occupied by stagnant groundwater (rNa/rCl<0.75) under hydrostatic (or slightly higher) pressure.

Key words: Rotliegend Basin, Permian, gas accumulations, hydrodynamic conditions, rNa/rCl coefficient.

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INTRODUCTION

Previous studies of the hydrodynamics of the Rotliegend Basin (Zawisza and Wojna-Dyląg, 1996; Zawisza, 2004, 2007; Zawisza *et al.*, 2010; Zawisza and Machowski, 2011) indicated the existence of a regional hydrodynamic field controlling the transfer of formation waters. Unfortunately, these studies were not based on the results of correct, full-scale reservoir simulations. Simulations carried out on several gas accumulations indicate tilting of the gas-water contact, in spite of the "linear" increase in pressure with depth. Contrary to some suggestions (e.g., Sorenson, 2005; Muggeridge and Mahade, 2012), the existing structural discontinuities (normal faults) do not constitute hydrodynamic barriers to fluid flow. The analysis of fluid properties and reservoir pressures permit a more comprehensive understanding of the migration and conditions of accumulation within any petroleum basin. The recent distribution of hydrocarbons in the Silesian segment of the Rotliegend Basin is an effect of the equilibrium attained between the solid phase (reservoir rock) and the liquid phase (reservoir fluids). This equilibrium gave rise to the formation of zones of limited fluid exchange within the interconnected pore spaces of the reservoir. Such zones are reflected in the hydrochemical record of the fluid by the rNa/rCl coefficient. If hydro- chemical considerations are supported by hydrodynamic analysis to determine the zones of reduced confining pressure, potential hydrocarbon accumulations can be identified.

GEOLOGICAL SETTING

The Polish part of the sedimentary Rotliegend Basin is the southeastern extension of the South Permian Basin (Gast *et al.*, 2010). In terms of petroleum system principles, this basin is a part of the Carboniferous–Rotliegend Total Petroleum System (Magoon and Schmoker, 2000), which includes the economically important petroleum provinces of western and central Europe (see e.g., Glennie, 1998; Klett *et al.*, 2000; Karnkowski P. H., 2007; Pletsch *et al.*, 2010). In this petroleum system, the source rocks are Carboniferous sediments, whereas the reservoir rocks are Rotliegend and

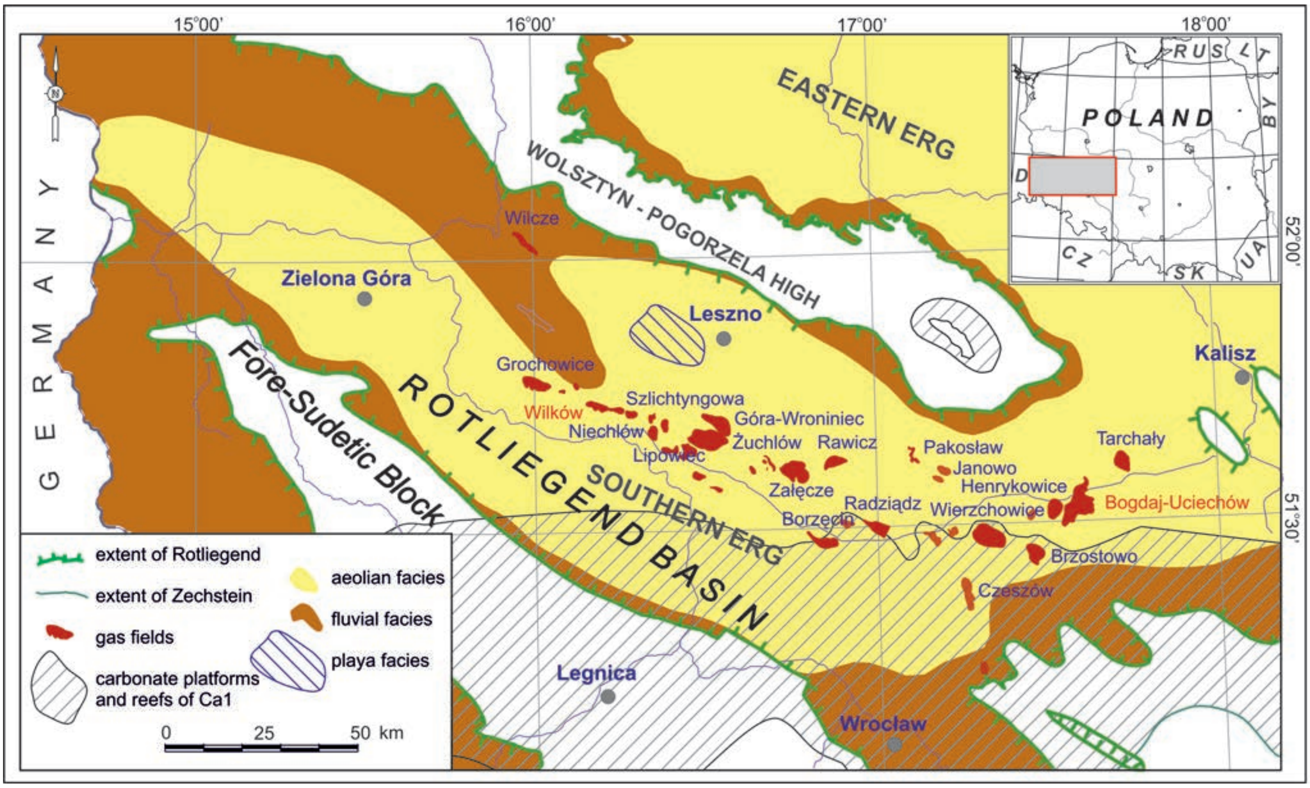

Fig. 1. Location map of Rotliegend and Zechstein Limestone (Ca1) reservoirs with reference to reservoir facies distribution (modified after Papiernik *et al.*, 2008).

Zechstein Limestone (Ca1) strata. The regional sealing mechanism is provided by thick Zechstein evaporites.

The South Permian Basin in Poland is a vast, extensional depression, resembling a half-graben (Pokorski, 1998). It is filled with a thick succession of aeolian, fluvial alluvial and lacustrine sediments. Analysis of the Rotliegend depositional environments permitted the recognition of several palaeogeographic units: the Central Basin (Pokorski, 1997); the Eastern Erg, a dune field extending along the southern margin of the Central Basin and dominated by aeolian sandstones (Kiersnowski, 1997; Kiersnowski and Buniak, 2006; Jarzyna *et al.*, 2009); and the Silesian segment of the Rotliegend Basin, an area dominated by aeolian (in central part) and fluvial deposition. A dune belt in this part of the basin (Fig. 1) is known as the Southern Erg (Karnkowski P. H., 1994; Kiersnowski, 1997).

In the northeast, the Silesian segment of the Rotliegend Basin is separated from the Central Basin by the Brandenburg-Wolsztyn-Pogorzela High (Kiersnowski *et al.*, 2010), while in the southeast it borders on the Fore-Sudetic Block. The tectonic pattern of the Silesian segment of the Rotliegend Basin is closely related to Late Carboniferous–Permian tectonic activity, which strongly influenced both the facies development and the thickness distribution of the Rotliegend sediments. This activity resulted also in the formation of a number of horsts and grabens, which were the predecessors of the small sub-basins of the Silesian segment of the Rotliegend Basin (Karnkowski P. H., 1999; Kiersnowski *et al.*, 2010).

In the Silesian segment of the Rotliegend Basin, Rotliegend sediments occupy an area, up to 60 km wide. The thickness of the Upper Rotliegend (Saxonian) varies from 0 (on the Wolsztyn-Pogorzela High) to more than 400 m in the axial parts of the basin, whereas the maximum thickness of the Zechstein Limestone (Ca1) strata is 60 m (Papiernik *et al.*, 2008).

The Silesian segment of the Rotliegend Basin hosts 24 gas fields out of a total of 68 accumulations discovered up to now in the Polish part of the Rotliegend Basin. Their reserves are estimated at about 120 Bm^3 (Wolnowski, 2004; Burzewski *et al.*, 2009; Górecki *et al.*, 2011). The first gas field in this area, i.e. the Bogdaj-Uciechów Field, was discovered in 1964 (Karnkowski P., 1999) and the largest gas accumulation is the Żuchlów Field, with recoverable reserves of about 24 Bm^3 (Karnkowski P., 1999).

The gas accumulations occur at depths in the range 1,200–1,700 m, in the uppermost part of Rotliegend aeolian sandstones. Locally, these sediments are in hydrodynamic continuity with the Zechstein Limestone strata (Fig. 2).

Genetic concepts relate these deposits to large piles of dune sands, which partly survived the Zechstein marine transgression and provided geomorphological traps (Kiersnowski and Tomaszczyk, 2010; Papiernik *et al.*, 2012).

METHODS AND DATA

The characterization of the deep waters saturating the Rotliegend terrigenous sediments was based upon the results of downhole measurements and analyses of samples from oil wells, completed by petroleum companies during the last 40 years of hydrocarbon exploration in the Fore-

