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Methane potential of the Upper Silesian Coal Basin carboniferous strata – 4D petroleum system modeling results

The work was based on the results of a research project aimed at quantifying the accumulation of CBM (Coal Bed Methane) natural gas in hard coal seams and tight gas in mudstone and sandstone formation in the western part of the Upper Silesian Coal Basin (USCB). The area covered is about 1300 km^2, which accounts for almost 25% of the USCB area within the Polish territory The task was realized out using the method of dynamic spatial modeling of petroleum systems, using Petrel and PetroMod software. The input data for building the model were structural surfaces of major lithostratigraphic series and array of geological and geophysical data from 10 wells in the research area. Particular attention has been paid to the optimization of lithological models of individual facies, as well as the thermal model, as well as the integration and calibration of all component models of the general hydrocarbon system model, which allowed for a fairly precise reconstruction of the current structural and parametric image. The processes of hydrocarbon generation had the most intense course during the upper Carboniferous, which was associated with their buried and reaching the highest temperatures Numerous alternative models have been constructed and simulated under various scenarios of structural and thermal evolution, which have allowed us to estimate the resource potential of Carboniferous USCB formations. Total amounts of generated and stored gas in individual lithostratigraphic series with free gas localized in unconventional (tight) accumulations and adsorbed gas (in coal seams) have been estimated. The results obtained from the scenario considered by the authors as the most likely are presented and analysed. The decisive influence on the amount of accumulated hydrocarbons seems to have the tectonic's activity timing, due to results of the model simulation proved to be the most sensitive to the length of the interval opening the faults.

Key words: methane content, CBM, petroleum system modelling, Upper Silesian Coal Basin.

Metanonośność utworów karbońskich Górnośląskiego Zagłębia Węglowego w świetle wyników przestrzennego dynamicznego modelowania 4D systemów naftowych

Praca powstała na podstawie wyników przedsięwzięcia badawczego, którego celem było oszacowanie ilościowej akumulacji gazu ziemnego typu CBM (*coalbed methane*) w pokładach węgla kamiennego oraz typu *tight gas* (gazu zamkniętego) w formacjach mułowcowych i mułowcowo-piaszczystych w zachodniej części Górnośląskiego Zagłębia Węglowego (GZW). Analizowany obszar zajmuje około 1300 km^2, co stanowi prawie 25% powierzchni GZW znajdującego się w granicach Polski. Zadanie zrealizowano za pomocą metody dynamicznego przestrzennego modelowania systemów naftowych, używając oprogramowania Petrel oraz PetroMod. Jako dane wejściowe do budowy modelu wykorzystano powierzchnie strukturalne głównych wydzieleń litostratygraficznych oraz szereg danych geologicznych i geofizycznych pochodzących z 10 otworów wiertniczych znajdujących się w obszarze badań. W ramach realizacji przedsięwzięcia skonstruowano i symulowano wiele alternatywnych modeli według różnych scenariuszy ewolucji strukturalnej i termicznej. Optymalizacja, integracja i kalibracja wszystkich modeli składowych ogólnie pojętego modelu systemu naftowego umożliwiły dość precyzyjne odtworzenie obecnego obrazu strukturalnego i parametrycznego w analizowanym obszarze. Procesy generowania węglowodorów najintensywniejszy przebieg miały w czasie górnego karbonu, co wiązało się z ich najgłębszym pogrążeniem oraz osiągnięciem najwyższych temperatur. W wyniku przeprowadzonych symulacji obliczono szacunkową metanonośność karbońskich utworów GZW. Oszacowano całkowite ilości wygenerowanego oraz zakumulowanego gazu w poszczególnych seriach litostratygraficznych, z wyodrębnieniem gazu wolnego ulokowanego w akumulacjach niekonwencjonalnych typu *tight* i gazu zaadsorbowanego (w pokładach węgla). W artykule przedstawiono i poddano analizie wyniki otrzymane w rezultacie realizacji scenariusza uważanego przez autorów za najbardziej prawdopodobny. Wydaje się, że decydujący wpływ na ilość zakumulowanych węglowodorów ma czas aktywności tektonicznej analizowanego obszaru, gdyż wyniki symulacji modelu okazały się najbardziej wrażliwe na długość interwału czasowego otwarcia uskoków.

Słowa kluczowe: metanonośność węgla, gaz w pokładach węgla, modelowanie dynamiczne systemu naftowego, GZW.

Introduction

Methane, as the main component of CBM (Coal Bed Methane) type natural gas accumulations in hard coal seams, as of tight gas type accumulations in mudstone-sandstone formations between hard coal seams, is the energy source with the lowest coefficient of greenhouse gas emission intensity. Because of that, in the era of intensive actions preventing the global climate change, it is an extremely valuable energy raw material. Poland possesses one of the largest hard coal deposits in Europe, however methane accompanying the coal seams in coal basins so far was not the object of successful industrial scale exploitation.

Carboniferous formations filling the basin of the Upper-Silesian Coal Basin (USCB) together with its Mesozoic-Tertiary cover meet all the criteria of independent petroleum system. This fact encouraged the authors to attempt assessment of the methane potential of USCB Carboniferous formations by means of numerical simulations dedicated in a standard way to analyses of petroleum systems and used in hydrocarbon deposits exploration. Under the project Implementation, all components of a petroleum system were identified and parametrised – for the first time in Poland – and then spatial dynamic 4D modelling of petroleum processes was carried out in the western part of the USCB.

The results of modelling allowed us reconstruct the course of hydrocarbons migration and accumulation processes proceeding on the geological time scale and to assess their quantitative effects. Unit and total amounts of generated hydrocarbons were estimated and the zones of increased gas accumulations were located in clastic formations between hard coal seams (being tight gas type accumulations), as well as in coal seams themselves (where adsorbed methane is the main component).

Geological settings

The investigated area is located in the central – western part of the Upper Silesian Coal Basin (USCB) (Figure 1). The USCB is one of the largest bituminous coal basin in Europe (7250 km^2) and the largest part of this area (5650 km^2) lies in the territory of Poland [15]. The basin was formed at the final stages of the evolution of the Moravo-Silesian Palaeozoic Basin and was developed in the Moravian-Silesian foreland of the Variscan orogene and became a part of its outer zones [25].

