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Geological interpretation of spectral gamma ray (SGR) logging in selected boreholes

This paper presents the interpretation of the spectral gamma ray (SGR) log focused on geological analysis regarding determination of the clay content in studied deposits, evaluation of the types of clay minerals, identification of fissure zones, determination of the organic matter content, determination of radiogenic heat value secreted during the decay of radioactive elements, and the characteristics of sedimentary conditions. The method was tested on data collected from five boreholes.

Key words: spectral gamma ray log (SGR), clay minerals, organic matter, sedimentary conditions, fissure identification.

Geologiczna interpretacja spektrometrycznego profilowania gamma (sPG) w profilach wybranych otworów wiertniczych

Bezpośredni pomiar koncentracji potasu, uranu i toru jest cenną informacją geochemiczną, mineralogiczną i w niektórych przypadkach złożową. W niniejszym artykule przedstawiono interpretację spektrometrycznego profilowania gamma (sPG) pod kątem określania wielkości zailenia badanych utworów oraz oceny rodzaju minerałów ilastych. Przedstawiono także wyniki w zakresie identyfikacji stref szczelinowych, wyznaczania zawartości substancji organicznej, wielkości ciepła radiogenicznego wydzielonego podczas rozpadu pierwiastków promieniotwórczych oraz charakterystyki środowiska sedymentacji. Metodę przetestowano na materiałach pochodzących z pięciu otworów wiertniczych.

Słowa kluczowe: spektrometryczne profilowanie gamma (sPG), minerały ilaste, substancja organiczna, środowisko sedymentacji, identyfikacja szczelin.

Introduction

Natural radioactivity of rocks is the result of the presence of natural isotopes: potassium – ^{40}K, uranium – ^{238}U, ^{234}U, ^{235}U and thorium – ^{232}Th and the products of their decay. These isotopes initially contained mainly in acidic igneous rocks are transported due to geological processes to the sediments where they usually accumulate in a clayey substance. Natural radioactivity is an important lithological indicator easily obtained by geophysical measurements. Direct measurement of potassium, uranium and thorium concentrations is a valuable geochemical, mineralogical and sometimes ore deposit data information.

Typically, high gamma-ray response indicates the presence of fine-grained deposits or clay-rich rock formation, such as shale, claystone, mudstone, while the relatively low gamma radiation indicates the presence of coarse-grained sandstone and carbonate rock, which exhibits higher water-transmitting capacity [1, 4, 14, 12, 22]. However, the main feature of spectral gamma ray log (SGR) is the ability to distinguish gamma emissions from potassium, uranium and thorium. Typically, SGR log is used to determine the clay content of rocks. Determination of this parameter based on gamma log is often biased by the radioactivity of the non-clay rock components, which leads to over-reading the clay content and in consequence to erroneous evaluation of the reservoir properties of the studied deposits. With the increase of the TOC content of the sediment, the U and Th concentrations usually increase, while the K-content decreases [24].

The ability to measure concentration of thorium, uranium and potassium in combination with the knowledge of mineral composition in studied rock formations allows solving the clay contamination problem in a satisfying manner. The applied method includes the elimination of the uranium component from the total natural radioactivity due to the high geochemical mobility of this element. Although the presence of uranium negatively influences the evaluation of the clay content it is a very significant factor in determining organic matter content in rock and rock fissuring. Information of the Th, U and K concentrations is also used to analyze the sedimentary conditions as well as to identify the mineral composition of studied deposits. A short characteristic of the radioactive elements Th, U and K (Table 1) and the range of issues that can be solved using the ratios between Th/U, U/K and Th/K, and therefore the application of spectral gamma ray log (SGR) in geological interpretation (Table 2) are presented below.

Table 1. Characteristics of Th, U and K [11]

Element	Characteristics
Thorium	• Insoluble in water. • Usually combined with shales, may supply certain information on the clay content. • Combined with heavy minerals in igneous rocks.
Uranium	• Usually not linked to the clay contamination of rocks. • Depends on the organic matter content.
Potassium	• One of the basic components of shale rocks. • Indicator of the presence of feldspars and micas. • Mainly occurs in oxidized form (K_2O). • Stabilizes clay minerals as kcl.