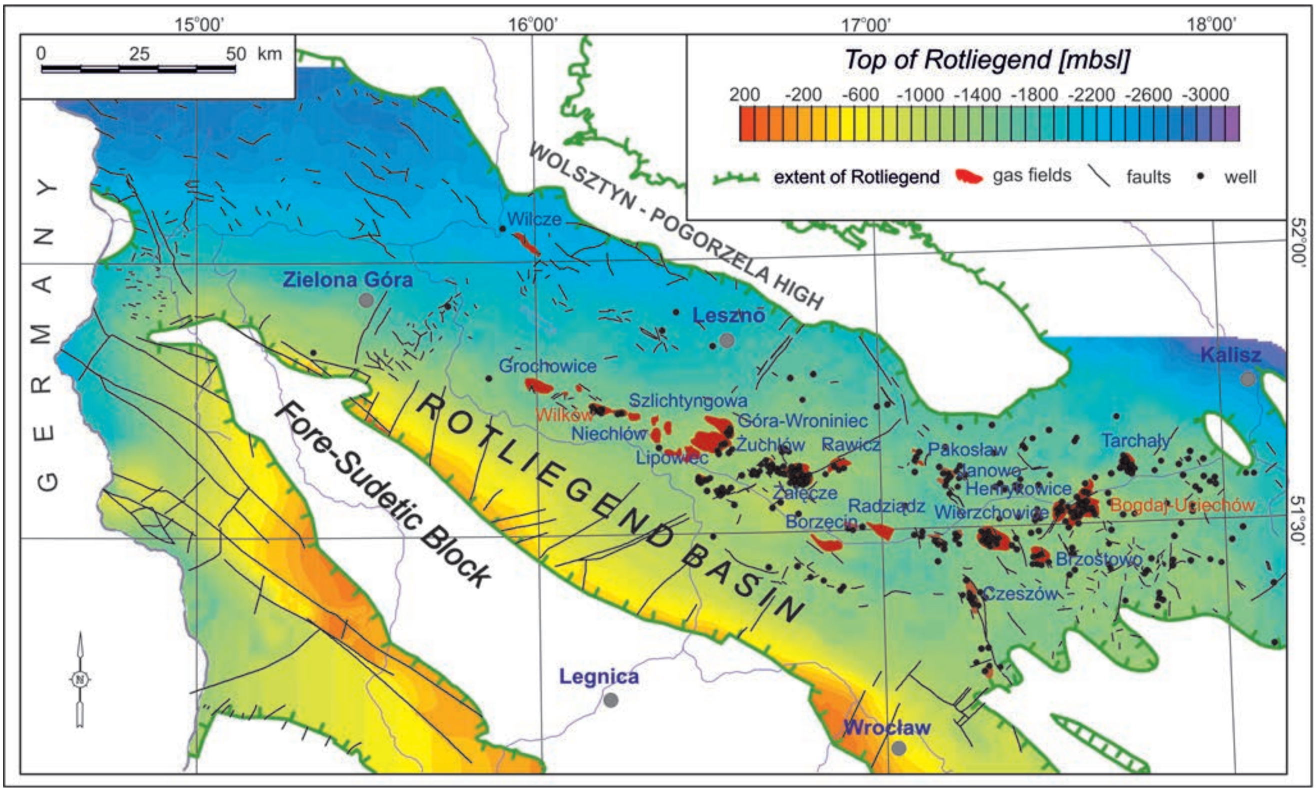

Fig. 2. Map of upper surface of Rotliegend Formation showing localization of gas fields.

Sudetic Monocline. For construction of plots and maps describing the dynamics of reservoir waters, the results of 328 measurements of reservoir pressure were used. The pressure values were either interpreted by means of Horner's method using the records of downhole manometers or measured during production tests carried out in the gas wells. For hydrochemical considerations, the results were used of 42 representative groundwater analyses, carried out in the laboratories of the Zielona Góra and the Piła Polish Oil and Gas Company.

Hydrodynamic assumptions

In any petroleum basin, the hydrodynamic conditions change in response to variations in thermodynamic factors: temperature, pressure and volume of pore space (Philips, 2009; Djunin and Korzun, 2010). In the Permian Basin, the structural rearrangement initiated during the Laramide orogeny caused important changes to both the hydrogeological conditions and the dynamics of fluid transfer (Słupczyński, 1979; Zawisza *et al.*, 2010; Muggeridge and Mahade, 2012). The hypsometry of the basin formed during the Laramide movements has become the crucial controlling factor of groundwater migration.

The anticlinal concept of hydrocarbon accumulation represents only one of many specific models of natural gas concentration in the pore space of a reservoir. It is valid as long as the reservoir waters remain in hydrostatic equilibrium. In almost all gas deposits discovered in the Rotliegend formations, hydrocarbons have accumulated in the uppermost part of the Saxonian, specifically on local, structural and erosional highs, where the gas attained its energy minimum, i.e., the kinetic energy was equal to zero at the lowest possible potential energy (Hubbert, 1953; Słupczyński, 1979; Jucha *et al.*, 1992; Zawisza, 2004, 2007). If the reservoir waters are stagnant or migrate slowly, the gas-water phase contact surface is horizontal. Inclination of this surface indicates the presence of a hydrodynamic trap and the direction of groundwater migration is defined by the direction of that slope, as given by formula (1):

$$tg \quad \frac{z}{x} \quad \frac{_w}{_w \quad _g} \quad \frac{h_w}{x} \qquad (1)$$

where:

$\frac{z}{x}$ – inclination of phase contact surface [nondimensional];

$_w$ – density of reservoir water [kg/m^3];

$_g$ – density of oil (gas) under reservoir conditions [kg/m^3];

$\frac{h_w}{x}$ – component of inclination of potentiometric surface towards x direction [nondimensional];

– inclination angle of deposit contour [°].

The changes in pressure with depth observed in the largest hydrocarbon accumulations in fields in the part of the Rotliegend Basin studied are listed in Fig. 3. On the basis of the fitting function, the average pressure gradient in the reservoir was calculated. Taking into account the fact that not all the pressures were measured exactly in the top part of the reservoir, the pressure values were re-calculated on the basis of the average reservoir-pressure gradient. These calculations facilitated the arithmetic operations nec-

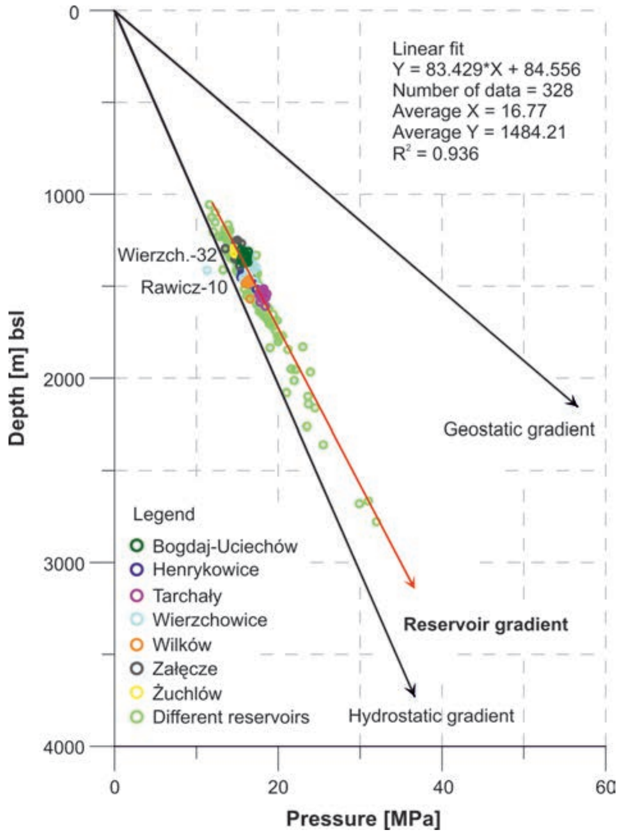

Fig. 3. Plot of variation in reservoir pressure with depth.

essary for the construction of the maps (formula 9). The horizontal distribution of the reservoir pressure gradients (dP/h) calculated is illustrated in Fig. 4.

The construction of hydrodynamic potential maps for reservoir waters in the Rotliegend formations was based mainly on the methodology developed by Hubbert (1953), Słupczyński (1979), Jucha *et al.* (1992), Wojna-Dyląg (2003) and Zawisza (2004, 2007).

The indicators of the migration of reservoir fluids (oil, gas, water) are local energy conditions. If a volume of fluid is selected at any point in the pore space of the reservoir, this volume has a certain potential energy, which for unit mass, constitutes its fluid potential, proportional to the piezometric head. Hence, the potential can be expressed as:

$$\Phi^{\circ} = g \cdot H;$$

where:
g – standard gravity, 9.81 m/s^2;
H – piezometric head referred to the sea level datum [m].

The potential of force at a given point can be defined as the amount of work necessary to move a unit mass of fluid from an initial site (e.g. sea level as a datum) to a new site (i.e. the measurement point), excluding the role of friction. The value of the potential of force of a specific fluid (liquid or gas), for which the density is constant or is a function of pressure, considered for any point of pore space with sea level as a datum, is given by the formula:

$$gz \quad {}_{0}^{P}\frac{dP}{\ } \qquad (2)$$

where:
– potential of force (of fluid) [m^2/s^2];
g – standard gravity, 9.81 m/s^2 ;
z – elevation of measurement site over the sea level datum [m];
P – reservoir pressure [Pa];
– fluid density within the reservoir [kg/m^3].

At constant fluid density, the integral in formula (2) is reduced to zero and the formula becomes:

$$gz \quad \frac{P}{\ } \qquad (3)$$

In both equations (2) and (3), the first expression represents the potential energy of a unit mass of fluid placed in the Earth's gravitational field and the second expression represents the energy of a unit mass of fluid resulting from the reservoir pressure. At any site in the pore space, in which the fluid potential is not constant, the force generated, acts on unit mass of fluid according to formula:

$$\vec{F} \quad grad \quad \vec{g} \quad \frac{1}{\ } gradP \qquad (4)$$

This force causes the migration of fluid towards the site of decreasing potential. If vector $\vec{F}$ is reduced to zero, the fluid attains hydrostatic equilibrium, i.e. its kinetic energy approaches a minimum and the migration of unit volume of fluid in the pore space of the reservoir ceases.

For the Rotliegend reservoir, where a double-phase system is present (reservoir waters and natural gas), two different values of potential will occur at any point of the hydrodynamic field, one for reservoir waters and one for the gas:

$$ {}_{w} \quad gz \quad \frac{P}{{}_{w}} \qquad (5)$$

$$ {}_{g} \quad gz \quad {}_{0}^{P}\frac{dP}{{}_{g}} \quad {}_{0}^{P_c}\frac{dP}{{}_{g}} \qquad (6)$$

where:
$,\ {}_{g}$ – densities of water and gas, respectively, under reservoir conditions [kg/m^3], assuming that gas density ${}_{g}$ is solely a function of pressure (isothermal reservoir);
P_c – capillary pressure (i.e. additional pressure exerted on a gas molecule, owing to the presence of capillary forces, insignificant in the case of gas) [Pa].

