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MAREK NIEĆ[1], ANGELIKA MUSIAŁ[2], JUSTYNA AUGUŚCIK[3]

Shale gas deposit model and preliminary resources estimation based on mud logging data on gas content variation

Introduction

The natural gas deposit* may be defined as a natural accumulation of hydrocarbon gases, which can be commercially exploited (Levorsen 1967). In conventional reservoirs, the gas occurs in traps (structural, lithological, and stratigraphic), primarily in free form in the pore space of gas-bearing (reservoir) rocks. Its migration is possible under the influence of hydrodynamic factors. Shale gas deposits are different from conventional ones (Jenkins 2011). The gas accumulation in shales does not have strictly defined borders, as it occurs

* In petroleum geology the terms "pool" and "field" are applied for hydrocarbon accumulations, that occur in the free state in reservoir rock. The term "deposit" (commercial deposit) is used for hydrocarbon occurrence of a size and grade that warrant exploitation (and sale of the product) independently of profitability (Levorsen 1967).

✉ Corresponding Author: Marek Nieć; e-mail: mark@min-pan.krakow.pl
[1] Mineral and Energy Economy Research Institute of the PAS, Kraków, Poland; ORCID iD: 0000-0001-6689-034X; e-mail: mark@min-pan.krakow.pl
[2] AGH University of Science and Technology, Kraków, Poland; ORCID iD: 0000-0002-7575-6887; e-mail: amusial@agh.edu.pl
[3] Mineral and Energy Economy Research Institute of the PAS, Kraków, Poland; ORCID iD: 0000-0003-1162-1980; e-mail: auguscik@min-pan.krakow.pl

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in a large area of shale occurrence. The gas in shale is either absorbed in organic matter or confined in pore space or fractures. Hydrodynamic factors have no significant effect on its movement. Gas recovery is possible only after its release by means of appropriate measures, in particular, fracturing.

The gas bearing shales which are the host rocks for hydrocarbons, are rich in organic substances, from which gas after generation did not undergo significant expulsion and was preserved in them. The total organic carbon (TOC) content in potentially recoverable gas-bearing shales is greater than 2% as a rule (Kiersnowski and Dyrka 2013).

The fundamental difference in the conditions of occurrence of natural gas in conventional and unconventional reservoirs is the reason why different resources estimation methods are used. In the case of shale gas, a key issue for the assessment of the possibility of its exploitation is the estimation of the amount of gas accumulated in the gas-bearing rock, which can be recovered in an economically justified way.

The knowledge on the amount of gas, the recovery of which is really possible is based on the extraction results. In the advance to exploitation, the expected gas reserves are estimated in the area of the possible occurrence of gas-bearing rocks (Zou et al. 2017; Nieć 2014) using several methods, including:

- varied analogy methods, for example the USGS FORSPAN model (Schmoker 2002),
- a genetic method based on the assessment of the generation potential and the range of possible gas expulsion,
- volumetric methods on the basis of the confirmed or predicted thickness of rocks with the organic carbon content indicating their potential gas content and their porosity,
- simulation methods.

By means of these methods, gas resources, the occurrence of which is possible but not determined, are estimated.

1. The gas content in shales as a basic parameter for resources estimation

The occurrence of gas confined in rocks allows us to consider it as a component of the host rock. A characteristic feature of shale or tight gas is, therefore, the gas content in gas bearing rock, that may be expressed by the amount of gas contained per mass or volume unit of rock (m^3/t or m^3/m^3).

Assuming that the gas is a component of the rock, it is necessary to know the gas content in shales in order to estimate the actual resources (Nieć 2014). The total gas resources are then:

$$Q_c = F \cdot m \cdot \gamma_o \cdot g \tag{1}$$

↳ F – the reservoir (deposit) area within defined limits [m^2],
m – reservoir (deposit) thickness [m],

γ_o – bulk (volumetric) density of shales [t/m^3], approximately and simplified: $\gamma_o = 2.5$ t/m^3,

g – the gas content in shales [m^3/t].

It can be expected that within a series of potentially gas-bearing shales their actual gas content is variable, and gas production is possible in areas where it is higher than the minimum value for economically justified and technically feasible gas extraction. This minimal gas content sets the boundaries of the "gas deposit".

Gas content in shales can be determined by means of direct measurements of gas content in rock, for example by the USBM method, which is used when estimating methane resources in coal seams; however, such measurements should have to be carried out continuously throughout the gas-bearing series.

2. Gas content assessment based on mud logging data

In the search for estimation methods of gas content in shales the attention was paid to the possibility of utilization of gas content measurements in the drilling fluid. This method was previously proposed for estimating methane resources in coal seams (Donovan 1998).

In the case of conventional deposits, the amount of gas entering the drilling fluid and contained in it depends on a number of factors (Klara 1966). The gas content [g in m^3/t] in drilled rocks may be evaluated as follows:

$$g = \frac{4K_g V_{pl}}{v\pi {d_o}^2 \gamma_o} \tag{2}$$

or:

$$g = \frac{K_g qt}{S_s \gamma_o} \tag{3}$$

K_g – gas concentration in the drilling fluid [dm^3/dm^3],

V_{en} – flow rate of the drilling fluid in [dm^3/min],

v – drilling speed [cm/min],

${d_o}^2$ – diameter of the well [cm],

γ_o – spatial density of rocks [g/cm^3],

q – efficiency of pumps [dm^{3}s],

t – drilling time for a well section s,

V_s – the volume of drilled rocks in the well section.

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Difficulties in the accurate determination of these parameters and the constant inflow of gas to the well are the reasons why such an assessment of the gas content in the reservoir rock in conventional deposits is not very precise and only applies to the determination of gas entry points.

In the case of unconventional (shale) gas deposits, the gas content in shale depends on the quantity of organic matter contained in it, its gas generation potential and the amount of gas retained after the expulsion. Taking the specific features of its occurrence into account, the following assumptions can be made:

- the gas either does not flow freely into the borehole, or the inflow is very limited,
- the gas contained in the drilling fluid is released from the cuttings of the gas-bearing rock,
- in the drilling fluid, the gas is released from the pore space and fractures of drilling cuttings,
- the composition of the gas released in the drilling fluid (the content of hydrocarbons in the gas) is the same as the gas composition in the gas-bearing rock,
- the reservoir pressure of the gas released from the pore space is not greater than the lithostatic pressure.

It is assumed that there is no gas migration in the drilling fluid stream and the free gas movement from the vicinity of the well is insignificant.

With such assumptions, the gas content in drilled rocks can be described as:

$$g = \frac{n \cdot w \cdot H(1 - S_w)}{10\,132} \ [\mathrm{m^3/t}] \tag{4}$$

↳ H – depth [m],
n – porosity of rocks at the H depth [%],
S_{in} – saturation with water,
w – hydrocarbon content [%] based on mud logging data at the H depth.