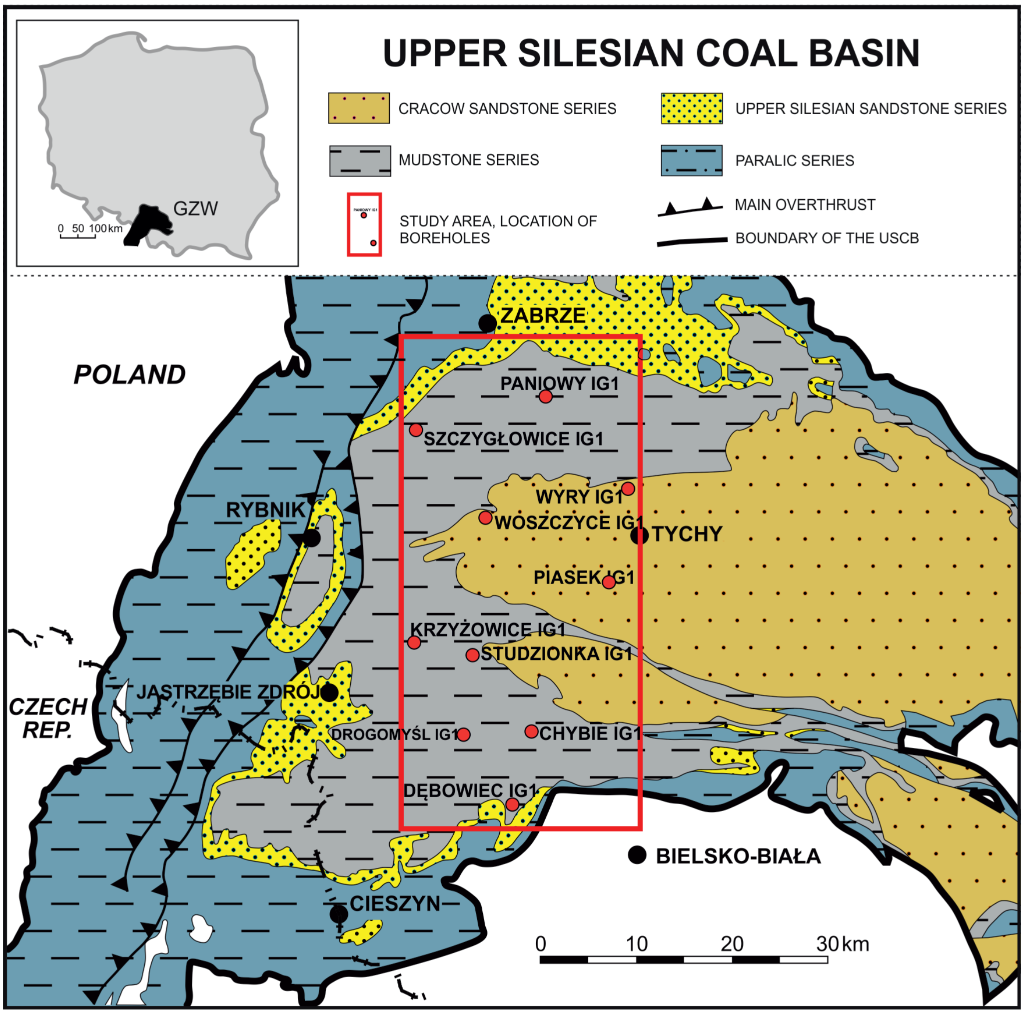

Fig. 1. Geological map of the USCB without the post-Carboniferous cover (modified [17]), with the studied area marked in red

Lithostratigraphy

Geological profile within the Upper Silesian Coal Basin begin by metamorphic and igneous rock of the Brunovistulicum crystalline. Crystalline basement is covered by sediments of Cambrian, Ordovician and Devonian units. Carboniferous sedimentation begins with pre-flysch carbonates, continues through the marine clastic sediments of the Culm's flysch facies stage to the coal-bearing terrigenous molasses [5].

The sequence of USCB, reaching 8000 m thickness in the central part, is divided into the two main parts consisting of four lithostratigraphic series. The lower part is Paralic Series, marked by wide spectrum of clastic type of sediments, from marine to terrestrial-marine and thin coal seams (rarely achieving 2 m thickness). The upper part of the coal bearing sediments was deposited after sedimentary break and is composed of continental deposits developed as three separate series: Upper Silesian Sandstone Series, Mudstone Series and Cracow Sandstone Series (Figure 2) [17].

The Upper Silesian Sandstone Series lies discordantly upon the Paralic Series, comprises of sandstones (predominance – 60% of the profile), and conglomerates of mudstones and claystones. Thick coal seams (510 coal seam reaches over 20 m) make up about 9% of the series profile. The thickness of all series is quite diverse and decreases to the east [29].

The overlying Mudstone Series represents the monotonous complex dominated by fine-grained clastic rocks, mainly claystones and mudstones (80% of the series), and sandstones. Coal seams constitute 5÷7% of this unit. The thickness of that series varies from about 2000 m in the western part to about 150 in the eastern part of USCB [29].

The youngest part of USCB is Cracow Sandstone Series and is distinguished by the substantial of coarse-grained sediments (more than 70% of the series). Claystone and mudstone occur as several meter thick strata accompanying the thick coal seams (6÷7 m of thickness). This series does not occur in the south-west part of the USCB [29].

The Carboniferous paleosurface is an irregular erosion surface and is covered by Permian rocks in the northeastern part of the USCB, by Triassic clastics and calcareous rocks in the northern part and by Jurassic rocks in the eastern part [10]. The lowermost part is Miocene sequence that covers a considerable part of the basin, comprises clays, claystone and conglomerate. Carpathian nappes driven from the south over the Carboniferous rocks partly cover the Miocene sequence.

All of the described USCB series occur in the study area and all of data accessible were used in the geological model (see: the Structural Model part)

Tectonics

The USCB is divided into three different tectonic units. The largest – central part of the basin is occupied by a tectonically disturbed zone. This area is characterised by normal and normal-transcurrent faults trending NNE-SSW and WNW-ESE with throws up to 1200 m. The western part is sub-meridian fold belt, with two major overthrusts and several different fold systems. The eastern part of the basin is dominated by block zone tectonics [29].

The study area is situated in the block zone of the USCB, within extended and gentle structure, cut by numerous faults.

Coal bed methane origin and spatial distribution in the USCB

The coalification process and coal bed methane (CBM) origin In the Upper Silesian Coal Basin was subject of research by several authors [1, 18, 19, 20, 21, 23, 26, 28, 31]. The investigations included origin, spatial distribution and estimation of resources coal bed methane in the USCB.

Coal bed methane (CBM) generation in the USCB is directly connected with coalification process. This process occurred in two main stages [28]. The first one was during pre-orogenic basin formation in the late Carboniferous and was completed in the Asturian phase. Organic matter was heated within foredeep burial. The second stage went on during post-orogenic phase in Mesozoic or Paleogene times and was resulting in coalification associated with heating in a tensional tectonics regime.