Table 2. Application of SGR log in geological interpretation [11]

Ratio	Significance
Th/U	• Analysis of sedimentary conditions: – Th/U > 7 continental environment, oxidizing conditions, weathered soils, etc., – Th/U < 7 marine sediments, grey and green shales, greywackes, – Th/U < 2 marine black shales, phosphorites, reducing conditions. • Estimation of the organic matter content in claystones. • Detection of basic discontinuities. • Used in stratigraphic correlations by determining transgressive-regressive and oxidizing-reducing conditions.
U/K	• Evaluation of the organic matter content in clay sediments. • Used in stratigraphic correlations. • Detection of diagenetic changes in clay and carbonate sediments, etc. • Used in correlation of natural fissure systems in deeper formations.
Th/K	• Recognition of types of sediments representing various facies. • Determination of sedimentary condition types, distance to palaeo shorelines, etc. • Determination of diagenetic changes in clay sediments. • Determination of the type of clay minerals; Th/k ratio increases in the following direction: glauconite → muscovite → illite → mixed-layer minerals → kaolinite → chlorite → bauxite.

Interpretation of spectral gamma ray log (SGR)

Clay content determination

Clay content is a significant parameter influencing the rock reservoir properties – clay minerals decrease permeability by blocking pores and cannels; and also decrease rock porosity by filling empty voids. Using only gamma ray log which register only the sum of natural radioactivity from isotopes mentioned above (thorium, potassium, uranium) and products of their decay may lead to erroneous evaluation of the reservoir properties of the studied rock layer due to the background radiation from non-clay rock components causing over-reading clay content values [8].

The main components biasing the unequivocal relationship of total radioactivity with the clay content are: organic matter usually containing high uranium concentrations as well as feldspars and micas characterized by increased concentrations of potassium. Similarly, the low content of accessory minerals such as zircon or monazite hampers correct recognition of the clay content [7]. The main advantage of SGR logging is the possibility of significant clay content evaluation improvement. Individual concentrations of thorium, uranium and potassium linked with expected mineral composition data of the studied formations would allow to determine the clay content using SGR [12]. It is assumed that the best indicator of the clay content is thorium, occasionally potassium, and most rarely uranium [22]. In practice, the uranium-free gamma ray curve is applied, thus eliminating radiation not linked with the clay content but derived from organic matter, fissuring or productive layers.

Clay mineral type evaluation

Determination of clay minerals content is restricted to five typical minerals which are significant for the oil industry: chlorite, glauconite, illite, kaolinite and smectite [21]. Clay minerals are formed in continental and marine environments, which influences their variability with regard to the chemical composition, despite maintaining numerous common structural features. The type of the clay mineral being generated is strongly influenced by the reaction of the sedimentary and diagenesis environments, e.g. kaolinite is formed at pH 5.5÷7.8, and montmorillonite at pH above 7.8. There can be various factors influencing pH changes e.g. environmental acidification can be a result of volcanic exhalations, reaction of juvenile waters, oxidation or decay of organic matter, it's transformation to peat or brown coal, and flora growth and development.

Information about clay mineral types occurring in a studied formation is used for example, for selecting a proper drilling fluid, because application of inappropriate fluid may cause swelling of clay minerals. Each clay mineral is strongly linked with the variable content of radioactive isotopes, mainly potassium and thorium. The Th/K ratio depends also on the crystal structure of the mineral, its dimensions, concentration of radioactive ions during formation of the mineral and the weathering and diagenetic processes taking place from the moment of mineral formation [25].

The type of dominating clay minerals may be determined based on a cross-plot of thorium to potassium (Fig. 1). The correct grouping of the plotted points allows to eliminate certain types of clay minerals.