The amount of gas (methane) released as a result of desorption is not taken into account. It can be assumed that it is not higher than in the case of pure organic carbon, which practically does not exceed 25–30 m^3/t (Kim 1977; Czapliński and Ceglarska-Stefańska 1994)*. Thus, with a TOC content of 2–5%, the amount of absorbed gas will be around 0.5–1.5 m^3 per ton of rock. The desorption of gas from dispersed organic matter is slow and, given a small content, it can be assumed that it has no significant effect on the amount of gas

* The maximum sorption capacity of the carbonaceous matter depends on the degree of its transformation, pressure, and temperature and maximally reaches about 30 m^3/ton of pure coal substance of humic origin, with R_0 close to 2%. The sorption capacity of pure organic coal matter of sapropelic origin is not exactly known. It may be supposed to be higher but not significantly enough.

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released into the drilling fluid. It can therefore be assumed that the gas in the drilling fluid is released from the entire pore space only.

The filling of the entire free pore space with gas is a debatable issue. The gas generated in shales should primarily occur in a tight pore space. In the well, the gas can be released into the drilling fluid from the cuttings. Its content may correspond to the amount recoverable as a result of fracturing operations. The assessment of the gas content in shales based on the results of gas content registered in drilling fluid is undoubtedly biased by a certain error, the size of which cannot yet be determined. It also results from possible errors of depth assessment, the measurement of hydrocarbon content in the drilling fluid, and its degassing degree.

3. Gas content in shales and its variability

The proposed method has been tested on the example of two boreholes: A and B in the gas-bearing complexes of the Silurian and Ordovician shales in northern Poland (Fig. 1),

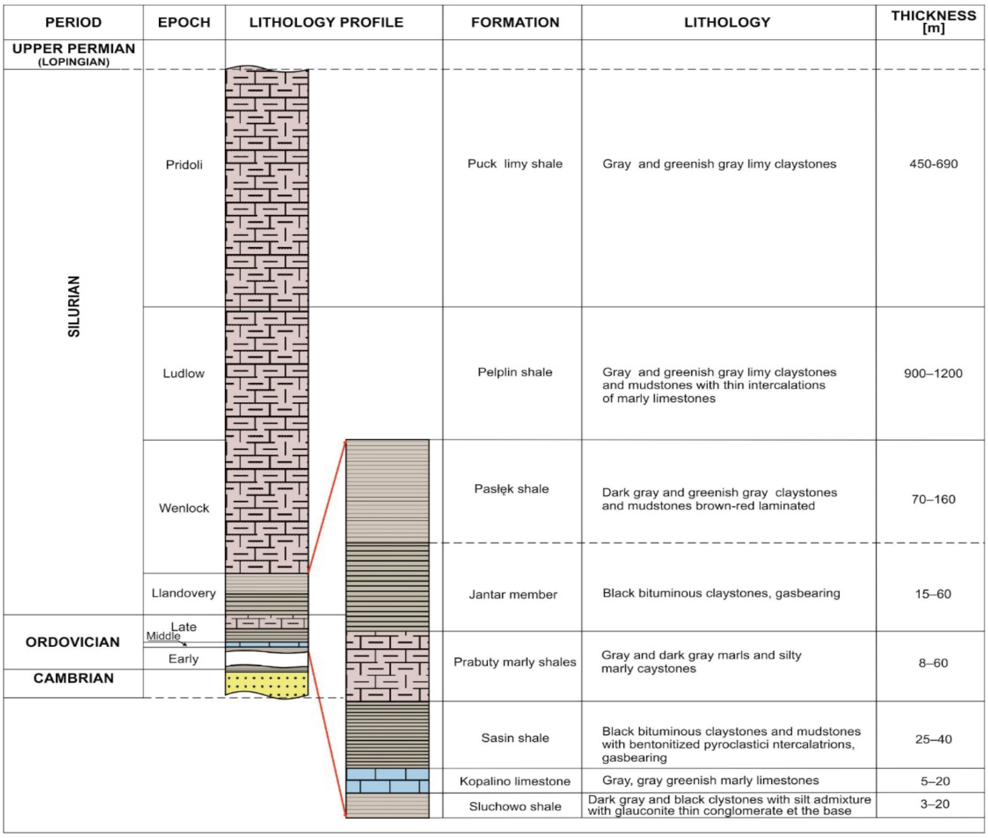

Fig. 1. Stratigraphy of studied shales formations

Rys. 1. Stratygrafia badanych formacji łupkowych

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respectively: Jantar member of the Silurian Pasłęk formation and the Ordovician Sasin formation (Modliński i Szymański 1997; Modliński et al. 2006). Since the aim of the paper is to apply the proposed method of the evaluation of gas content in shales and present the shale-gas deposit model, the data on the location of the discussed wells, which are irrelevant to further discussion, are omitted.

The data for the gas content assessment were the measurements of hydrocarbon content in 10-centimeter sections of mud, and evaluation of porosity as well as the rate of water saturation of drilled rocks was based on geophysical well logging.

Based on the results of mud logging and the gas content evaluation determined by the formula (2), it can be stated (Fig. 2) that:

- the transition from sections with low gas content to sections with high gas takes place very rapidly in the interval of few tens of centimeters, so the possible migration of gas in the mud column is very limited,
- gas content in the log of the shale series is highly variable,
- it is possible to distinguish sections with high gas content separated by sections with low gas content.