The forces exerted on a unit mass of water or gas are given by formulae:

$$\vec{F}_w \quad \vec{g} \quad \frac{1}{{}_{w}} grad\ P \qquad (7)$$

$$\vec{F}_g \quad \vec{g} \quad \frac{1}{{}_{g}} grad\ P \qquad (8)$$

As concluded from both formulae, the resultant vectors: $\vec{F}_w$ and $\vec{F}_g$ will have different values and directions for both components of the double-phase, water-gas system. As a result, fluids will migrate in different directions with different velocities, perpendicularly to their equipotential surfaces

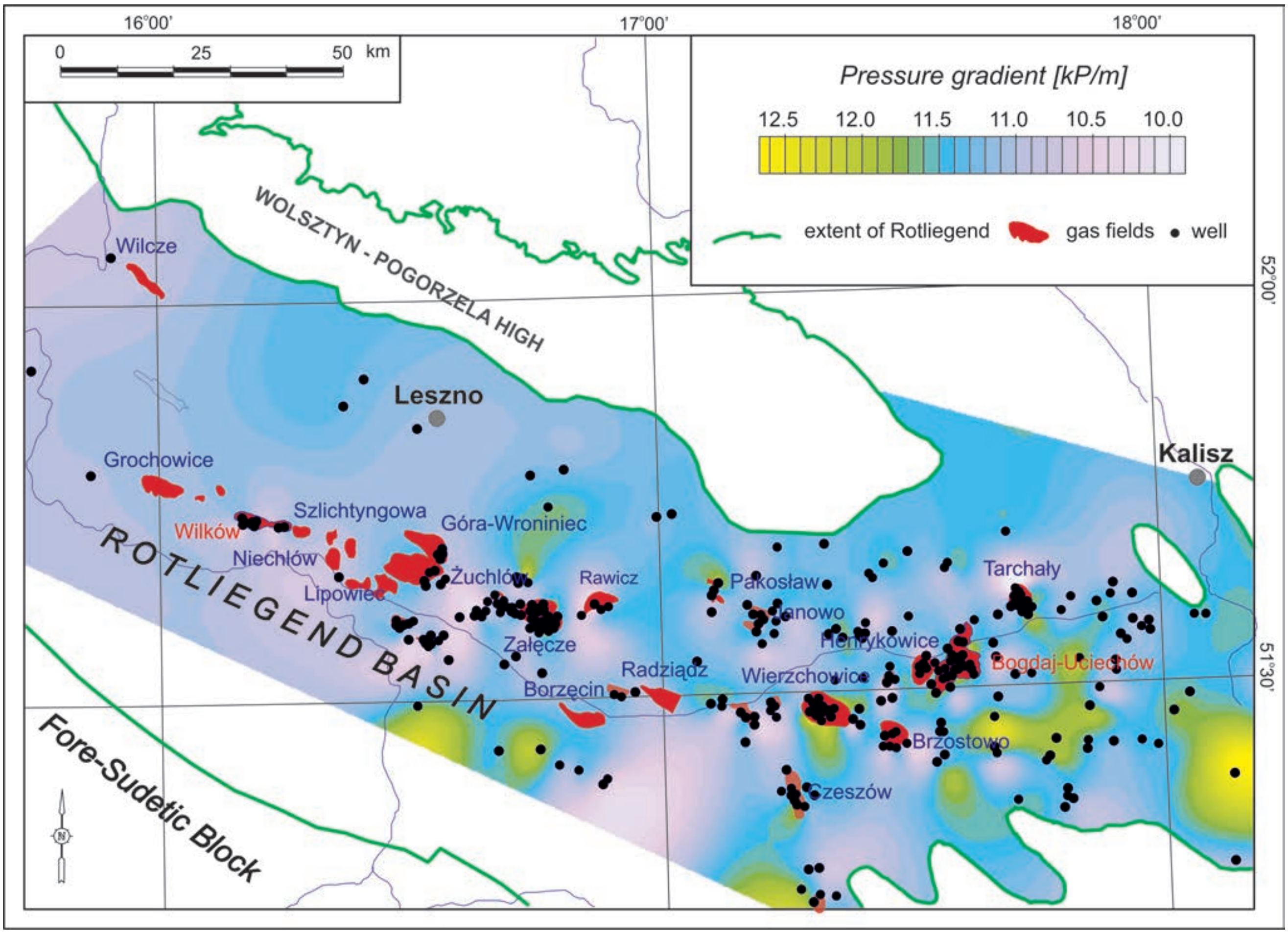

Fig. 4. Map of hydrodynamic gradient.

and towards locations of decreasing potential. Thus, gas will migrate from the zones of higher potential towards those of lower potential and will accumulate in traps or zones, where its potential will attain a local minimum. Consequently, gas traps will occur in the zones of low potential, under the impermeable caprocks.

If gas potential is constant in all directions within the reservoir pore space, no force will be exerted on a unit volume of fluid and such a fluid will not migrate.

The value of the potential of reservoir water H_{fw} can be determined for a particular well, using the formula (9):

$$H_{fw} \quad z \quad \frac{p}{_{fw}} \qquad (9)$$

where:
H_{fw} – potential expressed as a height of fresh water column (fw – fresh water);
p – reservoir pressure [Pa];
z – depth to the top of reservoir horizon reduced to the sea level datum [m],
$_{fw}$ – specific weight of fresh water [N/m^3].

According to formula (9), reservoir pressures were reduced with respect to sea level as a datum and expressed in the form of hydraulic heads. The hydraulic head is the height to which a fluid will be displaced from a well under the reservoir pressure. The results are illustrated in Fig. 5, as a map of fresh water potential.

Hydrochemical assumptions

Taking into account the current state of knowledge and the available measurement techniques, water samples taken for laboratory analyses commonly have inherent errors. The presence of hydraulic contacts between the Rotliegend and the Zechstein Limestone sediments caused that in most sampled wells, waters from both the Rotliegend sandstones and the Zechstein Limestone carbonates were collected.

In order to select representative data for waters from the Rotliegend reservoirs, the following factors were considered (Machowski, 2006):

– sampling method;

– completness of analyses (the lack of Total Dissolved Solids and principal ions data precluded the control of ionic equilibrium);

– specific weight of water (water samples of γ_w<1.1 g/dm^3 indicate a potential sampling error);

– pH (significant variations of pH suggest dilution of sampled reservoir waters with the fresh water from drilling mud);

– regional hydrochemical background.

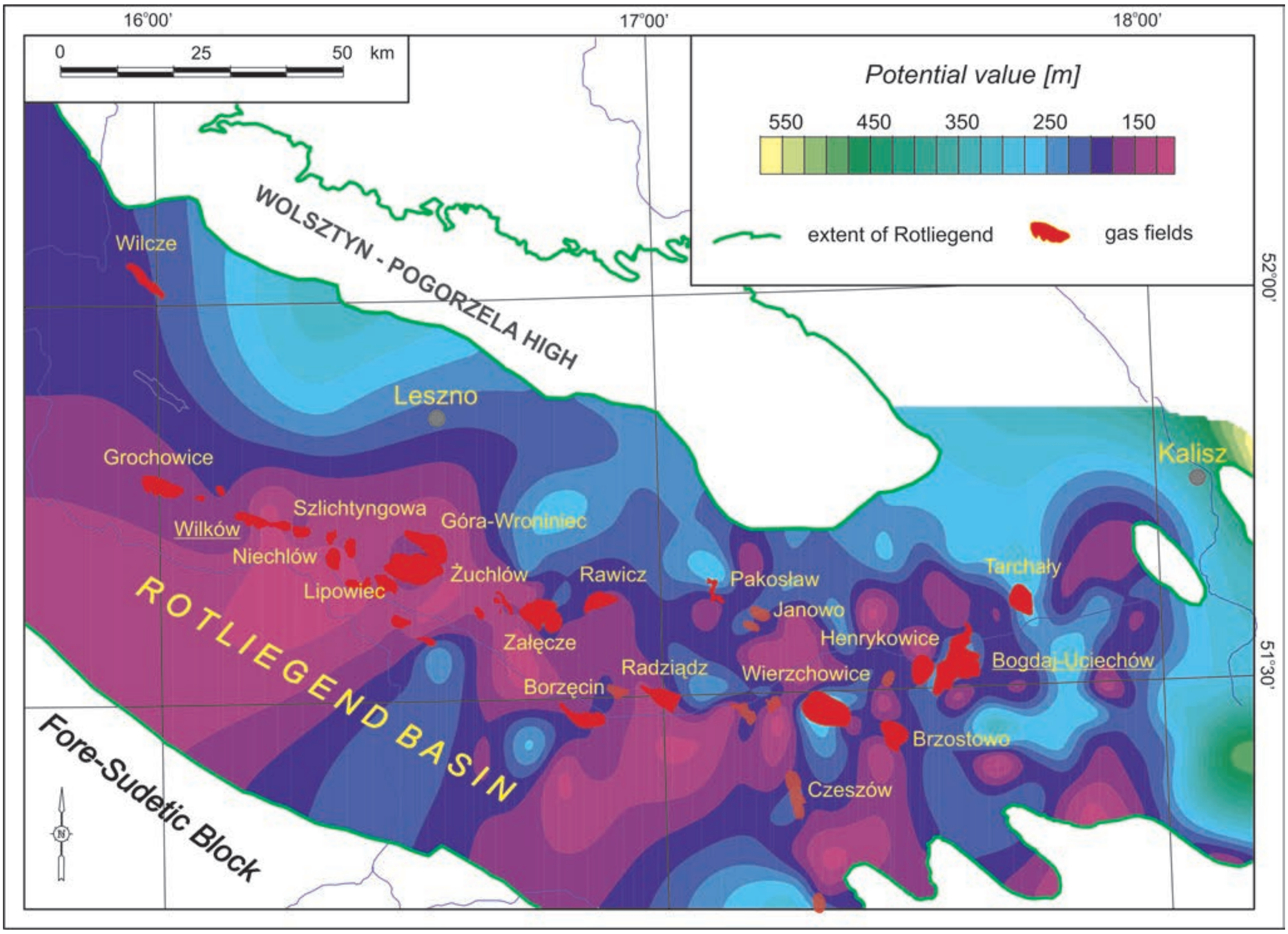

Fig. 5. Map of hydrodynamic potential.

In the selection of comprehensive chemical analyses of waters, the principal parameters were: pH, density and TDS. Specifically, the authors distinguished as uncontaminated only waters of pH from 4.0 to 10 and of density over 1.1 g/dm3. If water density was close to 1.0 g/dm^3, combined with low TDS and increased HCO_3^- and SO_4^{2-}, then contamination of the sample was regarded as very probable.

The recently observed composition of groundwaters results from many factors, among which the most important are: (i) initial composition of water and (ii) its later transformations caused by reactions at depths and by equilibration of groundwaters with infiltrating waters (Nawrot and Schoeneich, 1973; Schoeneich, 1973; Suchariew, 1974; Bojarski, 1976; Cimaszewski, 1976). These waters play a double role, being simultaneously the carriers and the moderators of chemical reactions active during the diagenesis.

The TDS, density and chemical composition of groundwaters filling the porous and/or porous/fractured rocks are controlled by lithology (precisely, by mineral composition of the rocks). Moreover, the present chemical composition is affected by specific P-T relationships, governed by changing geological conditions (Pazdro, 1964; Macioszczyk and Dobrzyński, 2002). The P-T conditions include pore pressure, temperature at particular depths and volume of pore/fracture space of rocks (McCain, 1990).