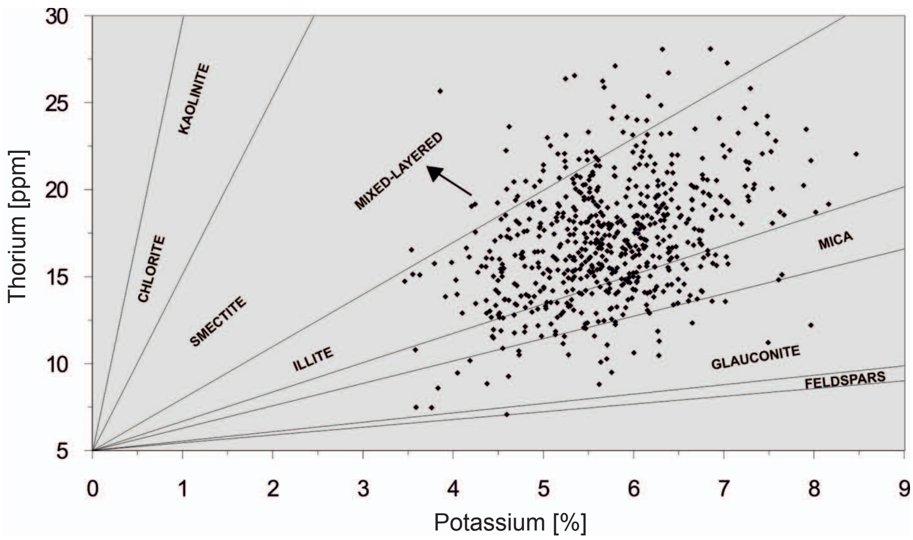

Fig. 1. An example of dominating clay mineral types determined from the potassium and thorium ratio [21]

Fissure identification

Determination of the rock reservoir parameters is the most important task during the interpretation of geophysical measurements [14]. Porosity in carbonate rocks is dependent on the fissure system, which can be recognized by SGR log. The above is possible, based on the fact that in reducing conditions, in which carbonate rocks are formed, circulation of hydrothermal waters may cause precipitation of uranium salts in the fissures; moreover, high radioactivity in fissures results from the presence of uranium and radon isotopes. Due to the fact that it is not possible to distinguish uranium from radon on SGR curves, the total gamma radiation in the fissures linked to their presence is attributed to uranium. It is necessary to notice that the presence of uranium in carbonate rocks may also be related to the presence of stylolites and phosphorus compounds, therefore the fissure presence must be confirmed by the results of other logs (e.g. acoustic imaging log). In complex fissure systems the SGR curves are sometimes blurred due to low concentration of radioactive elements. These formations are much better recognized by the following ratio curves:

- uranium/potassium,
- thorium/uranium,
- thorium/potassium,
- uranium/uranium-free.

Collation of U/K and Th/U curves is strongly recommended [25]. These curves are inversely proportional and the associated change of uranium content causes the curves to dip in opposite directions.

Determination of the organic matter content and the value of radiogenic heat

Hydrocarbon generation requires the presence of potential source rocks. The first step in evaluating rocks as potential sources of hydrocarbons is determination of the organic carbon content (TOC). It's minimal concentration that allows considering the rock as a source rock is 0.5% wt. Empirical relationships between TOC determined in laboratory and results of SGR log allow to evaluate the content of the organic matter in the entire log along the borehole axis. Deposits rich in organic matter are usually characterized by increased natural gamma radiation coming from uranium. This quantity depends both on the organic matter content and its maturity. Uranium occurs in chemical and detritic sedimentary rocks, e.g. shales, arcosic conglomerates, sandy conglomerates, phosphorites and tufas. It is tied with the organic matter and also with accessory minerals, e.g. zircon, monacite, epidote and apatite [20]. It is easily absorbed by dispersed or layered carbonates, particularly in a reducing environment. The processes include: reduction of U^{6+} from the solution to U^{4+} and formation of uranium-organic colloids and/or their compounds. Depending on the temperature-temporal conditions type and amount of organic matter and its association with the sedimentary environment influences both volume and properties of generated hydrocarbons [17].

Another crucial issue is the possibility of using SGR log to determine the value of radiogenic heat, released during the decay of radioactive elements. This parameter is used in simulations of the process of organic matter transformation into hydrocarbons and in the analysis of sedimentary basins.

In Poland, pioneers of studies focused on radiogenic heat were M. and S. Plewa [18], who presented in their publications the theoretical concepts as well as the results of radiogenic heat studies for igneous, metamorphic and sedimentary rocks from different regions of Poland. Last years several papers published the results of SGR interpretation in aspect of radiogenic heat determination in different regions of Poland [1, 5, 10, 13].

The value of radiogenic heat emitted by a rock medium is determined from the L. Rybach formula [2, 19] based on the concentration of isotopes from the three radioactive families ^{238}U, ^{235}U, ^{232}Th and from the potassium isotope ^{40}K.

$$A = 0.01\,\delta\,(9.52\,U + 2.56\,Th + 3.48\,K) \qquad (1)$$

where:

A – radiogenic heat [μWm^{-3}],

δ – rock density [g/cm^3],

U, Th, K – rock content of U [ppm]; thorium Th [ppm]; potassium K [%].