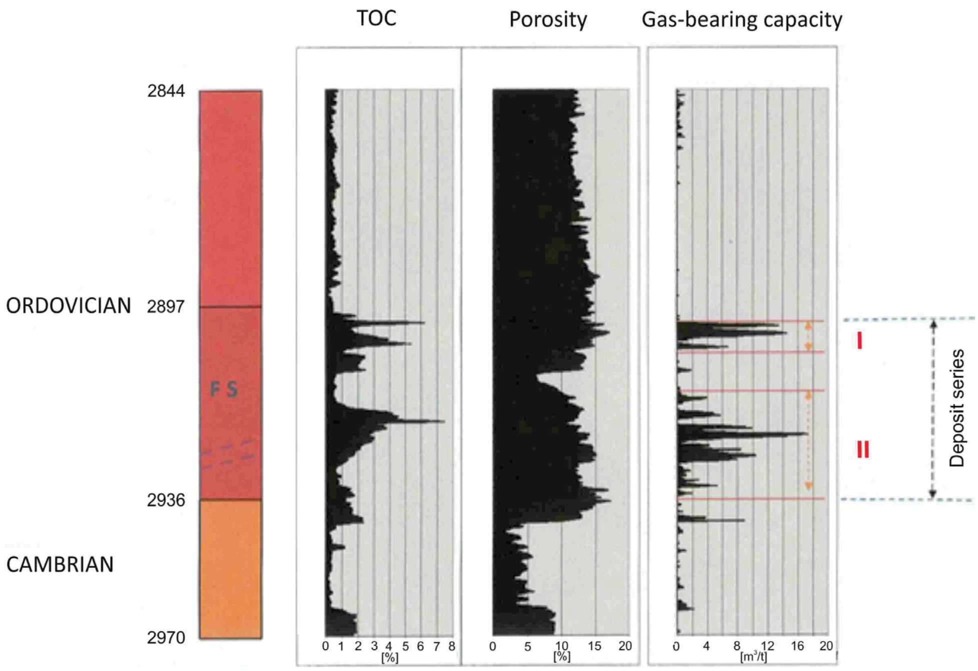

Fig. 2. The variation of gas content evaluated from mud logging data, total porosity and TOC (kerogen) according to geophysical well logging, in the “A” well

Rys. 2. Zmienność gazonośności (zawartości gazu), porowatości całkowitej i TOC (kerogenu) w profilu utworów ordowiku w otworze „A” określona na podstawie profilowania geofizycznego i gazowego

These observations confirm the preliminary assumptions that it is possible to determine gas-bearing zones and estimate the gas content in the drilled rocks on the basis of gas logging of the drilling mud.

A clear demarcation between the gas-bearing and non-gas-bearing zones indicates that it does not have a significant impact on the variability of the gas content in the drilled formations.

The increased gas content in shales takes place in zones generally enriched in TOC, but the direct correlation between the gas content and the TOC within this zones is imperceptible (Figs 2 and 3). However the structure of TOC variation, described using the variogram (Fig. 4) is identical to the structure of gas content variation, determined independently. The gas content variogram is shifted in relation to the TOC by approx. 3 m. Therefore the relationship between the calculated gas content and the measured TOC is not direct. The lack of direct correlation of measurements of both parameters may be due to the discrepancy in their depth location.

The structure of gas content variation (presented in the variogram) clearly suggests its periodic nature. The C_0 parameter determining the variation of gas content at the measurement site is approx. 5 $[m^3/t]^2$. This is due to a measurement error which is the ≈ 2.2 m^3/t (square root of C_0).

The correlation of gas content with total porosity is clear (Fig. 5), which is the consequence of the methodology of its determination. However, a non-linear variation of this dependency is noted.

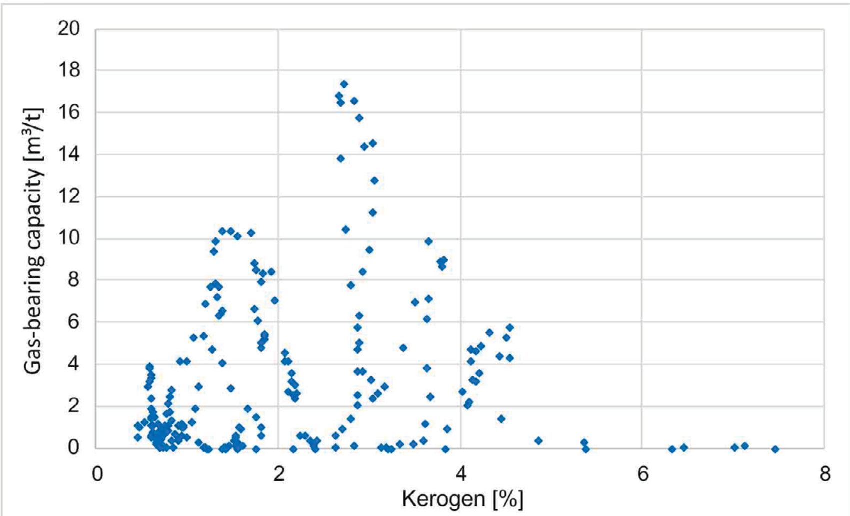

Fig. 3. The dependence of gas content in shales on TOC in the "A" well the Ordovician Sasin formation in the "A" well

Rys. 3. Zależność gazonośności od TOC w profilu utworów ordowiku, w otworze „A"

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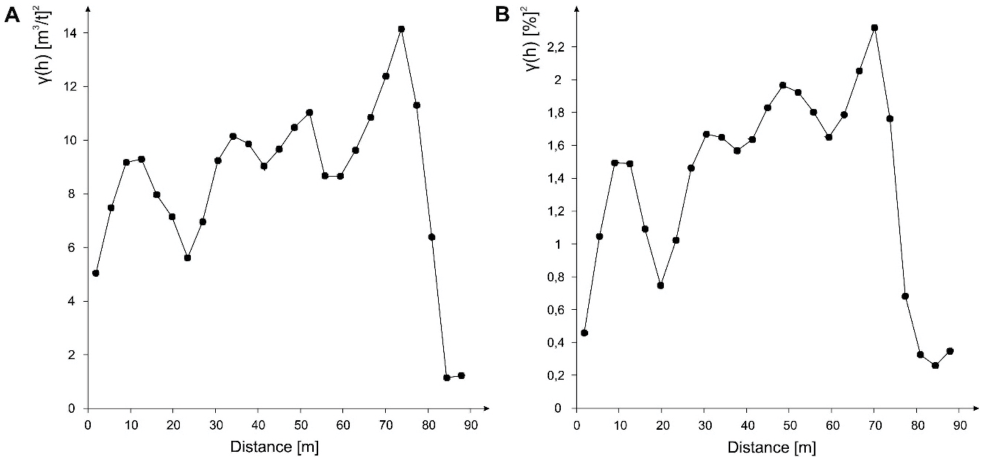

Fig. 4. The gas content variograms (A) and TOC (kerogen, B) in the profile of Ordovician Sasin formation in the "A" well

Rys. 4. Wariogramy gazonośności (A) i TOC (kerogenu, B) w profilu utworów ordowiku w otworze „A"