Based on Apatite fission-track and helium dating studies [1], coalification was mainly controlled by processes related to a deep Variscan burial event. The maximum temperature (90÷100°C) in the Upper Silesian Coal Basin was reached between the Carboniferous and Permian periods

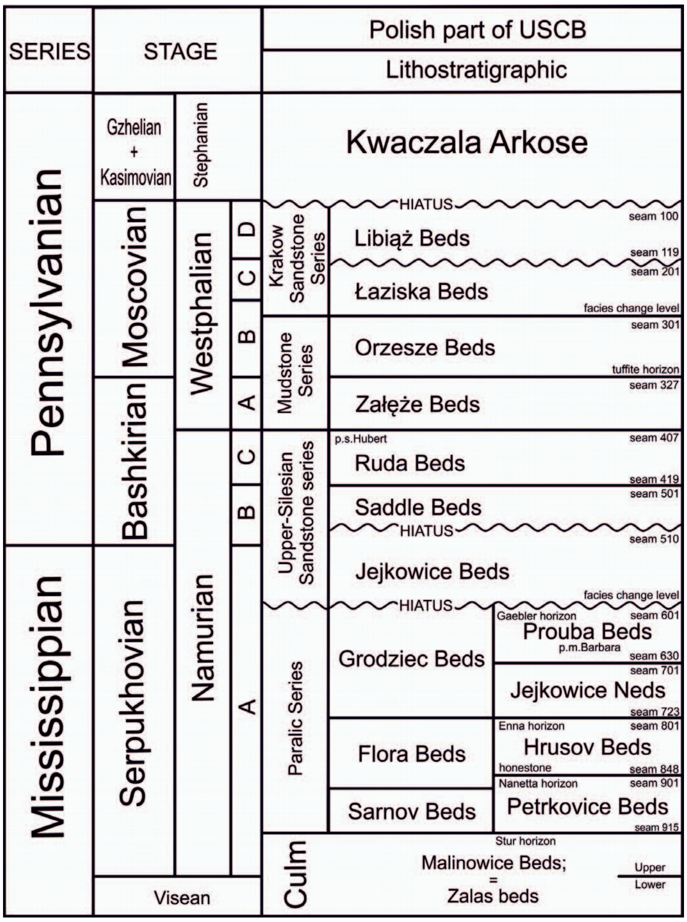

Fig. 2. Lithostratigraphic chart of USCB Carboniferous ([2] with changes – [14], [24])

Base on this and other information coal bed methane in the Upper Silesian Coal Basin is a product of coalification during late Carboniferous times and prior to the Asturian orogenic phase [18, 21, 22].

Generally, northern and southern CBM regions in the USCB differ in methane variability depending on depth [27]. In the north part of the basin the most of gas rich interval occurring between 500 and 1500 m. The southern part of USCB is divided into two zones of a high methane content: the upper zone whit secondary kind of accumulation and the lower primary zone at greater depth [23].

This general bipartition is caused by erosion of the basin during uplifting event within the Mesozoic – Paleogene time. Much of the coal bed series was out-gassed. In the Paleogene, pressure decline was accelerated by an infiltration of meteoric water.

Structural model

The investigation area is located in the central – western part of the Upper Silesian Coal Basin (Figure 1) and was chosen based on two main factors: CBM content and distribution with the USCB (see above) [15] and also sufficient number of geological data, especially well data. The model's size is 25 ×50 km (Figure 1).

Two main types of input data were used to build the structural model:

- structural maps of main productive Carboniferous series, provided in the Geological-deposit atlas of Polish and Czech part of the Upper-Silesian Coal Basin with a scale of 1:20 000 [15],
- borehole data (geological and geophysical) from 10 wells: Paniowy-IG1, Szczygłowice-IG1, Wyry-IG1, Woszczyce-IG1, Piasek-IG1, Krzyżowice-IG1, Studzinka-IG1, Drogomyśl-IG1, Chybie-IG1, and Dębowiec-IG1 [3–12].

All of geological input data were taken from the National Geological Archive of the Polish Geological Institute – National Research Institute.

Structural model (Figures 3a, 3c) consist of 47 faults (Figure 3b) in the faults model and 28 structural surfaces. In addition to the main maps of the productive Carboniferous series, the model has:

- 5 coal seems – 358 and 405 within the Załęże Beds, 412 within the Ruda Beds, 504 and 510 within Siodłowe Beds,
- 3 sandstone layers: one within the Załęże Beds, two within the Ruda Beds,
- 1 mudstone layer within the Załęże Beds.