In the natural environment, beside the mentioned elements numerous radioactive isotopes of other elements occur, but when determining the value of radiogenic heat they can be omitted due to their long half-lives and their low concentrations.

Application of RADIOLOG software developed in the Oil and Gas Institute – National Research Institute, Poland by I. Gąsior (GEO system) allows to obtain a continuous record of radiogenic heat changes in relation to depth, thus enabling the observation of the heat field formation within particular lithostratigraphic units. It has been determined that the amount of heat emitted by sedimentary rocks is strictly associated with the content of clay minerals and other minerals containing increased concentrations of potassium (feldspars, micas), as well as the organic matter, often accompanied by the uranium compounds.

Analysis of sedimentary conditions

The term 'sedimentary environment' contains the accumulation area and its specific physical, chemical and biological conditions that influence occurring sedimentary processes and the resulting deposits. The term is therefore complex in composition and distinguishing different sedimentary conditions may be conducted using different methods, depending on the requirements, the study aspects and the applied division criteria. However, serious problems arise when attempting to systemize the distinguished sedimentary environments, due to the complex nature of that term not allowing to determine uniform subdivision criteria.

The most general criterion of subdivision is usually considered to be the widely understood accumulation area; thus, groups of continental and marine environments are distinguished with a transitional group of continental-marine environments. Even such a generalized subdivision is not consistent, because for example the accumulation of glacial sediments may be considered both as the continental and the marine environments. So far, studies have shown a strict relationship between the thorium/uranium ratio and the sedimentary environment. This relationship shows that high Th/U ratios are typical of the continental environment and low – of marine settings [11].

The boundary value of this ratio was determined as follows [14, 24]:

- for continental deposits: $Th/U > 7$,
- for marine deposits: $Th/U < 7$,
- high probability of reducing conditions: $Th/U < 2$,
- high probability of oxidation conditions: $Th/U > 7$.

Rainwater in-ground motion (infiltration) is accompanied by loss of oxygen, bacterial activity, reactions with the surrounding rocks, etc., which causes Ph change from positive values (oxidizing environment) to negative values (reducing environment).

Reducing environment (negative Ph)

Formation water linked with the presence of crude oil usually shows negative Ph values. In the presence of organic matter, hydrogen sulphide and sulphur dioxide, potential uranium ions transported by the migrating waters are precipitated as UO_2.

Oxidizing environment (positive Ph)

In oxidizing, slightly alkaline conditions, uranyl ions (UO_2^{++}) are dissolvable in groundwater, containing carbon oxide and dioxide as well as OH^- ions.

Another important parameter of the chemical reaction is the concentration of hydrogen ions as the pH parameter. It is the negative logarithm of the number of free hydrogen ions found in the solution and accepts the values in the range of 1 to 14, where:

- pH = 7 – neutral solution,
- pH < 7 – acidic solution,
- pH > 7 – alkaline solution.

For the majority of potential source rocks generating crude oil, pH varies in a narrow range from 3.5 to 4 in its lower limit to 9 in its upper limit [11].

SGR interpretation based on measurements from the D-1, Z-8K, Ł-20, P-29, Ż-8 boreholes

Similarly to the results of conventional gamma logging, the results of spectral gamma ray logging are biased by the influence of borehole diameter and the drilling fluid, and in cased boreholes – by pipe columns and the cement bond. Measurements used in this paper were collected from open boreholes and therefore the corrections refer to borehole diameter and density of the drilling fluid.

Evaluation of clay mineral types using borehole D-1 as an example

Evaluation of the types of clay minerals was performed for borehole D-1 within 920÷1390 m interval (Fig. 4). SGR interpretation referred to the following lithostratigraphic units: Menilite Beds, Globigerina Marls, Variegated Shales I, and Ciężkowice Sandstones I. The interpretation included:

- determination of the types of clay minerals was based on a cross-plot of the potassium to thorium ratio [11] (Fig. 2), where particular minerals occur in the following ranges of the Th/K ratio:
  - feldspars: < 0.6,
  - glauconite: 0.6÷1.5,
  - micas: 1.5÷2.0,
  - illite: 2.0÷3.5,
  - mixed-layered: > 3.5.

It should be noted that the content of potassium and thorium linked with the type of clay minerals is caused both by primary as well as secondary factors, such as diagenesis, weathering, leaching, and the presence of volcanic ashes. Due to this fact the interpretation results should be treated as indicators of the presence of particular clay minerals [14].