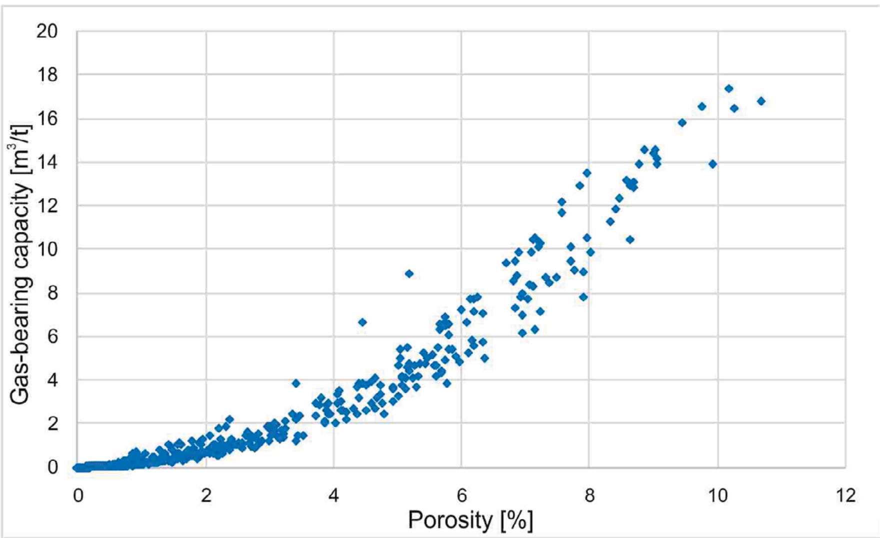

Fig. 5. The dependence of estimated gas content in shales on total porosity in the Ordovician Sasin formation in the "A" well

Rys. 5. Zależność gazonośności od porowatości całkowitej w profilu utworów ordowiku w otworze „A"

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The observed variations of the gas content in shales is not justified by their lithological features observed macroscopically. However, in the case of the "A" well, it can be stated that the highly elevated gas content in the Ordovician shales occurs in the place where, according to the description of core samples, they are strongly fractured.

Two gas-bearing layers at a depth of 2897 to 2936 m (Fig. 2) can be distinguished in the "A" hole in the Ordovician Sasin formation. Within each of them, several gas-bearing layers separated by sections with low gas content can be distinguished.

In the "A" well, the increased gas content in shales is marked also in the Jantar member of Silurian Pasłęk formation in the interval 2784.4–8343.9 m. It is highly variable, there is a number of intervals with increased gas content, but only occasionally exceeding 2 m^3 per ton (Fig. 6). The gas-bearing parts of Silurian shales have a small thickness and are less clearly delimitated than in the Ordovician formations. In general, the gas content in the Silurian Jantar member is lower than in the case of the Ordovician Sasin formation.

In the "B" well, two layers with increased gas content in the Ordovician Sasin formation (0.5 – approx. 2 m^3/ton) are clearly visible (Fig. 7). In the Silurian formations, the increased gas content is not noticeable.

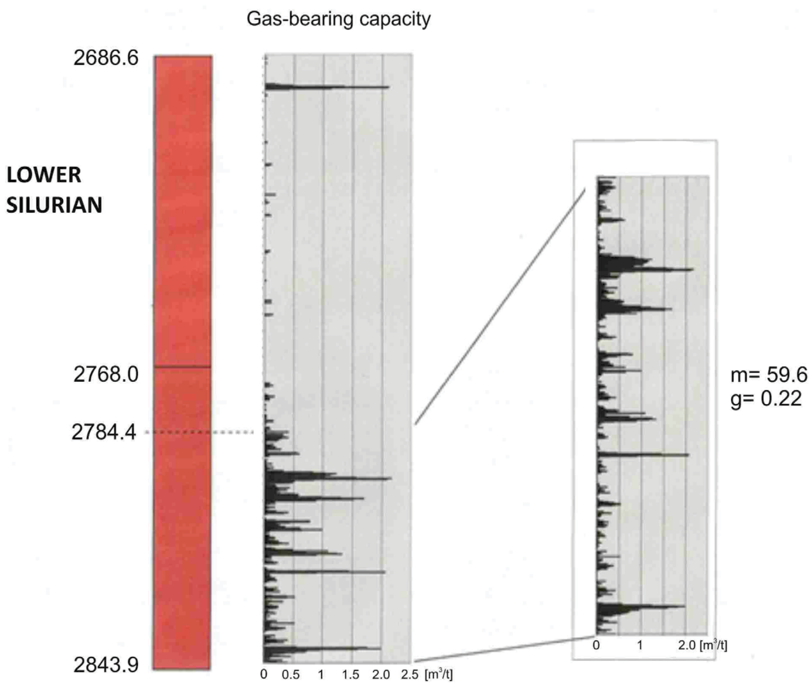

Fig. 6. The gas content in the Silurian Jantar member of Pasłęk formation in the "A" well evaluated on mud logging data
m – thickness of the gas-bearing zone; g – average gas content

Rys. 6. Gazonośność utworów syluru, ogniwa Jantaru, w profilu otworu „A"
m – miąższość strefy gazonośnej; g – gazonośność średnia

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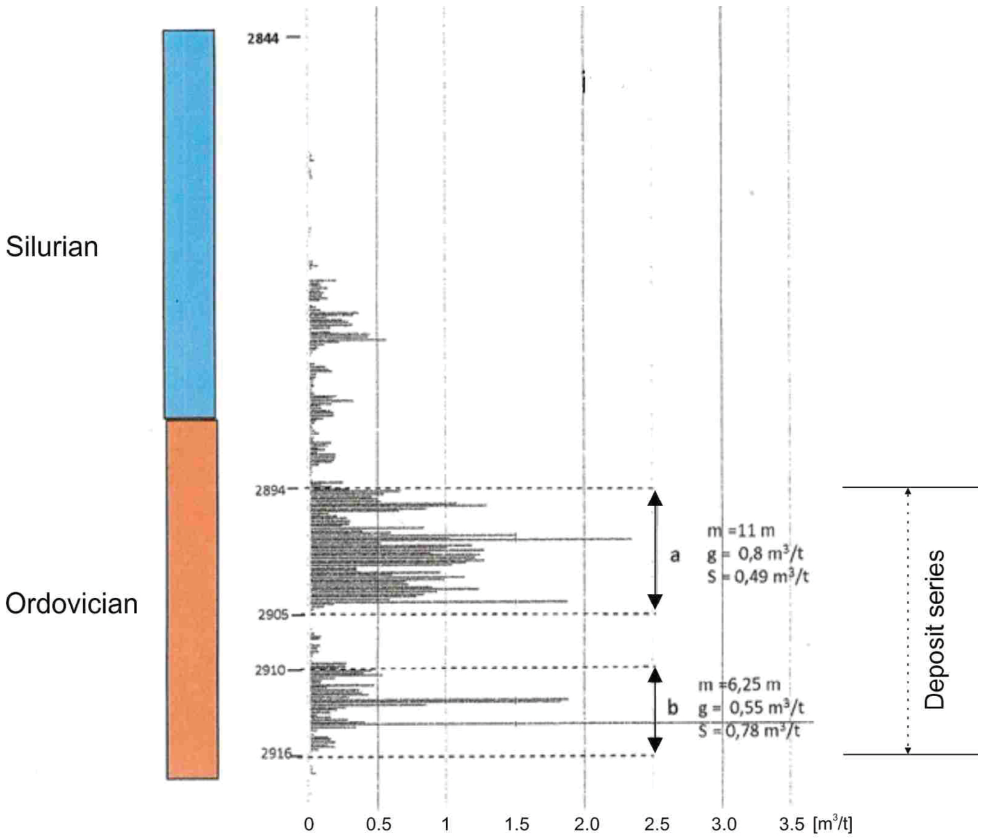