The specific weight of water (which results from its chemical and isotopic compositions, and from the mass of dissolved ions) and the TDS are so closely connected that the chemical composition of water can be determined directly from its specific weight (Levorsen, 1956). Vertical changes of both the TDS and the specific weight of analyzed reservoir waters are illustrated in figures 6 and 7.

The changes of pH document the varying concentrations of OH^{3+} ions, which results from different concentrations of carbonic acid, organic acids, gases, microorganisms, salt hydrolysis, etc. The sea/ocean water shows pH values from 6.86 to 8.40 with average: 8.0 (Riley and Chester, 1971; Collins, 1975; Carpenter, 1978). The pH of groundwaters can be lowered by hydrocarbons and particularly by carbon dioxide and hydrogen sulphide. Groundwaters in the Rotliegend Basin contain gaseous hydrocarbons and if these waters originated from ancient seawater (pH = 8), the coexisting gas must have lowered the pH values. The changes of pH with the depth for particular samples are illustrated in Fig. 8.

In order to determine the type of reservoir waters, Feret's ternary diagrams were drawn (Figs 9, 10) to illustrate the proportion of ions expressed on an ionic equivalent scale (% mval).

Taking into account the results of analyses of the basic ions, Cl, Na, K, Br, HCO_3, Ca, SO_4 and Mg, the hydro-

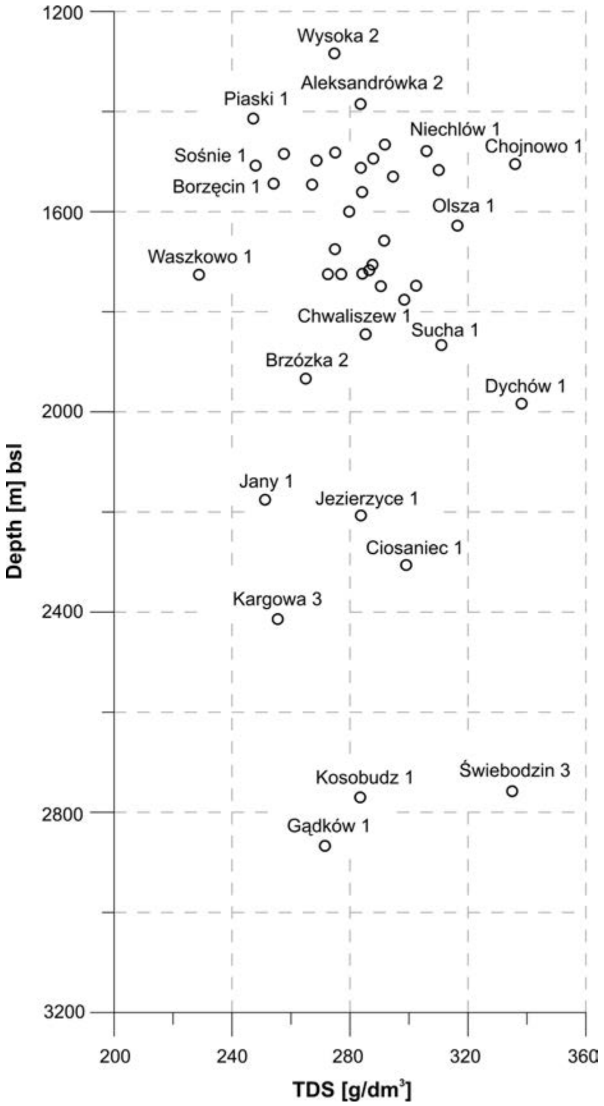

Fig. 6. Plot of variation in TDS with depth.

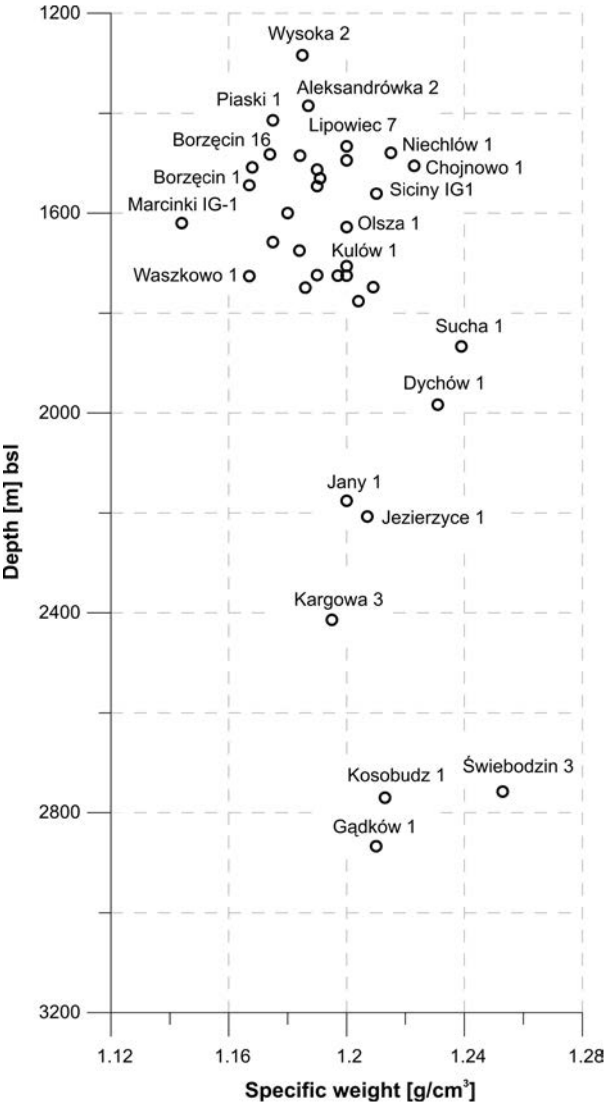

Fig. 7. Plot of variation in specific weight with depth.

chemical indices (ionic ratios) were calculated. Their values reflect changes in the chemical succession of deep groundwaters. For the purpose of petroleum exploration, attention was paid mostly to the rNa/rCl coefficient. This ratio reflects diagenetic transformations (ion exchange) of groundwaters, i.e., it illustrates the replacement of sodium by calcium in solution. At rNa/rCl>1.0, these are chloride waters. Decreasing rNa/rCl values, i.e., decreasing sodium contents, correspond to increasing transformation of groundwaters caused by gradually increasing ion exchange, which results in the progressive isolation of deep groundwaters from the infiltrating waters. Waters with decreased content of sodium and chloride ions usually show rNa/rCl>1.0; such values were absent from the population of samples studied. Waters of this type might have originated from the mixing with waters of lower TDS, due to indirect filtration. However, in the zones where rNa/rCl<1.0, water exchange is hampered, i.e., such waters show very limited contact with the infiltrating waters. Bojarski (1976) distinguished the following classes, based on the rNa/rCl coefficient:

– class I (rNa/rCl>0.85), which indicates a low-stability zone with groundwater exchange, this zone has limited potential for the preservation of hydrocarbon accumulations;

– class II (rNa/rCl = 0.85–0.75), which indicates a border zone within a petroleum basin, showing low stability, this zone has limited potential for the preservation of hydrocarbon accumulations;

– class III (rNa/rCl = 0.75–0.65), which implies the isolation of groundwater horizons and favourable conditions for the preservation of hydrocarbon accumulations;

– class IV (rNa/rCl = 0.65–0.50), in which the reservoir horizons are completely isolated and relic-like brines appear;

– class V (rNa/rCl<0.50), in which highly altered relic brines are present; this makes such zones very prospective for hydrocarbons.

These classes were marked in a rNa/rCl-versus-depth plot (Fig. 11).

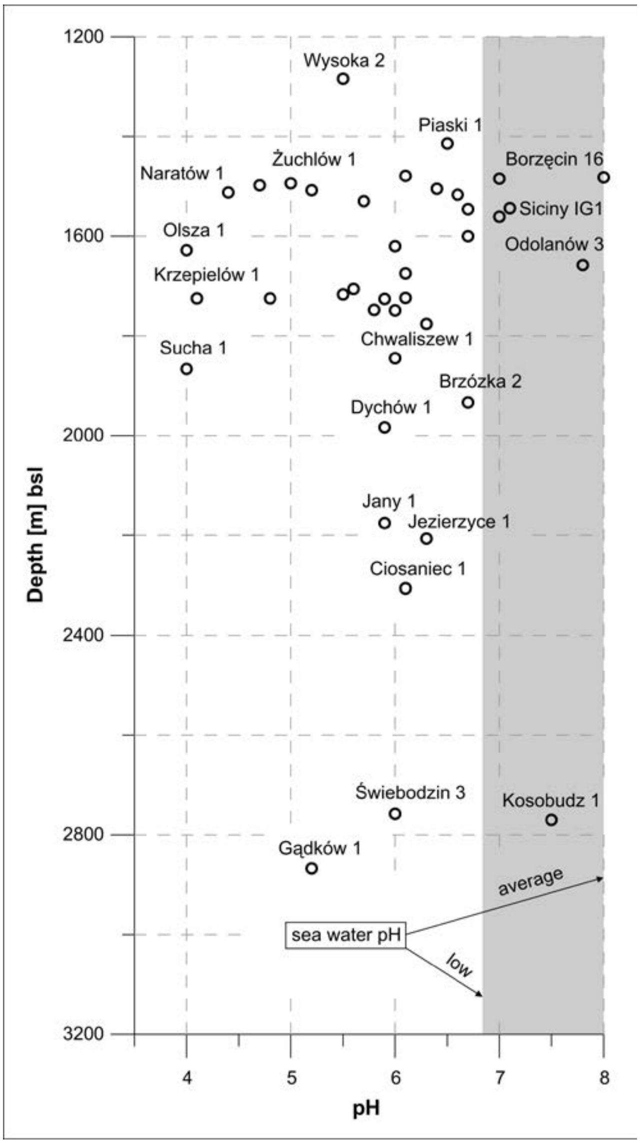

Fig. 8. Plot of variation in pH with depth.