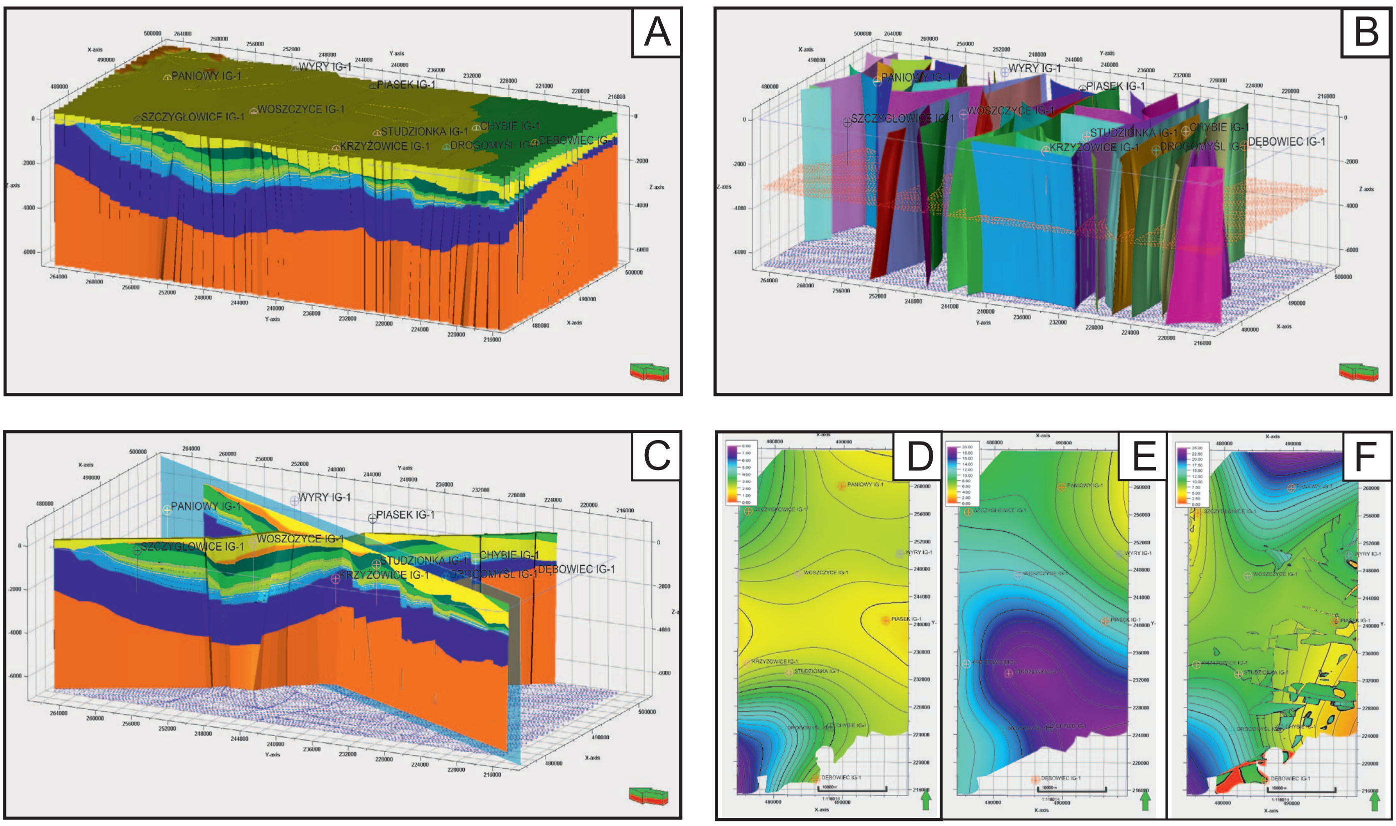

Fig. 3. A – structural model of the analysed area; B – fault network model; C – diagonal cross section by the model by vertical planes; D – map of the 405 seam thickness; E – map of the Załęże Beds mudstone thickness; F – map of the Załęże Beds sandstone thickness

Sandstone and mudstone layers are within the entire area of model and this is some kind of simplification. From the geological point of view this assumption is not correct because clastic beds were formed in the alluvial depositional system like a meandering rivers, crevasse splays, overbank sand wedges etc [13]. Hence identification of sandstone and mudstone distribution without seismic data and/or dense net of wells was not possible. Layers of this kind of clastic beds were necessary for gas accumulation in the conventional and unconventional (thigh) reservoir rocks.

Methodology

The 4D petroleum system modelling is a reconstruction of the evolution of a spatial petroleum system model on the geological time scale. Apart from a parameter geologic and lithologic model that presents the current sedimentary basin architecture and the spatial distribution of specific significant parameters, such as organic matter content, temperature, porosity, permeability etc., the evolution of those parameters proceeding along with the development of the sedimentary basin can be presented. It shows also the dynamics, location and the time of such processes as the structural and tectonic evolution, thermogenesis and migration of heat, transformation of kerogen, generation, sorption, and expulsion of hydrocarbons, as well as formation and filling of traps, evolution of pressures, migration of deposit media leading to the formation of hydrocarbon accumulations. The process of petroleum systems modelling is based on a creation of static model illustrating the current state of the sedimentary basin and building a dynamic simulation (forward modelling) of its evolution course afterwards, beginning with the oldest depositions of sediments, via the periods of full deposits sequence (including also the deposits eroded), till the current state. The implementation of a simulation model consists of creation and integration of interrelated component models of a generally understood petroleum system model, which are:

- **geological and lithological model** illustrating the structural and tectonic evolution of the sedimentary basin (paleobathymetry, dynamics of such processes as subsidence, deposition and erosion of sediments, emergence of faults), as well as evolution of parameters of all lithostratigraphic subdivisions proceeding along with the evolution of basin,
- **thermal mode**l showing the heat flow density evolution, changes of paleoclimate and thermal parameters of rocks filling the sedimentary basin which determine paleotemperature estimates in the sedimentary profile of the basin,
- **the kerogen kinetic model** describing the course of kerogen conversion to the form of hydrocarbons as the function of time and the source rock level temperature.

The dynamic modelling of petroleum system reconstructing the course of petroleum processes (generation, expulsion, migration and accumulation) at any stage of its evolution allows us to understand them better, contributes to rationalisation of costs and to increases the effectiveness of prospective works.

The construction of basic dynamic geological model of the USCB

A spatial dynamic model of the petroleum system was built based on a static model of the current geological and structural image of the sedimentary basin (Figure 4). Its design consisted in integration of the interrelated models that reconstruct the course of significant physicochemical processes, which determine changes of physical, petro-physical, and geochemical parameter values of sedimentary formations in the geological time and as in the formation and preservation, or dispersion of hydrocarbons.

For each layer separated in the spatial geological and structural model was determined the absolute age of sedimentation as well as the lithotype (facies) was defined. Models of lithology (lithotypes) for individual strata subdivisions placed between the coal seams were developed on the based on the interpretation of well logging calibrated by laboratory measurements, and the absolute age of strata was defined on the basis of the stratigraphic chart (acc. to ICS 2008 contained in the editor of the PetroMod software) [33].

In the history of structural and tectonic evolution of the USCB 4 main episodes of erosion were identified. Their absolute time of duration and thicknesses of the eroded formations were estimated (Table 1).

Coal seams were defined as potential source rock for the gas; similarly to mudstone and sandy mudstone formations separated between them that contained dispersed organic matter. Values of geochemical parameters TOC (Total Organic Carbon) and HI (Hydrogen Index) were estimated for the source rock levels, and kerogen kinetic models were also defined. The geochemical parameters of coals were measured at the INiG – PIB based on the results of Rock-Eval pyrolysis analysis of coal samples from seams 411, 412, 413 in the Zofiówka coal main. The level of their thermal transformation expressed by the value of pyrolysis parameter T_{max} was 466÷470°C, what in the vitrinite reflectance scale (R_o) corresponds to values of 1.28÷1.30%. They contain approx. 85% of Total Organic Carbon (TOC). The measured value of its residual hydrocarbon potential HI is

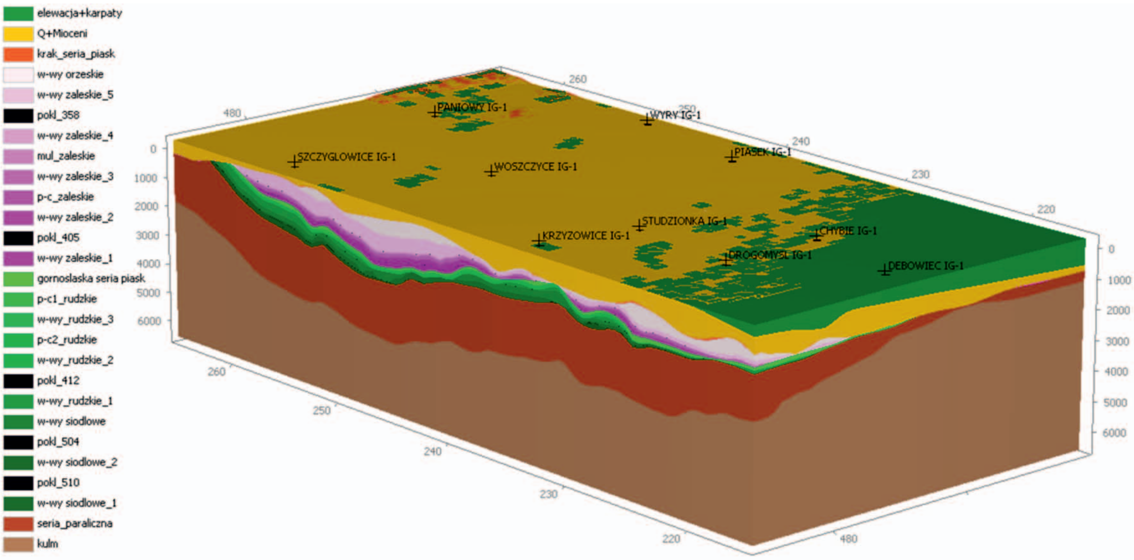

Fig. 4. Current geological-structural depiction of the analysed area

90÷100 mg HC/g, which allows estimating its initial potential at approx. 200 mg HC/g TOC.