Fig. 7. The gas-content Ordovician formations in the "B" borehole
m – thickness of the gas-bearing sholes, *g* – average gas content, *s* – standard deviation of gas content

Rys. 7. Gazonośność utworów ordowiku w otworze „B"

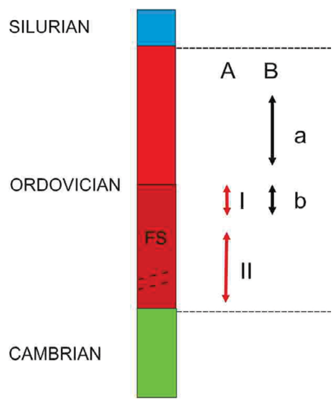

Fig. 8. The correlation of gas-bearing layers in boreholes "A" and "B"

Rys. 8. Korelacja poziomów gazonośnych w otworach „A" i „B"

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In both discussed wells, the Ordovician Sasin formations have a different thickness, which makes it difficult to correlate the distinguished gas-bearing layers. Assuming their similar position in relation to the top and the bottom of gas bearing shale formation, these layers can be correlated in the manner shown in Figure 8. Therefore, it is possible to distinguish one continuous layer, with a highly variable gas content, between these wells and two other discontinuous layers, respectively below and above.

4. The lateral variation of gas content in shales

The results of gas content analysis in the horizontal section of the "A" borehole (Fig. 9) provide data on the variation of gas content in shales at a depth of approximately 2924–2925 m.

The gas content in shales is determined at one depth interval, so it is not a full picture of the spread of gas-bearing intervals that can be distinguished in the vertical section of the borehole. Nevertheless, it gives us some idea of the horizontal range of gas-bearing zones. The gas content is highly variable (Fig. 9). The structure of its variation is illustrated by the variogram (Fig. 10). The local variation, defined by C_0 parameter, is approximately 5 $(m^3/ton)^2$. This can be interpreted as a variance of the gas content estimation error. Thus, this error is approx. 2.2 m^3/ton.

The gas content variogram is a complex one. Three sections: 0–350 m, 350–750 m, and 750–900 m can be distinguished. For greater distances, the variogram is unreliable due to the small number of gas content measurements.

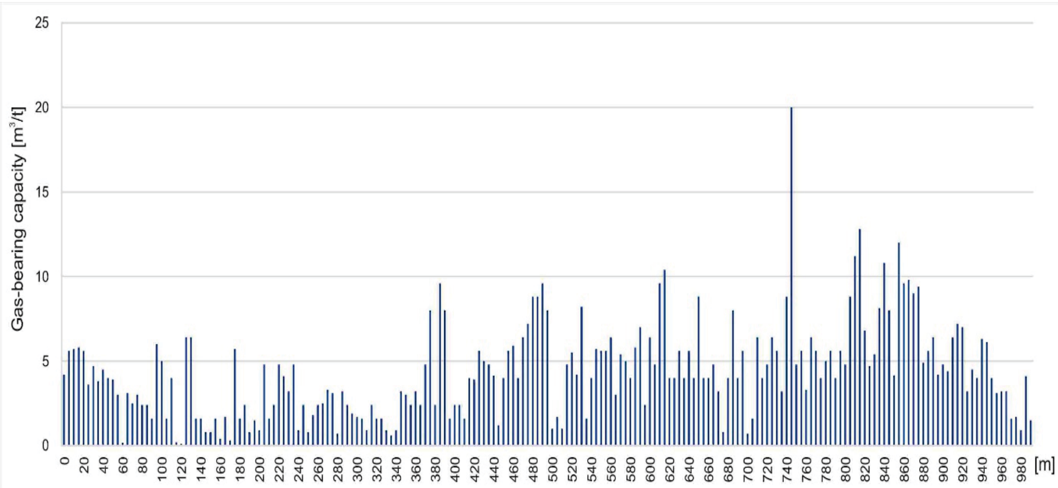

Fig. 9. The variation of gas content in the horizontal portion of "A" well, at the depth of 2924–2925 m

Rys. 9. Zmienność gazonośności w poziomie w otworze „A" na głębokości 2924–2925 m

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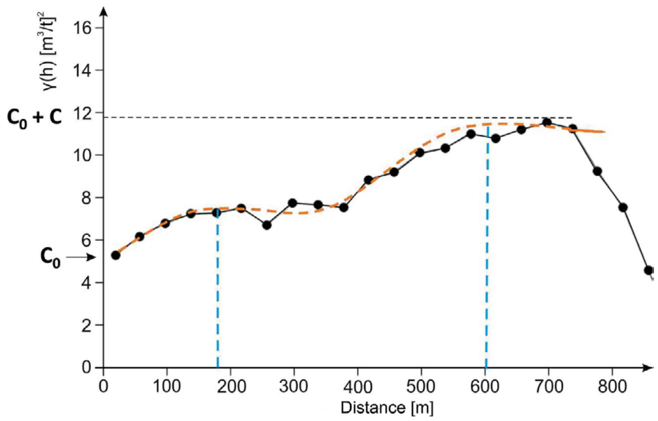

Fig. 10. The variogram of gas content in shales in the "A" borehole at depth of 2924–2925 m

Rys. 10. Wariogram gazonośności łupków w otworze „A" na głębokości 2924–925 m

In the case of the first two sections, the variogram can be described using a spherical model. The non-random component of the variability of gas content is noted in each of these sections of the variogram up to a distance of about 200 m between the measurement points. This indicates the lenticular form of gas-bearing zones. The change in the structure of the variation of the gas content (of the variogram model) for the distance between the measurement points over 700 m suggests a change in the conditions of gas accumulation. This may be caused, for example by a fault, changing the location of gas-bearing formations.

6. The model of shale gas deposit

The presented variation of gas content in shales and the comparison of the location of gas-bearing zones in both wells (A and B) makes it possible to formulate a view on the model of the shale gas deposit. The data suggests that there are a series of lenses of gas-bearing shales of up to several hundred meters of horizontal size or stratoidal gas-bearing zones with accompanying lenses within the gas-bearing formations (Fig. 11). Increased gas content or an increase in the thickness of gas-bearing beds can be observed in tectonically disturbed (fractured) shale formations. This confirms the previous hypothetical assumptions on this subject (Nieć 2014). The structure of the shale gas deposit can be modified by faults.