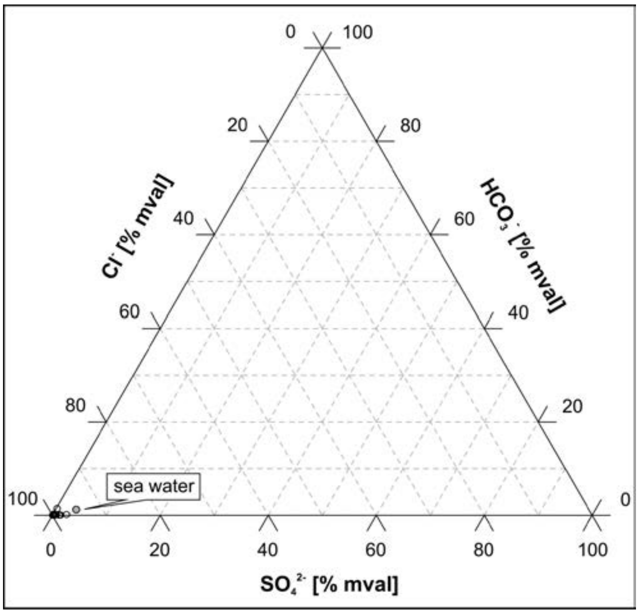

Fig. 9. Feret's ternary plot of anion concentrations.

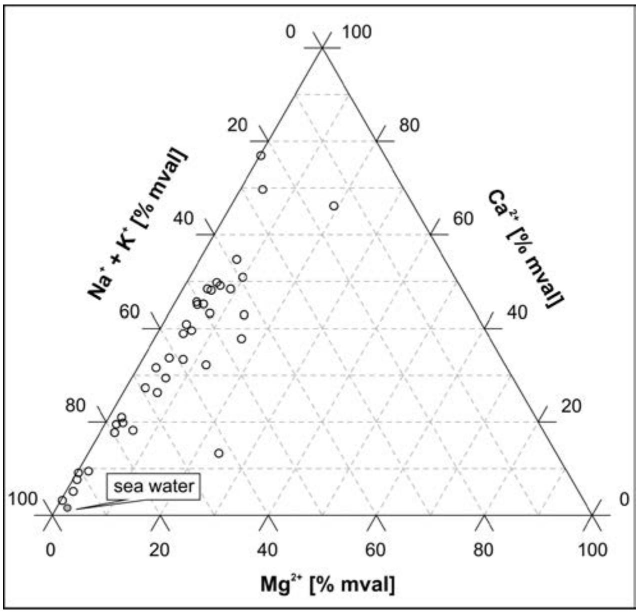

Fig. 10. Feret's ternary plot of cation concentrations.

RESULTS AND DISCUSSION

The results presented above demonstrate the regional dependence between hydrodynamic and hydrochemical equilibria and the distribution of natural gas accumulations in the Rotliegend Basin. To date, such analyses were carried out for individual fields (Cimaszewski, 1976). More regional attempts were presented by Słupczyński (1979), Zawisza (2007) and Zawisza *et al.* (2010).

Dynamics of Rotliegend reservoir waters

Pressure

Pressure measurements were made for the depth interval from 1,057 to 3,050 m below sea level. The values measured vary from 11.6 to 36.68 MPa. Pressure changes with depth are illustrated in Fig. 3, where the fitting function is described by the linear equation:

$$y = 83.429\, x + 84.556$$

for the correlation coefficient: $R^2 = 0.936$

The high fitting coefficient clearly indicates a linear trend of pressure-depth variation, which proves the presence of a continuous hydrodynamic field (Słupczyński, 1979; Zawisza, 2007; Zawisza *et al.*, 2010). Analysis of this trend reveals convergence of the fitting function and the average pressure of the groundwater column, named the hydrostatic gradient. Taking into account the fact that some pressures were measured at various stages in the exploitation of the gas fields, these measurements recorded pressure drops below the hydrostatic gradient of the reservoir waters (e.g., Wierzchowice-32, Rawicz-10 wells). For fields in the eastern part of the study area (e.g., Bogdaj-Uciechów, Henrykowice, Tarchały, Wierzchowice), the reservoir pressures are somewhat higher than the average pressure gradient for that part of the Rotliegend Basin (Zawisza, 2007; Zawisza *et al.*, 2010). In contrast, the fields located farther to the west (e.g., Wilków, Załęcze, Żuchlów) show lower pressures, although still exceeding the hydrostatic gradient values.

The results of reservoir modelling and simulation for the largest accumulation, the Bogdaj-Uciechów gas field, indicate a linear trend of pressure/depth variation, without any indication of reservoir compartmentalization (Fig. 12).

Pressure gradient

The pressure gradient values calculated fall into the range from 10.757 kPa/m in the Kargowa-3, Czechnów-4 and Wiewierz-22 wells, and up to nearly 13 kPa/m in the Pełczyn-2, Wierzchowice-1 and Bogdaj-Uciechów-29 wells. For developed gas accumulations, these pressures generally exceed 11 kPa/m (Fig. 4). The highest pressure gradients were found in the eastern part of the study area (Ostrzeszów-Międzybórz region) and abnormally high values of the pressure gradient (about 12 kPa/m) were observed in the Bogdaj-Uciechów, Wierzchowice and Czeszów fields. In contrast,, the western part of the study area shows the lowest values of pressure gradient, except for the Załęcze Gas Field (Słupczyński, 1979; Zawisza, 2007; Zawisza *et al.*, 2010).

The hydrodynamic pattern, determined by values of the primary reservoir pressures and their decreases in value as functions of distance (gradient) and time (exploitation), is closely related to depth, which supports the presence of a continuous hydrodynamic field (Zawisza *et al.*, 2010).

The hydrodynamic tests, carried out for many deposits in the part of the Rotliegend Basin studied, confirm the volumetric nature of hydrocarbon production, i.e. gas expansion is the only drive mechanism for production. Considering the overall mass balance, a pressure drop is foreseen with progressing exploitation of the accumulations (Górecki *et al.*, 1996).

Hydrodynamic potential

Basing on the results of hydrodynamic potential calculations made for particular measurement sites (representing the wells), the map of horizontal pattern of hydrodynamic field was drawn (see Fig. 5 and Hubbert, 1953; Słupczyński, 1979; Jucha *et al.*, 1992; Zawisza and Wojna-Dyląg, 1996; Zawisza, 2004, 2007; Zawisza *et al.*, 2010). In the Rotliegend Basin, the values of hydraulic heads vary from 100–150 m of fresh water column in the zones related to gas accumulations at 250–350 m, in the vicinity of the Wolsztyn-Pogorzela High, which is a hydrodynamic barrier for the transfer of reservoir fluids, up to 450–550 m in the vicinity of Kalisz. This pattern of hydraulic heads proves the presence of two fluxes of groundwater migration. The first flux is directed from the Wolsztyn-Pogorzela High to the south and southwest, towards the basin outcrops. The second flux is located deeper in the basin, in Kalisz area, and is directed to the southwest.

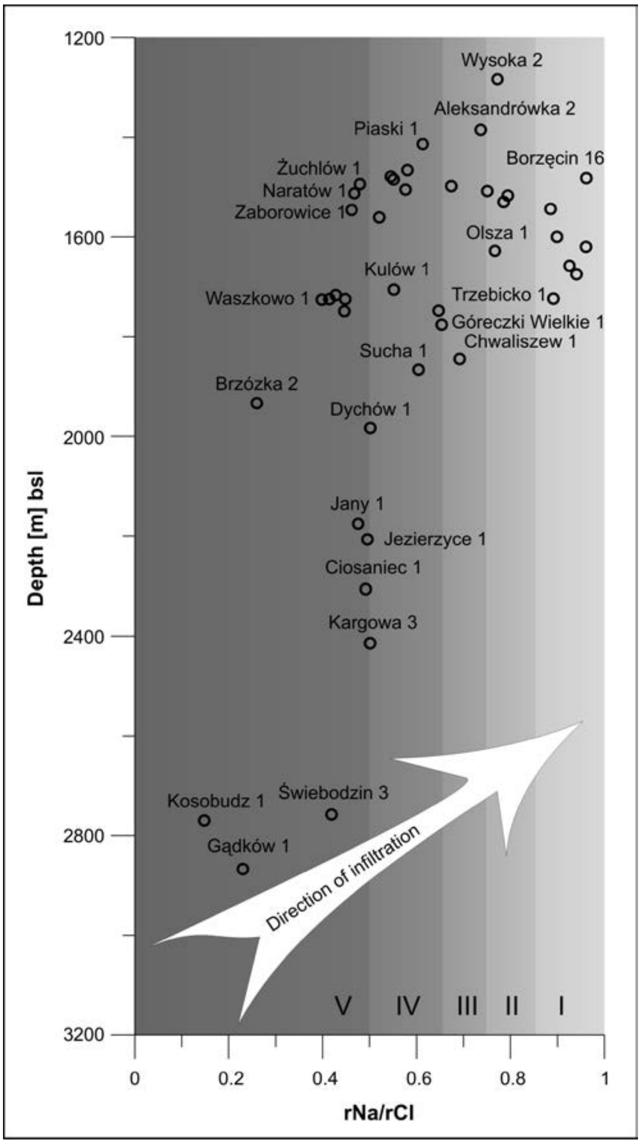

Fig. 11. Plot of variation in rNa/rCl coefficient with depth.

The increased potentials (250–300 m) in deposits located in the eastern part of study area (Tarchały, Wierzchowice) are related to the greater depth of the upper surface of the Rotliegend formation, despite the positive closure caused by local uplift of the reservoir horizon. Also the Pakosław accumulation reveals increased values of potential (200–250 m), which is explained by close proximity of the Wolsztyn-Pogorzela High, acting as the regional hydrodynamic barrier that controls the localization of deposits. However, in the southwestern part of the study area, a progressive decrease in potential is observed down to about 100 m, as revealed in the Wilków, Szlichtyngowa, Niechlów and Lipowiec fields.