Based on literature data [7] Total Organic Carbon (TOC) and the Hydrogen Index (HI) values were estimated for the mudstone and sandy mudstone formations implemented in the model. They are:

- TOC – 1.0%, HI – 200 mg H/g TOC – for the Paralic Series,
- TOC – 5.0%, HI – 200 mg H/g TOC – for the Upper-Silesian Sandstone Series,
- TOC – 4.0%, HI – 200 mg H/g TOC – for the Mudstone Series,
- TOC – 2.0%, HI – 200 mg H/g TOC – for the Krakow Sandstone Series.

Moreover, the kinetic kerogen models (distributions of activation energy) were developed both for coals and for the dispersed organic matter in the clastic formations, and for the coal seams – also a sorption model (Figure 5).

The kinetic model of coals, assumed in the simulation model, was developed based on determinations of activation energy distribution for coals from the Ruhr region [30] and is dedicated to the simulation of methane production from hard coal seams. The adsorption model (Langmuir parameters) for the USCB coals was prepared based on the curves of methane sorption isotherm sampled from seams 412 and 413, from the USCB.

Table 1. Episodes of erosion in the analysed area

Erosion episode/Eroded layer	Time interval	Eroded layer thickness
	[Ma]	[m]
I – Paralic Series	322÷320	200÷700
II – Orzesze Series	307÷305	100÷400
III – Krakow Sandstone Series	300÷17	2300÷3400
IV – Miocen, Carpathians	2÷0	100÷300

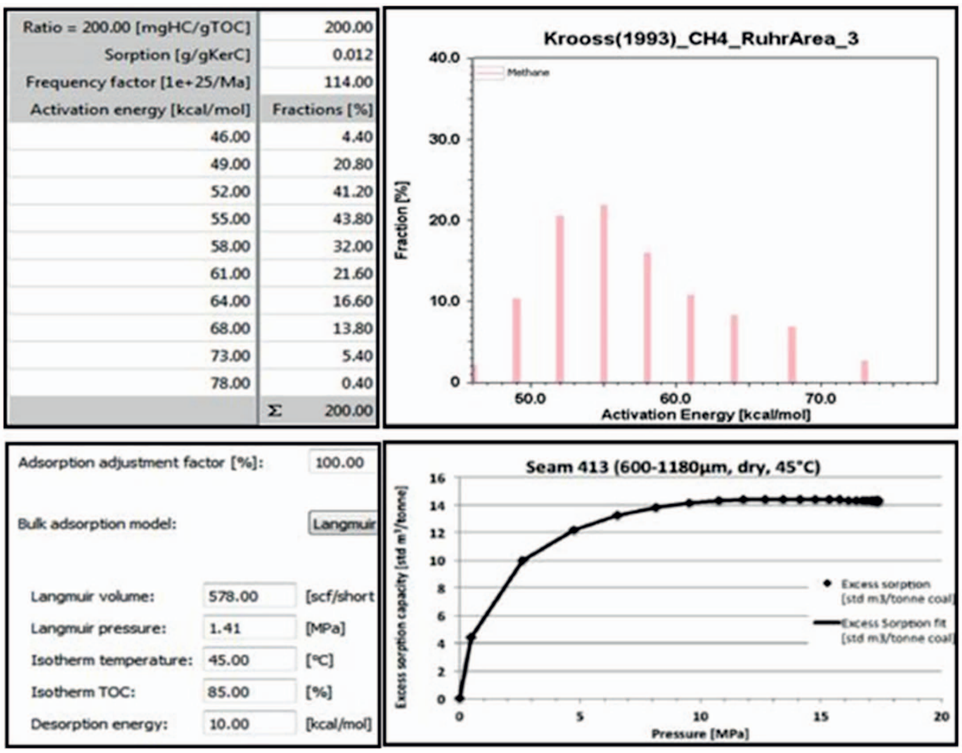

Fig. 5 Kinetic and sorption model of coal adopted in the simulation model of the petroleum system of the USCB

Temperature is the factor controlling not only the course of the process of hydrocarbon generation, but other processes (diagenesis, cementation of sediments) affecting the development of porosity and permeability of the reservoir and sealing rocks too. Their appropriate time coincidence determines the hydrocarbon accumulation. Therefore a correct reconstruction of paleotemperatures evolution in the sedimentary basin is crucial for a possibility of genuine reconstruction of the course of those processes in the simulation model. The current temperature distribution was the starting point for the reconstruction of paleotemperatures during the past geological epochs. If the determination of contemporary sorption isotherms is relatively easy, then their determination in a distant geological time is very difficult and is usually performed based on indirect indicators documenting persistently maximum temperatures in the form of e.g. the degree of transformation of organic matter measured by the values of vitrinite reflectance R_o [%].

The thermal model of the basin was built based on the values of the contemporary heat flow resulting from the measurements of temperature profiles in borehole and thermal parameters of strata drilled. The calculated contemporary values were the starting point for the reconstruction during the geological time. The model used complied with paleoclimatic and palaeobathymetric changes of the basin too.

The time interval setting for the maximum temperatures occurrence, enabling the time correlation of processes significant for the possibility of gas accumulation formation, requires the application of advanced analytical methods and is burdened with relatively high incertainty. The research on the coalification time of the Upper Carboniferous formations in the Upper-Silesian Coal Basin based on apatite dating by means of fission track analysis and helium dating [15] have shown that the maximum paleotemperatures were reached by those formations at the turn of Carboniferous and Permian. These data were taken into account while constructing the thermal model of the study area by the authors of this report.

The prepared thermal model was calibrated by measured values of vitrinite reflectance R_o. The best match results were achieved after increasing the density of heat flow in the Carboniferous period by a few to a dozen mW/m^2 (depending on the borehole location) in the ratio of the current values and heat flow's uniform drop till the present time.

Calibration of the model of the USCB petroleum system

Multiple simulations of the model were carried out based on the principles of structural evolution described above and lithological models (lithotypes) defined. The compaction of layers (the evolution of petro-physical parameters and pressures) was being calculated in a spatial depiction. After each simulation the results from boreholes were extracted and compared with the calibration data. The application of lithologic models (lithotypes), defining interrelationships between individual parameters and of spatial principles of evolution of the basin enabled reconstruction of these parameters values (porosity, permeability etc.) at any stage of the sedimentary basin development.