7. The estimation of gas resources based on gas logging data

Assuming that shale gas is an immovable constituent of the gas-bearing rock, the problems related to assessing gas resources in shales and metal content in ore deposits

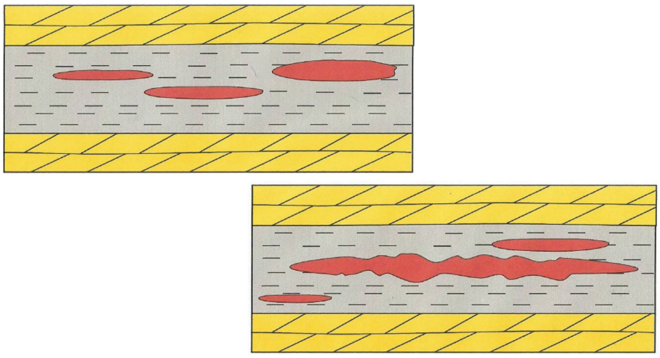

Fig. 11. Conceptual models of the shale gas deposit

Rys. 11. Modele koncepcyjne złoża gazu ziemnego w łupkach

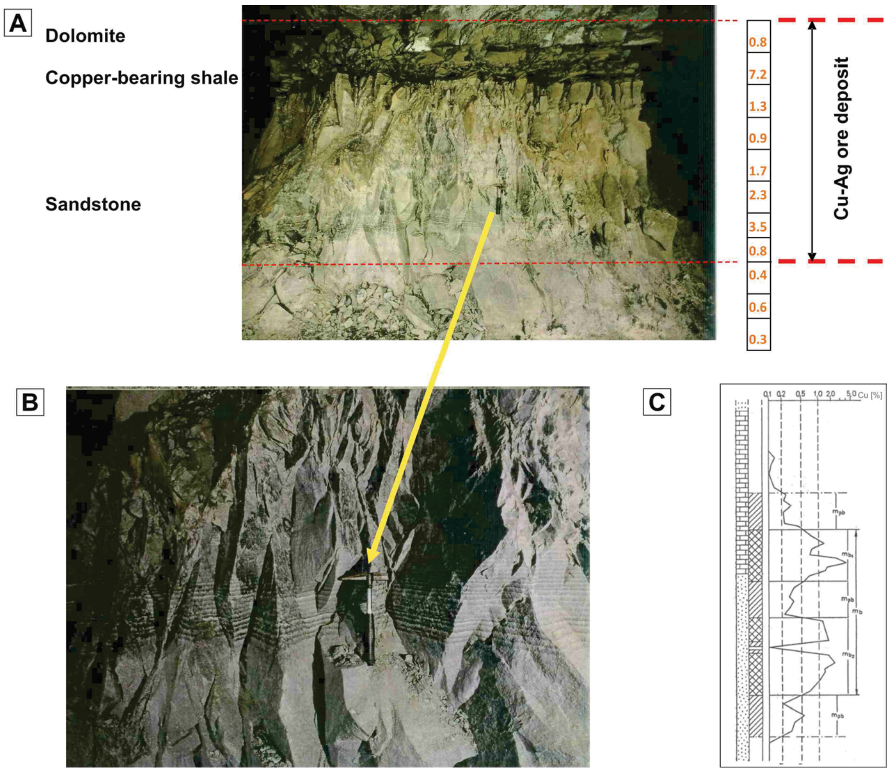

Fig. 12. An example of determining the boundaries of the copper ore deposit
in the profile of the copper-bearing series (Rudna mine, Poland)
A – sampling scheme for determining the vertical boundaries of the deposit (copper content in samples),
B – detail of ore bearing sandstone C – example of the deposit series profile

Rys. 12. Przykład wyznaczania granic złoża rudy miedzi w profilu serii miedzionośnej
(kopalnia Rudna, Polska)

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(e.g. copper) are similar. Therefore, the methodology used in the exploration of ore deposits, where the metal content (understood as a useful component) is the basis for determining the boundaries of the deposit and calculating the resources, can be also applied to estimate shale gas deposit boundaries and resources in a similar way as in the assessment of resources of any ore deposit, e.g. copper, deposit (Fig. 12).

The lack of natural boundaries in the shale gas deposit means that they must be determined arbitrarily. The boundaries should delineate the zones of accumulation of gas as the useful component which may be profitably exploited. Such delineation may be based on (Fig. 13):

- the marginal (boundary) content of the useful component (p_b), at which its recovery is technically possible (in the case of gas-bearing shales, the minimum gas content in the rock at which it can be recovered), determining the location of the top and bottom of the deposit),
- the minimum average content of gas in the deposit profile, at which its recovery can be economically justified,
- the minimum thickness of the gas bearing deposit.

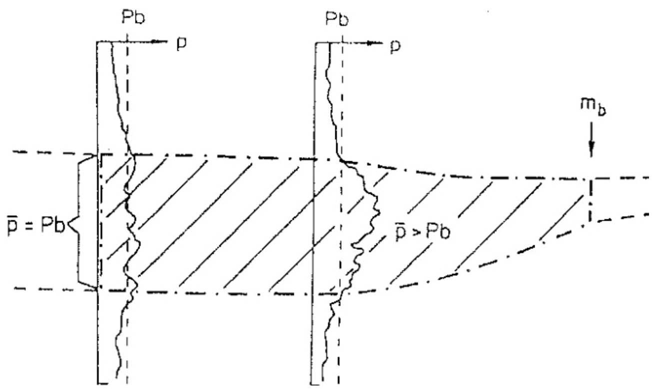

Fig. 13. The interpretation of the assumed boundaries of the deposit
p – content of the useful component in the rock (gas content), p_b – the marginal gas content,
$\overline{p}$ – the average gas content, m_b – the marginal (boundary) thickness of gas-bearing deposit

Rys. 13. Interpretacja granic umownych złoża
p – zawartość składnika użytecznego w skale (gazonośność), p_b – zawartość brzeżna (gazonośność brzeżna),
$\overline{p}$ – zawartość (gazonośność) średnia, m_b – miąższość brzeżna (graniczna) utworów gazonośnych

The location of assumed boundaries may be determined by interpolation carried out in sections where the shale gas content, higher and lower than the accepted limit content, has been determined. The marginal value is of great importance as it sets the limits of the intervals in the profile where the gas content is greater. To determine the boundaries of gas-bearing zones, the following parameters were arbitrarily used (Fig. 2):

- the marginal gas content (cutoff) defining the boundaries of the gas-bearing zone in the profile of gas bearing series: 1 m^3/t,
- the average gas content in the profile of the gas-bearing zone (gas bearing series as a deposit): minimum 3 m^3/t.