Inclination of phase contact

In order to demonstrate the flow of reservoir waters, hydrodynamic calculations were carried on, which indicated the impact of this flow on the gas-water contact in the Wilków Field (western part of study area) (Zawisza and

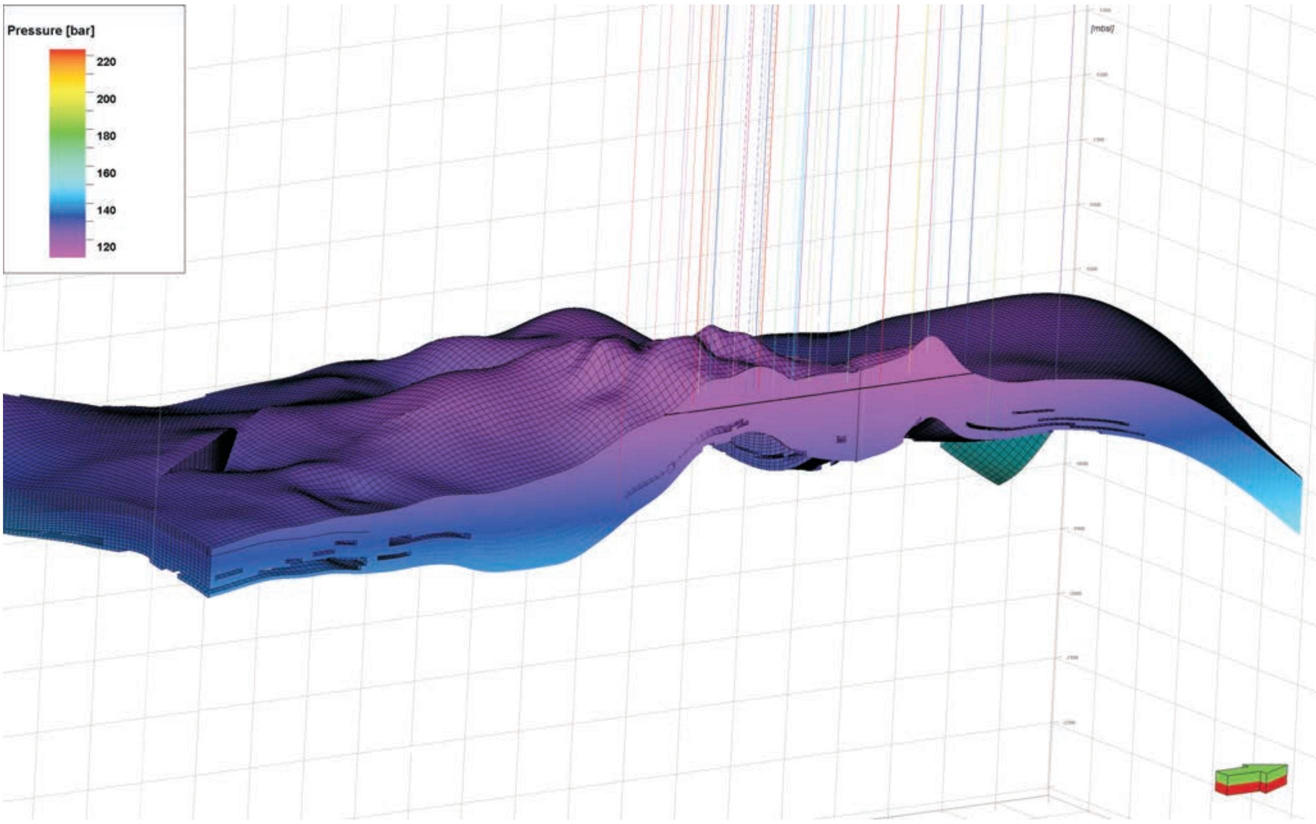

Fig. 12. Initial reservoir pressure in Bogdaj-Uciechów Gas Field (cross-section).

Machowski, 2011). The average densities of reservoir water ($_w$) and gas ($_g$) determined under reservoir conditions are:

$$_w = 1{,}190 \text{ kg/m}^3,$$
$$_g = 142 \text{ kg/m}^3$$

The calculations (not included into this paper) unambiguously revealed that in the Wilków Gas Field the gas-water phase contact is inclined towards the south. The slope angle was calculated from formula (1):

$$\mathrm{tg}\,\alpha = 0.01 \text{ thus, } \alpha = 0.6°$$

The tilting of the phase contact in this field compared with the map of hydrodynamic potential, demonstrates the obvious flow of reservoir fluids to the south, limited by the outcrops of reservoir horizon and a drop in hydraulic head (Hubbert, 1953; Słupczyński, 1979; Jucha *et al.*, 1992; Zawisza and Wojna-Dyląg, 1996; Zawisza, 2004, 2007; Zawisza *et al.*, 2010).

In the eastern part of study area, modelling of reservoir dynamics was carried out for the Bogdaj-Uciechów Gas Field (Fig. 13). The results indicate tilting of gas-water contact. In this area, the pressure/depth relationship is linear at similar values of vertical and horizontal permeability. This rather precludes the possibility of compartmentalization, due to the presence of a hydrodynamic discontinuity caused by a loss of permeability and the hydrophilic character of the reservoir rocks. The tilting of the phase contact shown in Fig. 13 is related to the flow of reservoir waters towards the south and southwest.

Hydrogeochemistry of Rotliegend groundwaters

Overall TDS

The current thermodynamic equilibrium in the water-reservoir rock system is reflected in the overall TDS, which corresponds to the concentration of ions for the dissolved chemical compounds.

The TDS values of the groundwaters studied do not always correspond to the recent temperatures in the subsurface. This is a result of overheating, caused by volcanic activity during the Saalian orogenic phase. The TDS values range from 228 g/dm^3 (the Waszkowo-1 well) to 338 g/dm^3 (the Dychów-1 well) (Fig. 6), which is consistent with the regional hydrochemical range for the Rotliegend formations. The analyzed samples were collected mostly from depths of 1,400–1,800 m, where the average TDS value is 283 g/dm^3.

Such high TDS values indicate that groundwaters from the Rotliegend formations are brines saturated with mineral substances, which is indicative of a basin with slow and stagnant mineralization processes (Cimaszewski, 1976; Słupczyński, 1979; Zawisza, 2004, 2007; Zawisza *et al.*, 2010). It is the common belief that TDS increase with the depth, which explains hydrochemical zonation. However, the trend of TDS changes shown in Fig. 6 is not fully linear and is even discontinuous for some depth intervals. Measurements carried on at about 2,000 m depth revealed an increase of TDS with depth, but below 2,000 m no clearly linear trend was found. The authors did not construct a distribution map of chemical parameters, because of the irregular pattern of the representative analyses.

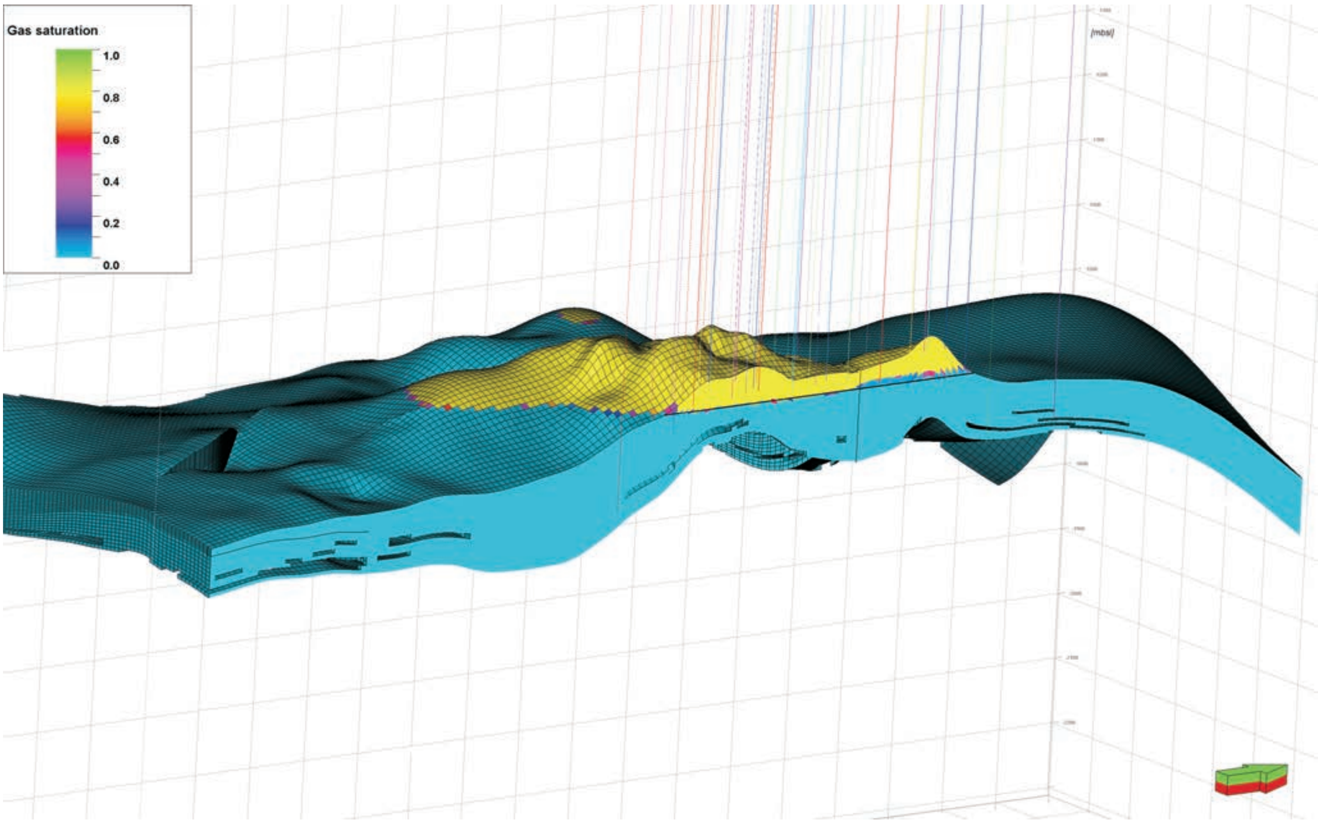

Fig. 13. Tilted gas-water contact in Bogdaj-Uciechów Gas Field (reservoir simulation results).

Data on pH

The analyzed samples revealed pH values from 4 (the Olsza-1 and Sucha-1 wells) to the average value for sea water (the Borzęcin-16 and Odolanów-3 wells). The vertical pH distribution is presented in Fig. 8. The lack of any clear trend of pH changes with depth is an effect of the presence of coexisting gas, which significantly lowered the pH (Bojarski, 1976; Cimaszewski, 1976). Gases from the Rotliegend formations contain, on average, about 50–60% methane, 40–50% nitrogen and about 1% combined carbon dioxide and helium, which results in a remarkable lowering of pH.

A comparison of the pH values with the distribution of gas accumulations demonstrates that the lowest pH values correlate well with the gas accumulations (e.g., the Żuchlów-1 well). Moreover, the pH values increase with increasing distance from the gas fields, which demonstrates that thorough pH measurements of reservoir waters can be an indirect indicator of gas potential in the Rotliegend formations.