Results of simulation were calibrated by average porosity for each layer (calculated for well logs calibrated by porosity samples from well core [3–12]) and pore pressures for one well [4]. The calibration of the thermal model began after obtaining high consistency of the values of parameters calculated in the simulation and the values of parameters measured. Figure 6a presents the results of calibration of the simulation model by values of porosity measured for a borehole sample, and Figure 6b visualises the current distribution of porosity in the analysed area.

On the basis of temperature history reconstructed the distribution of source rock thermal maturity was calculated

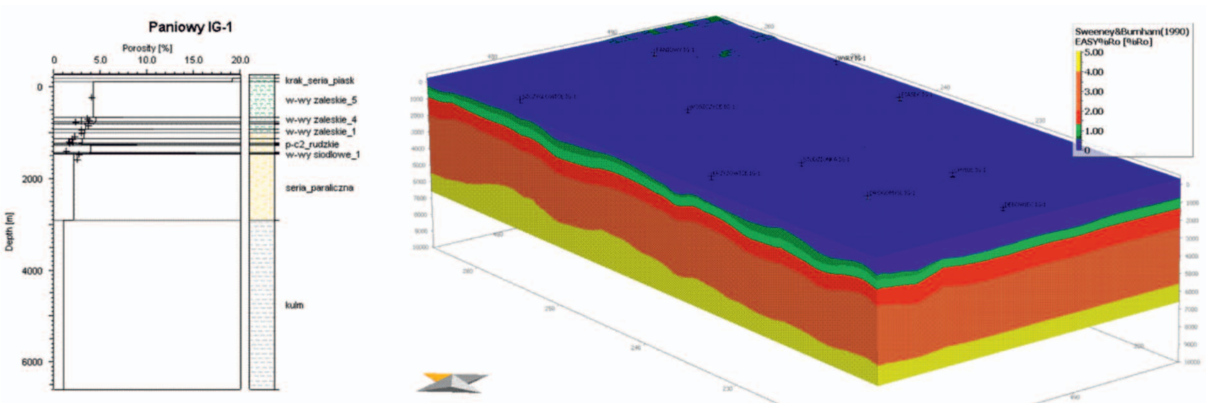

Fig. 6. A – the simulation model calibration by the measured values of vitrinite reflectance in the Paniowy IG-1 borehole; B – visualisation of the estimated spatial porosity distribution in the analysed part of the USCB resulting from the performed spatial modelling

according to Sweeney & Burnham model [32]. It was calibrated by measurements of vitrinite reflectance (Figure 7a). Figure 7b presents the current degree of thermal conversion in the analysed area.

Calibrated dynamic spatial models of geologic-structural and thermal evolution integrated with kerogen kinetic models of separate bed rocks provided the basis for the modelling of petroleum processes in the study area.

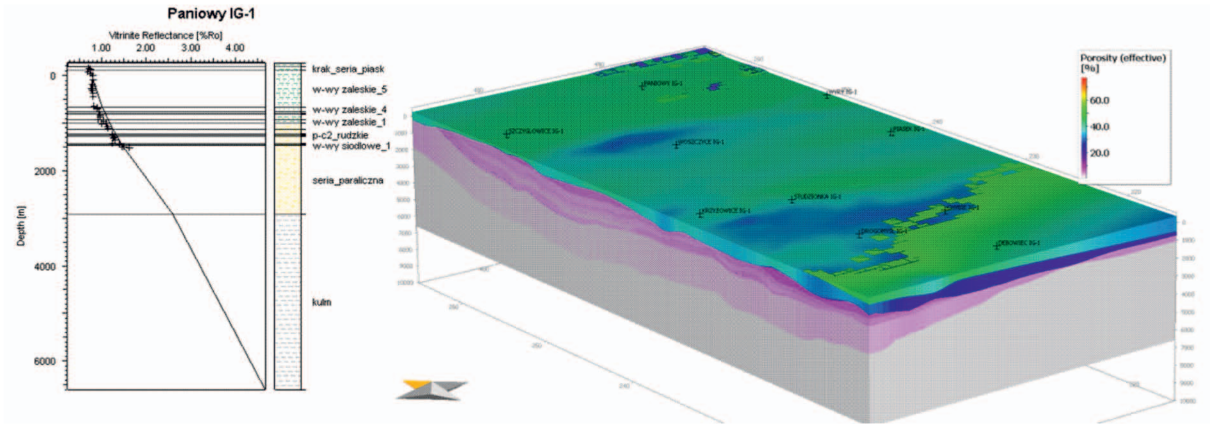

Fig. 7. A – the simulation model calibration by the measured values of vitrinite reflectance in the Paniowy IG-1 borehole; B – visualisation of the estimated thermal maturity distribution of the USCB formations resulting from the performed spatial modelling

Results of modelling

The initiation of a process of hydrocarbon generation in Carboniferous formations of the USCB is related to a sudden increase of the temperature, resulting from the sinking of sediments rich in the organic matter to great depths during the Upper Carboniferous. At the end of that period the formations of Paralic Series were buried to depths greater than approx. 3000 m in majority of the analysed area, reaching temperatures higher than 100°C, what initiated the hydrocarbon generation processes. Further intensive sedimentation of Upper Carboniferous formations resulted in fast falling and increase of the temperature to more than 150°C that caused a further development of the thermal conversion (up to 1.25÷1.30% on the vitrinite reflectance scale R_o) and the increment in the amount of hydrocarbons generated by them. In Lower Permian, the temperature of layer – started to decrease as a result of the area elevation and of intensive erosion and this trend was maintained up till now. The thermal processes of hydrocarbon generation, both from the coal seams and the mudstone formations containing dispersed organic matter, have basically stopped already at the end of Permian, because of the temperature decrease. The course of petroleum processes in younger formations of the Upper-Silesian Sandstone Series and Mudstone Series was slightly shifted in time, commensurate with temperatures achieved by the series resulting from the depth of buried (Figure 8).