There are several zones, or sets of layers, where the gas content is clearly low in the considered cases of "A" and "B" wells (Figs 2, 5, and 6), within the whole gas bearing series. Therefore, it is possible to distinguish useful (gas bearing) and barren intervals. The whole set of useful and barren intervals between the highest and the lowest useful interval forms the "gas bearing, deposit series". A set of useful and barren intervals may be considered as a deposit in which the average gas content (hence the total of both useful and barren intervals) is greater than or equal to the assumed value (3 m^3/t in the presented case).

In the case of several gas-bearing zones in the "deposit series", numerous variants of shale gas deposit interpretation are possible (Fig. 14). The choice of the appropriate variant should depend on the horizontal continuity of the distinguished gas-bearing layers.

The data collected so far on the possible deposit model allow us to formulate suggestions for resource estimation. In the case under consideration, the range of the variogram (600 m) suggests the size of the gas accumulation area, within the limits of which non-random variation of gas content can be observed. Resources within a radius of up to 600 m in the vicinity

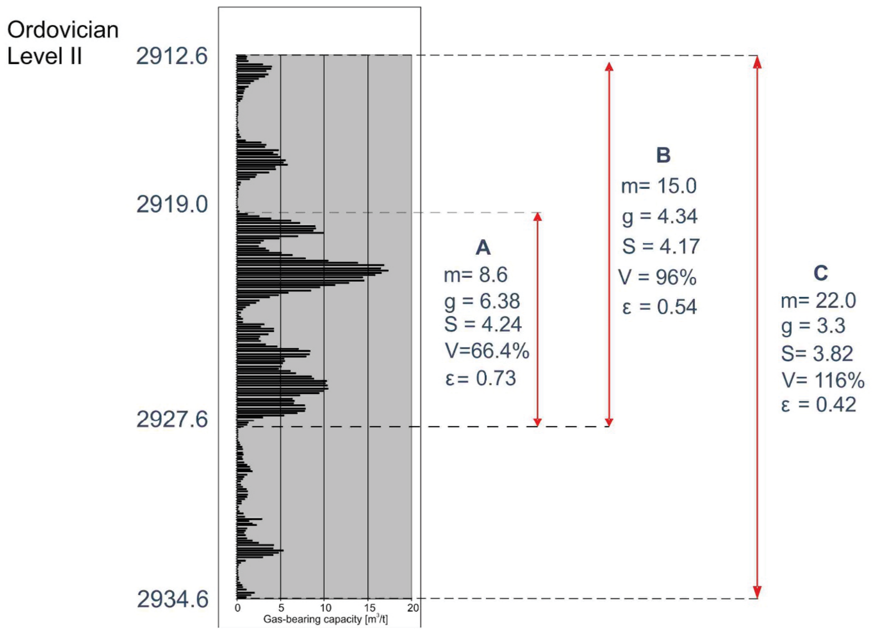

Fig. 14. The possible interpretations of the shale gas deposit boundaries in the "A" well log
m – thickness, g – average gas content, s – quadratic deviation of gas content, V – coefficient of variation,
ε – possible error of the average gas content estimation at the confidence level of 0.9

Rys. 14. Możliwe warianty interpretacji granic złoża w profilu otworu „A"

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of the well can be considered as explored, and within a radius of up to 200 m as discovered and, the extrapolated boundaries of the relevant resources around the well can be determined (Fig. 15).

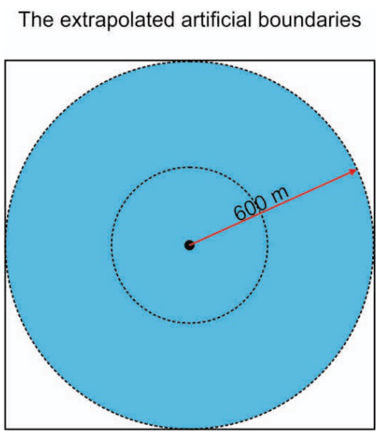

Fig. 15. Resources estimation area around the exploratory borehole within extrapolated boundaries

Rys. 15. Obszar obliczenia zasobów wokół otworu rozpoznawczego

A possible error in resource estimation is determined based on the variance of the borehole data extension to the adjacent area. It is (Wellmer 1996):

$$\sigma_e^2 = C_0 + M(C_0 + C)$$

for $r = a$, $M = 1$; for $r = a/2$, $M = 0.4$

a – the maximum range of the variogram,
M – is the parameter of the share of non-random variability in the total variability, depending on the dimensions of the area within the boundaries, where the extension error is estimated,
C_0, $C_0 + C$ – parameters of variogram (see Fig. 10).

Respectively low estimated (G_{LE}) and high estimated resources (G_{HE}), in relation to the best estimated ones (G_{BE}), can be determined at a 90 % confidence level:

$$G_{BE} = g_{av} \cdot m \cdot \gamma_o \cdot F$$

$$G_{LE} = G_{BE} - 1{,}6\ \sigma_e \cdot m \cdot \gamma_o \cdot F$$

$$G_{HE} = G_{BE} + 1{,}6\ \sigma_e \cdot m \cdot \gamma_o \cdot F$$

g_{av} – the average gas content in the reservoir interval [m^3/t],
m – reservoir thickness [m],
γ_o – the spatial density of rocks [2.5 t/m^3],
F – surface [m^2].

Conclusions

The presented method of assessing the gas content in shales is undoubtedly subject to a certain error resulting from:

- errors in the measurement of the parameters used to calculate it,
- uncertainty about the degree of saturation of the pore space with gas.

It can be assumed that the values of C_0 – interpreted from empirical variograms mainly represent $\acute{\varepsilon}^2$ measurement errors. In the case of shale gas C_0 of 5 [m^3/t]^2 indicates the total error of its determination around 2.2 m^3/t. The error resulting from the uncertainty regarding the degree of saturation of the pore space with gas and, therefore, whether it occurs in the entire pore space, cannot be determined. If it occurs, it is a systematic error and therefore has no effect on the mutual relations between the gas content measurements and its variation.

In the shale series, the gas-bearing zones are distinguished by a marked increase in the gas content in the drilling fluid. This allows the boundaries of gas-bearing zones to be determined.

Observations made in the wells under consideration indicate multi-level gas accumulations in shales and their high horizontal (lenticular) variability, suggesting a multi-lens or multi-layered deposit model. The presentation of the model of shale gas deposit is the main achievement of interpretation of mud logging data and may be the main goal.

The obtained results indicate the need for wider use of mud logging in the estimation of unconventional resources, in particular for determining the boundaries of the gas deposit within the gas-bearing series and determining the model of its structure. The resources calculation based on such logging may be biased by the uncertainty of real gas content in shale, and burdened with an error greater than geostatistically calculated. It is suggested, however, that this can be useful for their preliminary estimation.