Specific weight of deep groundwaters

The changes in specific weight of groundwaters with depth are very similar to the changes in TDS. However, a thorough analysis of this relationship shows that such simple regularity is valid only for a certain level of TDS values (Cimaszewski, 1976), which is controlled by the strong affinity of Ca and Ba (in accordance with Polish regulations, Ba is not analyzed routinely) for certain ranges of TDS values. As well, the presence of deuterium can significantly lower the solubility and can increase the specific weight of groundwaters.

The reservoir waters analyzed exhibit specific weights from 1.14 g/cm^3 (the Marcinki IG-1 well) to 1.25 g/cm^3 (the Świebodzin-3 well) (Fig. 7) with an average value of 1.2 g/cm^3 (Cimaszewski, 1976; Słupczyński, 1979; Zawisza *et al.*, 2010).

Categorization of reservoir waters

The chemical characterization of reservoir waters is based on the contents of the principal ions, Cl, Na, K, Br, HCO_3, Ca, SO_4 and Mg. In order to categorize the analyzed waters, the ionic composition was displayed in Feret ternary diagrams, using the ion equivalent scale, %mval (Figs 9, 10). This approach to data presentation aims to demonstrate the contents of dominant cations (Na+K, Ca, Mg) in the waters sampled. Specifically,, the Na+K concentrations vary from 25 to 98%mval, Ca concentrations are from 2 to 75 % mval and those of Mg change from 1 to 25%mval. The Na+K sum was used, because such combined analyses are more common to company practice than separate determinations for Na and K. The analysis of diagrams enabled the authors to conclude that Na is the dominant ion in the Lower Permian reservoir waters, whereas the K content is insignificant. Among analyzed anions, Cl, HCO_3 and SO_4, the dominant ion is Cl (98% mval). Accordingly, this ion is of major importance in the categorization of the waters studied.

Generally, the reservoir waters from Rotliegend formations belong to chloride type. Precisely, these waters represent mostly the Cl-Na-Ca and Cl-Na types (Cimaszewski, 1976). The chloride ion is dominant in natural reservoir waters and plays the role of a “conservative” element, which controls the phase relationships between the fluids and the minerals.

With reference to the distribution of the gas accumulations, the reservoir waters show a zonal arrangement: typically Na or Cl waters occur close to the margins of the fields (Cimaszewski, 1976), whereas Ca waters are encountered only in the western part of the study area.

The rNa/rCl coefficient

The changes of rNa/rCl coefficient with the depth are illustrated in Fig. 11. Taking into account Bojarski’s classification (Bojarski, 1976), the samples analyzed fall into the following classes:

– class I, has low potential for hydrocarbon preservation (rNa/rCl>0.85); examples are the Trzebicko, Szklarka Myśliniewska, Odolanów and Brzostowo. This class includes also the Borzęcin Gas Field, located in the southern part of the study area. It can be suggested that owing to the successive flooding of the gas horizon and a location in the zone of increased potential, in this deposit either the flow rate of reservoir waters increases or the gas horizon is recharged with fresh waters;

– class II has low potential (rNa/rCl = 0.85–0.75); examples are the Wysoka-2 and Olsza-1 wells;

– class III is favourable for the preservation of hydrocarbon accumulations (rNa/rCl = 0.75–0.65); examples are the Czechnów-1 and Aleksandrówka-2 wells;

– class IV is very favourable for preservation of hydrocarbon deposits (rNa/rCl = 0.65–0.5); examples are the Lipowiec-7 and Niechlów-1 wells;

– class V is highly perspective (rNa/rCl<0.5); examples are the Żuchlów-1 and Naratów-1 wells.

The results indicate that the waters analyzed originated mainly from the areas favourable, very favourable or highly perspective for the preservation of hydrocarbon accumulations. Such waters are typical of deep zones with slow circulation, whereas in the center of the basin the stagnant waters occur, even more optimal for preservation of petroleum accumulations. The rNa/rCl values of over 0.85 in the Lower Permian groundwaters prove their low hydrochemical maturity and infiltrational provenance (Cimaszewski, 1976; Słupczyński, 1979; Zawisza, 2004, 2007; Zawisza *et al.*, 2010). The results of the present study demonstrate insignificant exchange of reservoir waters with fresh ones and a characteristic transition from stagnant hydrochemical conditions (e.g. the Kosobudz-1 well) to an increasing role of infiltration (e.g., the Marcinki IG-1 and Borzęcin-16 wells).

SUMMARY

Analyses of the reservoir waters filling the pore space of Rotliegend rocks in the Silesian segment of the Rotliegend Basin permitted an evaluation of the hydrodynamic and hydrochemical characteristics of the fluids and led to the following conclusions:

– the reservoir pressures measured in the depth interval 1,057–3,050 m below surface gave values from 11.6 to 36.68 MPa. High fitting coefficient of pressure values and depths indicates the presence of a continuous hydrodynamic field. In the eastern part of the study area, where the Bogdaj-Uciechów, Henrykowice, Tarchały and Wierzchowice gas fields were discovered, the reservoir pressures are higher than expected with respect to the average pressure pattern within the Rotliegend reservoir. The fields in the western part of the study area (e.g., Wilków, Załęcze and Żuchlów) show lower reservoir pressures, but still exceeding those estimated from the analysis of the average hydrostatic gradient;

– the calculated pressure gradients fall in the range of 10.757–13.0 kPa/m. In the vicinity of gas accumulations, these values exceed 11 kPa/m. In the eastern part of the study area, where the Bogdaj-Uciechów, Wierzchowice and Czeszów fields occur, the gradients are higher and reach about 12 kPa/m, whereas in the western part (Wilków, Szlichtyngowa, Niechlów and Lipowiec gas fields) the values for pressure gradient are the lowest in the study area;

– the hydrostatic head values vary from 100 to 150 m of fresh water column in the zones of gas accumulations, from 250 to 350 m in the vicinity of the Wolsztyn-Pogorzela High and from 450 to 550 m in the vicinity of Kalisz town. Such a hydrostatic head pattern forces the fluid flow from the Wolsztyn-Pogorzela High towards the south and southwest as well as from the deeper parts of the basin (in the vicinity of Kalisz) towards the southwest. The increased potentials (250–300 m) noticed for the Tarchały and Wierzchowice gas fields (the eastern part of the study area) are related to the greater depth of the reservoirs. The increased potentials (200–250 m) in the Pakosław Field reflect the influence of the Wolsztyn-Pogorzela High, which is the hydrodynamic barrier controlling the distribution of the gas accumulations. The southwestern part of the study area (Wilków, Szlichtyngowa, Niechlów and Lipowiec fields) reveals the lowest potential values of over 100 m.

– the hydrodynamic calculations made for the Wilków gas field demonstrate tilting of the gas/water phase contact surface at $\alpha = 0.6°$. Such an inclination indicates migration of the reservoir waters towards the south, where there are lower values of hydraulic head;

– the reservoir waters collected from the depth interval 1,400–1,800 m below surface show high TDS values: from 200 to 300 g/dm^3 (283 g/dm^3, on average). In the gas fields the TDS values are even higher. High TDS indicates the presence of brines, typical of basins with slow and/or stagnant mineralization processes;

– the pH values of the waters analyzed are lower than the pH of sea water (8) and are significantly lower in the areas of hydrocarbon accumulations;

– the specific weights of the waters analyzed fall in the range 1.14–1.25 g/cm^3, with an average value of 1.2 g/cm^3;

– the reservoir waters of the Rotliegend formations belong to the chloride type, dominated by Cl-Na-Ca and Cl-Na compositions. Zonation was observed in relation to gas accumulations – a common feature is the presence of typical Na or Cl compositions close to the contours of hydrocarbon accumulations;

– the decreasing values of the coefficient rNa/rCl<0.75, observed in most part of the study area, indicate the mature character of the reservoir waters and low infiltration, hence, conditions favourable for the preservation of gas accumulations. According to Bojarski's categorization system, the reservoir waters prove favourable, very favourable or very perspective conditions for hydrocarbon preservation. Such waters are typical for zones of deep, slow circulation and indicate stagnant conditions in the central part of the basin, which are even more optimal for the preservation of petroleum accumulations;

– finally, it is concluded that the zones of low hydrostatic gradient, low hydraulic head and decreasing values of the genetic coefficient rNa/rCl<0.75 are potentially favourable for the preservation of gas accumulations within the Rotliegend Basin. Therefore, these parameters can contribute to successful petroleum exploration.

In summary, the results of hydrochemical and hydrodynamic analyses indicate that it is possible to predict the occurrence of gas accumulations in the Polish part of the Rotliegend Basin. Moreover, the reservoir simulations carried out for some of the gas fields together with mathematical analysis demonstrate the value of extrapolations and prognoses for the discovery of new gas accumulations.

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REFERENCES

Bojarski, L., 1976. Parametry hydrochemiczne jako pośredni wskaźnik ropogazonośności. *Nafta*, 3: 17–28. [In Polish.]

Burzewski, W., Górecki, W., Maćkowski, T., Papiernik, B. & Reicher, B., 2009. Prognostic gas reserves – undiscovered potential of gas in the Polish Rotliegend basin. *Geologia, Kwartalnik Akademii Górniczo-Hutniczej*, 35: 123–128. [In Polish, with English summary.]

Carpenter, A. B., 1978. Origin and chemical evolution of brines in sedimentary basin. *Oklahoma Geological Survey Circular*, 79: 60–77.

Cimaszewski, L., 1976. *Geologia naftowych anomalii hydrochemicznych*. Unpublished PhD. Thesis, AGH University of Science and Technology, Kraków, 242 pp. [In Polish.]

Collins, A. G., 1975. *Geochemistry of Oilfield Waters*. Developments in Petroleum Science, 1, Elsievier Publishing Company, New York, 496 pp.

Djunin, V. I. & Korzun, A. V., 2010. *Hydrogeodynamics of Oil and Gas Basins*. Springer Science, 395 pp., DOI 10.1007/978-90-481-2847-1,Springer Dordrecht Heidelberg London New York.

Gast, R. E., Dusar, M., Breitkreuz, C., Gaupp, R., Schneider, J.W., Stemmerik, L., Geluk, M. C., Geissler, M., Kiersnowski, H., Glennie, K. W., Kabel, S. & Jones, N. S., 2010. Rotliegend. In: Doornenbal, J. C. & Stevenson, A. G. (eds), *Petroleum Geological Atlas of the Southern Permian Basin Area.* EAGE Publications, Houten, pp. 101–121.

Glennie, K. W., 1998. Lower Permian Rotliegend. In: Glennie, K. W. (ed.), *Petroleum Geology of North Sea. Basic Concepts and Recent Advances*. London, Blackwell, pp. 137–173.