Many alternative models as per various structural and thermal evolution scenarios were developed and simulated during the implementation of study. Their execution allowed to achieve the current structural and parametric depiction. If at a good calibration of all models very similar amounts of the generated gas were provided as the result of their simulations, then the aggregate amounts of the accumulated gas calculated differed considerably. In the utmost cases they differed several times. The analysis of assumptions made and results obtained has shown that the differences observed result mainly from the duration of time intervals of faults opening. It is possible to consider that the key role in the generation and conservation of gas accumulation in the USCB belonged to the time

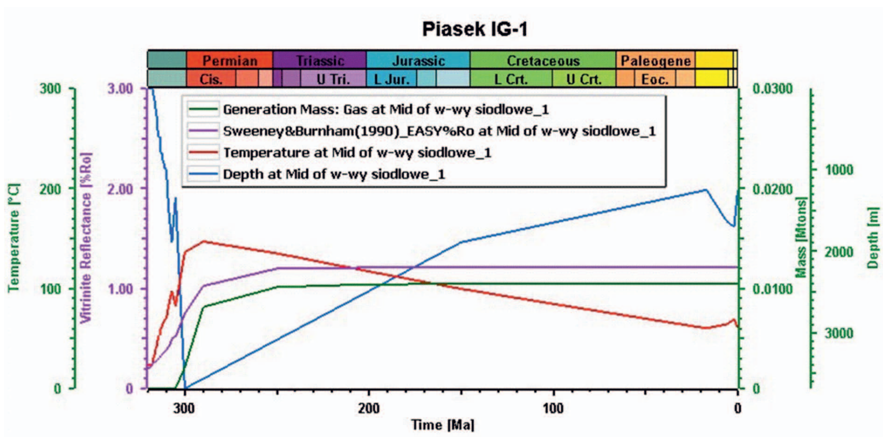

Fig. 8. The course of petroleum processes determined by the evolution of sedimentation basin of the USCB in the bottom part of the Saddle Beds in the Piasek IG-1 borehole

coincidence of petroleum processes in the Carboniferous USCB with its tectonic reconstruction and also the spatial relations of the hydrocarbon kitchen and the sealing rocks.

It results from each model simulation that the initial generating potential of these coals (in the context of methane production) has been executed already at 60÷70%, which means that the efficiency of coalification process of organic matter amounted to 140÷150 m^3 of methane per 1 ton of coal. In the area of 1 km^2, more than 150 million m^3 of gas were produced on average from one coal seam of average thickness of 1 m. At the overall thickness (including also subeconomic seams) exceeding considerably 100 m it gives more than 15 billion m^3 of methane/1 km^2 of the area. The results of modelling show that Carboniferous formations of the USCB situated within the boundaries of the model (of approx. 1300 km^2 area) produced more than 23 billion m^3 of gas, mainly methane. The distribution of production efficiency zones depends on the layer thickness and degree of its thermal conversion (resulting from the depth of layer sinking) (Figure 9).

The implementation of various scenarios (equally probable) has shown that the amounts of accumulated gas depend mainly on the course of structural and tectonic evolution of the basin, especially from the time of faults opening. The amounts calculated range is from approx. 1.5 billion m^3 at the faults opening in the 300÷200 Ma time interval, via approx. 2.5 m^3 at their opening in the 300÷290 Ma interval, to almost 4 billion m^3 at constant faults closure. The first scenario, considered by the authors as the most probable, yet the least optimistic, indicates a huge resource potential of Carboniferous USCB formations. The further part of the report will present and analyse the results obtained from the implementation of a scenario assuming the opening time of faults in the 300÷200 Ma interval.

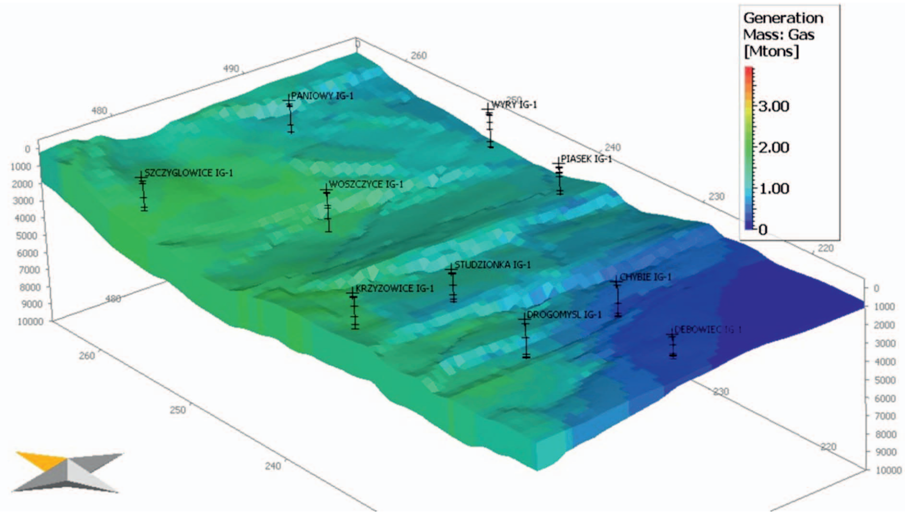

Fig. 9 Distribution of generation yield zone in the Paralic Series in the analysed area

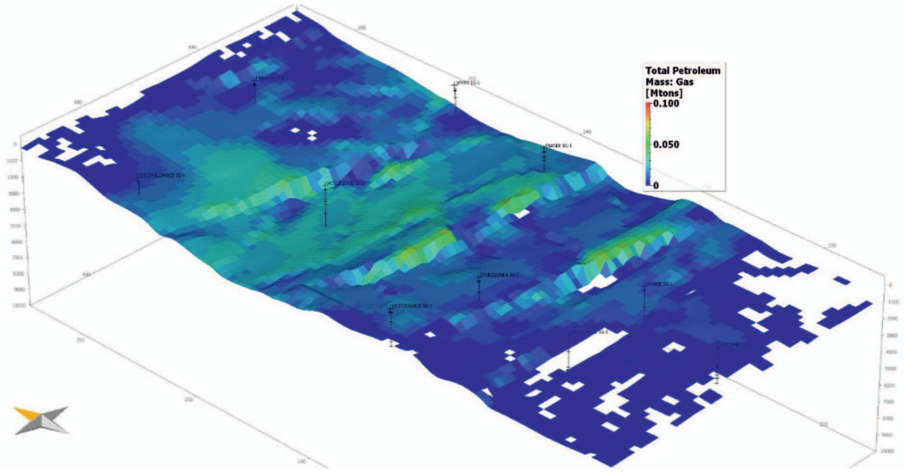

Fig. 10. Distribution of zones featuring increased gas contents in the sandy mudstone beds situated in Mudstone Series deposited directly under seam 405