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REFERENCES

Czapliński, A. and Ceglarska-Stefańska, G. 1994. *Sorption of gases and steams on hard coal* (*Sorpcja par i gazów na węglu kamiennym*) [In:] Czapliński A. *Hard (bituminous) coal*. Wyd AGH, Kraków, p. 161–182 (*in Polish*)

Donovan, W.S. 1998. *Determining Coal Gas using Mudlogging methods*. [Online] www.mudloggere.com [Accessed: 2019-10-02].

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

Jenkins C., 2011. *Shale gas* [In:] Guidelines for the Application of Petroleum Resources Management System. SPE. AAPG, WPC, SPEE, SEG.

Kiersnowski, H. and Dyrka, I. 2013. Ordovician-Silurian shale gas resources potential in Poland: evaluation of Gas Resources Assessment Reports published to date and expected improvements for 2014 forthcoming Assessment (*Potencjał złożowy ordowicko-sylurskich łupków gazonośnych w Polsce: omówienie dotychczasowych raportów i propozycje udoskonalenia metodyki oceny zasobów gazu w raporcie w 2014 r.*). *Przegląd Geologiczny* 61, pp. 354–373 (*in Polish, English abstract*).

Klara, W. 1966. Gas logging in oil wells (*Profilowanie gazowe w odwiertach naftowych*). *Geofizyka i Geologia Naftowa* 3–4, pp. 88–94 (*in Polish*).

Klara, W. 1966. Rules for the interpretation of gas logging (*Zasady interpretacji profilowania gazowego*). *Geofizyka i Geologia Naftowa* 11–12, pp. 273–285 (*in Polish*)

Kim, A.G. 1977. Estimating methane c 1977 – Estimating methane content of bituminous coal beds from absorption data. *US Bureau of Mines Report of Investigations* 8245, pp. 1–22.

Levorsen, A.I. 1967. *Geology of petroleum*. San Francisco: W.H. Freeman and Co.

Modliński, Z. and Szymański, B. 1997. The Ordovician lithostratigraphy of the Peribaltic Depression (NE Poland). *Geological Quarterly* 41(3), pp. 273–288.

Modliński et al. 2006 – Modliński, Z., Szymański, B. and Teller, L. 2006. The silurian lithostratigraphy of the Polish part of the. Peri-Baltic Depression (N Poland). *Przegląd Geologiczny* 54(7), pp. 87–796.

Nieć, M. 2014. Backgrounds of prospecting, exploration and reporting resources and reserves of shale gas deposits (*Podstawy metodyki poszukiwań, rozpoznawania i dokumentowania zasobów złóż w odniesieniu do złóż gazu ziemnego w łupkach gazonośnych*). *Przegląd Geologiczny – Polish Geological Review* 62(8), pp. 403–413 (*in Polish*).

Schmoker, J.W. 1995. U.S. Geological Survey Assessment Model for Continuous (Unconventional) Oil and Gas Accumulations – The “FORSPAN” Model. USGS Bulletin 2168.

Wellmer, F.W. 1998. *Statistical evaluations in exploration for mineral deposits*. Springer Ver. Stuttgard

Zou C. et al. 2017. *Unconventional petroleum geology*. Elsevier, Petroleum Industry Press.

SHALE GAS DEPOSIT MODEL AND PRELIMINARY RESOURCES ESTIMATION, BASED ON MUD LOGGING DATA ON GAS CONTENT VARIATION

Keywords

variability, shales, gas-bearing, deposit model

Abstract

The occurrence of gas confined in shales allows us to consider it as a component of the host rock. During drilling wells, the gas is released into the drilling fluid from finely ground gas-bearing rock particles. The amount of gas released can be determined on the basis of mud-gas logging; in addition, it is possible to determine the gas-content in shales expressed by the volume of gas released per mass unit of rock [m^3/ton]. The gas content in the Ordovician and Silurian shales (Sasin formation and Jantar member respectively) in two selected wells in northern Poland was determined using this method. It has been found that clearly distinguishable, highly gas-bearing sections, which are separated by very poorly gas-bearing ones, can be determined in the well log. The increased gas content in shales can be observed in zones generally enriched in TOC. No direct correlation between TOC and gas-bearing capacity was found however, but the structure of TOC variability and the gas-bearing capacity

described using variograms is identical. Correlations of the distinguished gas-bearing layers in the wells under consideration suggest a multi-lens or multi-layered reservoir model. The lack of natural boundaries in the shale gas reservoir means that they must be determined arbitrarily based on the assumed marginal gas-bearing capacity. In the case of several gas-bearing zones, numerous variants of interpretation are possible. In any case the low, best and high estimated resources may be evaluated, assigned to each borehole in the area with radii equal to the range of variogram of gas content in horizontal part of the well.

MODEL ZŁOŻA GAZU ZIEMNEGO W ŁUPKACH I ZMIENNOŚĆ ICH GAZONOŚNOŚCI NA PODSTAWIE PROFILOWANIA GAZOWEGO

Słowa kluczowe

zmienność, łupki, gazonośność, model złoża

Streszczenie

Występowanie gazu w łupkach w formie unieruchomionej pozwala przyjąć, że jest on składnikiem goszczącej go skały. W czasie wiercenia otworów uwalnia się on do płuczki z rozdrobnionych fragmentów skały gazonośnej. Ilość uwalnianego gazu można określić na podstawie profilowania gazowego i ustalić gazonośność łupków wyrażoną przez objętość gazu uwalnianego z jednostce masy skały [m^3/tonę]. Taką metodą określona została gazonośność łupków ordowiku i syluru (odpowiednio formacji z Sasina i ogniwa Jantaru) w dwóch otworach w północnej Polsce. Stwierdzono, że: w profilu otworów wyznaczyć można wyraźnie wyróżniające się odcinki silnie gazonośne, które przedzielane są bardzo słabo gazonośnymi. Podwyższona gazonośność łupków ma miejsce w strefach ogólnie wzbogaconych w TOC. Nie stwierdzono bezpośredniej korelacji TOC i gazonośności, ale struktura zmienności TOC i gazonośności opisana za pomocą ich wariogramów jest identyczna. Korelacje wyróżnionych poziomów gazonośnych w rozpatrywanych otworach sugerują model złoża wielosoczewowo-warstwowego. Brak naturalnych granic złoża gazu w łupkach powoduje, że muszą być one określone w sposób umowny na podstawie przyjętej brzeżnej gazonośności. W przypadku występowania kilku stref gazonośnych interpretacja taka może być wykonana wariantowo. W otoczeniu każdego otworu wiertniczego w każdym przypadku można określić zasoby nisko, optymalnie i wysoko oszacowane w obszarze o promieniu równym zasięgowi wariogramu gazonośności w poziomym odcinku otworu.