Górecki, W., Papiernik, B., Maćkowski, Reicher, B., Botor, D., Burzewski, W. & Machowski, G., 2011. Hydrocarbon potential of the Carboniferous – Lower Permian Total Petroleum System in the Polish part of the SPB. *Extended abstracts, 73rd EAGE Conference & Exhibition in corporating SPE EUROPEC, 23–26 May, Vienna*, P298. EarthDoc, EAGE Publications B.V. [30.12.2013].

Górecki, W., Słupczyński, K., Soboń, J. & Kicman, W., 1996. Hydrodynamic conditions of hydrocarbons accumulations in the Rotliegend reservoir complex, Western Pomerania, Northern Poland. *Oil and Gas News from Poland*, 6: 204–213.

Hubbert, M. K., 1953. Entrapment of petroleum under hydrodynamic conditions. *American Association of Petroleum Geologists Bulletin*, 37: 1954–2026.

Jarzyna, J., Puskarczyk, E., Bała, M. & Papiernik, B., 2009. Variability of the Rotliegend sandstones in the Polish part of the Southern Permian Basin – permeability and porosity relationships. *Annales Societatis Geologorum Poloniae*, 79: 13–26.

Jucha, S., Kulczyk, T., Zawisza, L. & Żołnierczuk, T., 1992. Hydrodynamic estimation of natural gas deposits Lipowiec, Żuchlów and Góra-Wroniniec. *Gospodarka Surowcami Mineralnymi*, 8: 597–626. [In Polish, with English summary.]

Karnkowski, P., 1999. *Oil and Gas Deposits in Poland*. Towarzystwo Geosynoptyków "Geos", Kraków, 380 pp.

Karnkowski, P. H., 1994. Rotliegend lithostratigraphy in the central part of the Polish Permian Basin. *Geological Quarterly*, 38: 27–42.

Karnkowski, P. H., 1999. Origin and evolution of the Polish Rotliegend basin. *Polish Geological Institute Special Papers*, 3: 1–93.

Karnkowski, P. H., 2007. Permian basin as a main exploration target in Poland. *Przegląd Geologiczny*, 55: 1003–1015.

Kiersnowski, H., 1997. Depositional development of the Polish Upper Rotliegend basin and evolution of its sediment source areas. *Geological Quarterly*, 41: 433–456.

Kiersnowski, H. & Buniak, A., 2006. Evolution of the Rotliegend Basin of northwestern Poland. *Geological Quarterly*, 50: 119–138.

Kiersnowski, H., Peryt, T., Buniak, A. & Mikołajewski, Z., 2010. From the intra-desert ridges to the marine carbonate island chain: middle to late Permian (Upper Rotliegend – Lower Zechstein) of the Wolsztyn-Pogorzela high, west Poland. *Geological Journal*, 44: 319–335.

Kiersnowski, H. & Tomaszczyk, M., 2010. Permian dune fields as geomorphological traps for gas accumulation: Upper Rotliegend – Zechstein Basin, SW Poland. In: Schwarz, E., Georgieff, S, Piovano, E. & Ariztegui, D. (eds), *Abstracts Volume, 18th International Sedimentological Congress*, Mendoza. *International Association of Sedimentologists*, La Plata, Argentina, p. 944.

Klett, T. R., Schmoker, J. W. & Ahlbrandt, T. S., 2000. *Assessment hierarchy and initial province ranking, Chapter AR, in U.S. Geological Survey World Energy Assessment Team, U.S. Geological Survey World Petroleum Assessment 2000 – Description and results.* USGS Digital Data Series DDS-60, Version 1.0, CD-ROM, Disk one, 31 pp.

Levorsen, A. I., 1956. *Geology of Petroleum*. W. H. Freeman and Co., San Francisco, 703 pp.

Machowski, W., 2006. *Characteristic of Geofluids Filling the Rotliegend Formation Pore Space*. MSc. Thesis. Department of Fossil Fuels, AGH University of Science and Technology, Kraków, 76 pp. [In Polish, with English summary.]

Macioszczyk, A. & Dobrzyński, D., 2002. *Hydrogeochemia*. Wydawnictwa Naukowe PWN, Warszawa, 448 pp. [In Polish.]

Magoon, L. B. & Schmoker, J. W., 2000. *The total petroleum system – The natural fluid network that constrains the assessment unit. Chapter PS, in U.S. Geological Survey World Energy Assessment Team, U.S. Geological Survey World Petroleum Assessment 2000 – Description and results*. USGS Digital Data SeriesDDS-60, Version 1.0, CD-ROM, Disk one, 31 pp.

McCain, W. D., Jr., 1990. *The Properties of Petroleum Fluids*. PennWell Publishing Co. Inc., Tulsa, 548 pp.

Muggeridge, A. & Mahade, H., 2012. Hydrodynamic aquifer or reservoir compartmentalization? *American Association of Petroleum Geologists Bulletin*, 96: 315–336.

Nawrot, T. & Schoeneich, K., 1973. Współczynnik korelacji w polskich wodach złożowych. *Geofizyka i Geologia Naftowa*, 7–8 (199–200): 24–27. [In Polish.]

Pazdro, Z., 1964. *Hydrogeologia ogólna*. Wydawnictwa Geologiczne, Warszawa, 336 pp. [In Polish.]

Papiernik, B., Buniak, A., Hajto, M., Kiersnowski, H., Zych, I., Machowski, G. & Jasnos, J. 2008. Model pojemnościowy utworów czerwonego spągowca i wapienia cechsztyńskiego na podstawie laboratoryjnych badań petrofizycznych i interpretacji geofizyki wiertniczej. In: Górecki, W. (ed.), *Zasoby prognostyczne, nieodkryty potencjał gazu ziemnego w utworach czerwonego spągowca i wapienia cechsztyńskiego w Polsce*. Raport projektu nr 562/2005/Wn-06/FG-sm-tx/D finansowanego przez Ministerstwo Środowiska w latach 2005–2008. Archiwum KSE AGH, Kraków. pp. 1–169. [In Polish.]

Papiernik, B., Kiersnowski, H., Machowski, G. & Górecki, W., 2012. Upper Rotliegend reservoir and facies models of geomorphological and structural gas traps in Silesian Basin – South-West Poland. *Extended Abstracts, 74th EAGE Conference & Exhibition in corporating SPE EUROPEC, 4-7 June, Copenhagen.* EarthDoc, EAGE Publications B.V. http://www.earthdoc.org/publication/publicationdetails/?publication = 59497 [30.12.2013].

Philips, O. M., 2009. *Geological Fluid Dynamics*. Cambridge University Press, Cambridge, 285 pp.

Pletsch, T., Appel, J., Botor, D., Clayton, C. J., Duin, E. J. T., Faber, E., Górecki, W., Kombrink, H., Kosakowski, P., Kuper, G., Kus, J., Lutz, R., Mathiesen, A., Ostertag-Henning, C., Papiernik, B. & Van Bergen, F., 2010. Petroleum generation and migration. In: Doornenbal, J. C. and Stevenson, A. G. (eds), *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v., Houten, p. 225–253.

Pokorski, J., 1997. The Lower Permian (Rotliegend). *Prace Państwowego Instytutu Geologicznego*, 153: 35–62. [In Polish, with English summary.]

Pokorski, J., 1998. Prospects of the occurrence of gaseous hydrocarbons in the Rotliegend deposits. *Prace Państwowego Instytutu Geologicznego*, 165: 293–298. [In Polish, with English summary.]

Riley, J. P. & Chester, R., 1971. *Introduction to Marine Chemistry*. Academic Press, London and New York, 465 pp.

Schoeneich, K., 1973. Wody naftowe permu podsalinarnego monokliny przedsudeckiej. *Geofizyka i Geologia Naftowa*, 7–8 (199–200): 12–16. [In Polish.]

Słupczyński, K., 1979. Warunki występowania gazu ziemnego w utworach dolnego permu monokliny przedsudeckiej. *Prace Geologiczne*, 118: 1–107. [In Polish.]

Sorenson, R. P., 2005. A dynamic model for the Permian Panhandle and Hugoton fields, western Anadarko basin. *American Association of Petroleum Geologists Bulletin*, 89: 921–938.

Suchariew, G. M., 1974. *Hydrogeologia złóż ropy naftowej i gazu ziemnego*. Wydawnictwa Geologiczne, Warszawa, 104 pp. [In Polish.]

Wojna-Dyląg, E., 2003. *Warunki tworzenia się przestrzeni wypełnionych węglowodorami*. PhD. Thesis, AGH University of Science and Technology, Krakow, 115 pp. [In Polish.]

Wolnowski, T., 2004. Prognoza zasobności czerwonego spągowca w basenie permskim Niżu Polskiego w świetle nowych technik poszukiwawczych. In: *Basen permski Niżu Polskiego, czerwony spągowiec, budowa i potencjał zasobowy. Konferencja Naukowo-Techniczna, Piła, 23.04.2004*. Wydawnictwo Naukowe Bogucki, Poznań, pp. 17–30. [In Polish.]

Zawisza, L., 2004. Hydrodynamic conditions of hydrocarbon accumulation exemplified by the Pomorsko and Czerwiensk oil fields in the Polish Lowland. SPE Paper 90586, *SPE Annual Technical Conference and Exhibition, Houston*, Texas, USA, 26-29 September 2004, Society of Petroleum Engineers Inc. – Richardson, pp. 1-10.

Zawisza, L., 2007. Hydrodynamic modelling of petroleum basins for assessing their reservoir perspectives. *The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (IGSMiE PAN Kraków)*, 140:1–89. [In Polish, with English summary].

Zawisza, L. & Machowski, W., 2011. *Warunki hydrodynamiczne złoża gazu ziemnego Wilków*. Unpublished report. Department of Fossil Fuels Archive, AGH UST, Kraków, pp. 1–10 [In Polish.]

Zawisza, L., Piesik-Buś, W. & Maruta, M., 2010. Rola wyniesienia wolsztyńskiego w rozmieszczeniu złóż węglowodorów w utworach czerwonego spągowca monokliny przedsudeckiej. *Wiertnictwo Nafta Gaz*, 27: 485–493. [In Polish.]

Zawisza, L. & Wojna-Dyląg, E., 1996. Hydrodynamiczne modelowanie basenów osadowych na przykładzie basenów naftowych Polski. *VII Międzynarodowa Konferencja Naukowo-Techniczna "Nowe metody i technologie w geologii naftowej, wiertnictwie, eksploatacji otworowej i gazownictwie"*. Kraków, 20–21.06.1996, pp. 89–96. [In Polish.]