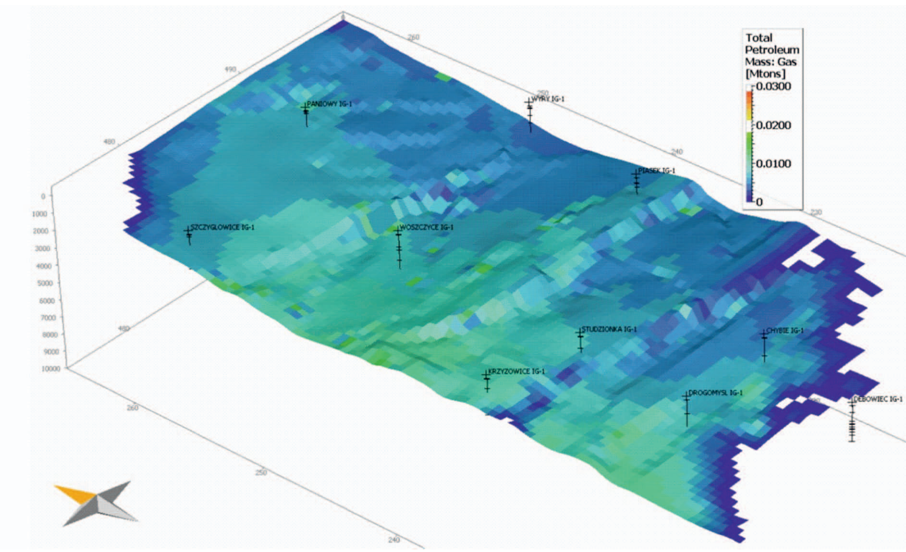

Fig. 11. Distribution of increased gas content zones in coal seam 358

The analysis of modelling results shows that a high majority of 1574 billion m^3 of hydrocarbons accumulated in the analysed area appears in an adsorbed form, and only approx. 45 billion m^3 in the form of free gas (Table 2). The amounts of liquid hydrocarbons are minute and it results both from the type of organic matter (land type III) and from the fact of relatively high thermal transformation of formations, which also resulted in the secondary cracking of heavier hydrocarbons also. This thesis is confirmed by a trend of a drop of oil hydrocarbons amount with the depth (temperature) (Table 2).

Table 2. Amounts of generated and accumulated hydrocarbons in individual formations

Formation	Generation [bn m^3]	Accumulation in source rocks [bn m^3]	
		free gas	adsorption
Krakow Sandstone Series	12.2	0.01	0.13
Mudstone Series	7965.0	3.30	894.6
Upper-Silesian Sandstone Series	8236144.0	11.70	463.9
Paralic Series	7144.2	29.70	171.2
Total	23357.6	44.70	1529.8

Almost all accumulated hydrocarbons exist in source rock formations, i.e. in coal seams as well as in mudstone and sandy mudstone formations, while they appear in more than 99% in an adsorbed form in coal seams. Whereas the share of adsorbed gas in mudstone and sandy mudstone formations runs from a few to a dozen or so %. Because of low porosities of clastic formations, methane contained in them exists in a form of non-conventional tight type of accumulations probably. In three sandstone beds, of thickness ranging from a few to a dozen or so metres, defined in the model as reservoir levels, in total only 146 million m^3 of gas were accumulated, which is slightly more than 0.3% of total free gas amount.

In the mudstone and sandy mudstone formations, both of the Upper-Silesian Sandstone Series and of the Mudstone Series, the zones of increased gas concentration are situated in up-thrown sides of the fault (Figure 10). This is a natural trend reflecting both reservoir parameters of formations and the pore pressure distributions. Moreover, in clastic formations situated between coal seams a very clear growing trend of saturation with gas is observed in beds situated directly under coal seams. It suggests that coal seams are a barrier for the vertical migration of gas and thereby the hydrocarbons generated were dispersed via horizontal migration. Such observations imply also specific prospecting conclusions.

In individual coal seams the unit contents of methane increase with the depth of deposition. This apparently unnatural trend results from the increase in the sorption capability of coals caused by the increased pressure. Moreover, this can result from the increase in the sorption capacity of deeper situated coals also, depending on their secondary porosity and growing with increase of degree of thermal conversion. The relationship observed proves a predominant share of methane existing in the adsorbed form (Figure 11).

The unit contents of gas in the coal seams are not high themselves, they reach 0.015 m^3 of gas/kg of coal at most (Figure 12), which is equivalent to 15 m^3 of gas per a ton of coal. These results are entirely consistent with published research [18–20] and the results of laboratory studies on the methane content in coal seams provided in the boreholes result documentation (situated in the analysed area) [3–12].

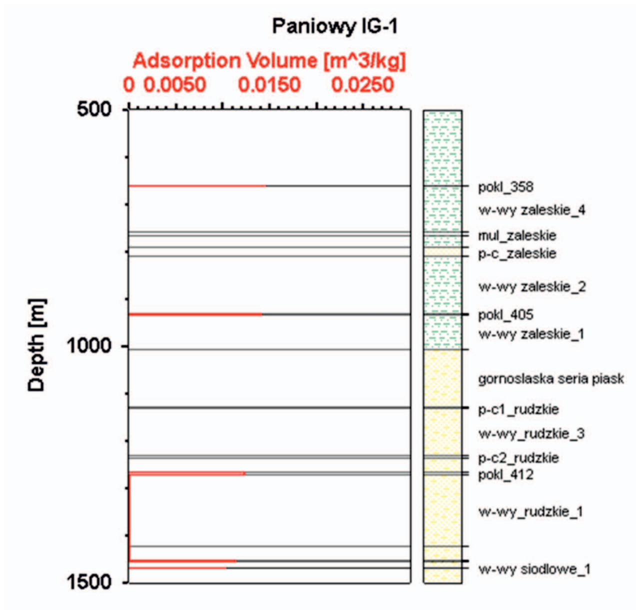

Fig. 12. Unit methane contents in individual coal seams

Summary and conclusions

The implementation of report consisted in developing a spatial dynamic 4D model of the Carboniferous petroleum system of the western part of the Upper-Silesian Coal Basin, which allowed to preliminary assess the methane potential of Upper Carboniferous formations situated in this area.

1. The processes of hydrocarbons generation were most intensive in the analysed area during Upper Carboniferous and could have been still continued, but on a much smaller scale, in Lower Permian.
2. Total amounts of gas generated, which in the analysed area of approx. 1300 km^2, constituting nearly 25% of Polish part of the USCB, amount to more than 23 billion m^3, were estimated.
3. A huge part of generated hydrocarbons was dispersed, but more than 1570 billion m^3 of gas were accumulated. Its great

majority is related to adsorption forces in coal deposited in a few dozen seams.

4. Obtained results of hydrocarbon generation and accumulation value are estimative. This is due to limited of deep wells on the scale of model, lack of boreholes measurements and insufficient recognition of lithological and structural geological feature in the USCB.
5. The time of faults opening (absolute age of their opening start and closing) seems to have a major impact on the amount of accumulated hydrocarbons existing in a free form, because the simulation results turned out to be most sensitive to this input parameter.
6. Increased concentrations of free gas in beds situated directly under coal seams suggest the mechanism of its dispersion via horizontal migration.
7. The highest probability of occurrence of deposit accumulations is assessed in top part of up-thrown sides of the fault, where the highest gas concentrations are observed.
8. The possibility of existence of multi-horizon gas accumulations is not excluded in clastic formations deposited between coal seams. The accumulation type will depend on the collector properties of rocks. Because of their low porosities, the existence of unconventional tight type deposits is forecasted in mudstone and sandy mudstone formations.

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