The presented interpretations show that the studied deposits are composed of the following clay minerals: glauconite, illite, micas and mixed-layered minerals. Histograms of the Th/K ratio show that the dominating clay mineral for all the series is illite (Th/K within 2÷3.5 range). The largest content of mixed-layered minerals (Th/K > 3.5) is noted in Variegated Shales I (Fig. 3a) and the lowest in the Menilite Beds (Fig. 3b). Moreover, the Menilite Beds (Fig. 3b) and the Ciężkowice Sandstones I (Fig. 3c) are characterized by the presence of glauconite (Th/K within 0.6÷1.5) and the highest content of micas (Th/K within 1.5÷2.0) (Fig. 3c).

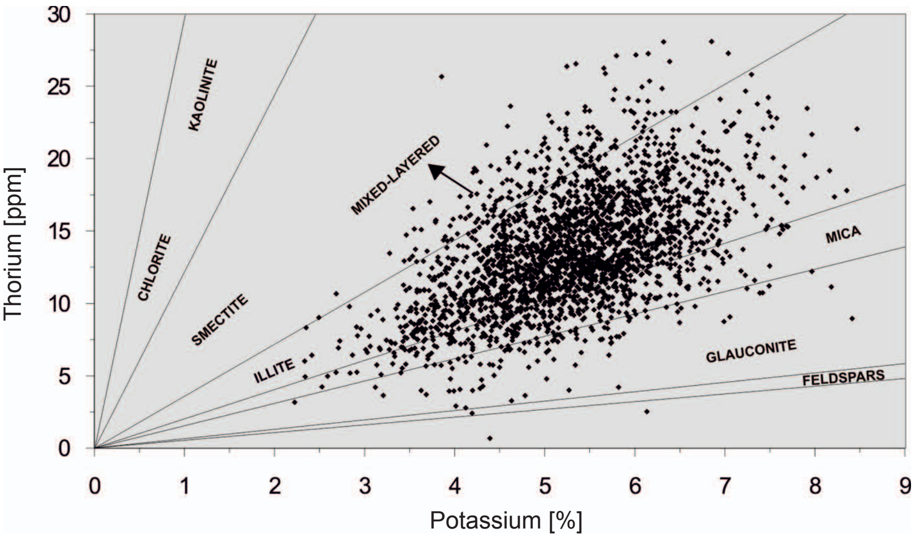

Fig. 2. Determination of the clay mineral types based on the K/Th ratio for borehole D-1

Application of cross-plot diagrams to determine the types

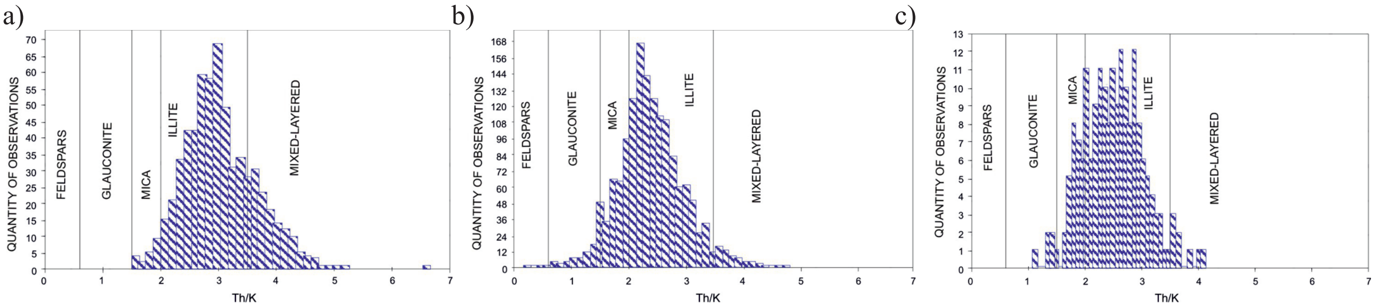

Fig. 3. Determination of the dominating minerals based on histograms of the Th/K ratio for particular lithostratigraphic units in borehole D-1: a) Variegated Shales I, b) Menilite Beds, c) Ciężkowice Sandstones I

of clay minerals has certain inconveniencies, because the interpretation results cannot be presented as a function of depth. Presentation of the Th/K ratio as a function of depth allows to trace the changes of the types of clay minerals in the core log [6] (Fig. 4). It fully confirms the results of statistic analysis, giving a similar but more clear representation and easier evaluation of clay mineral types.

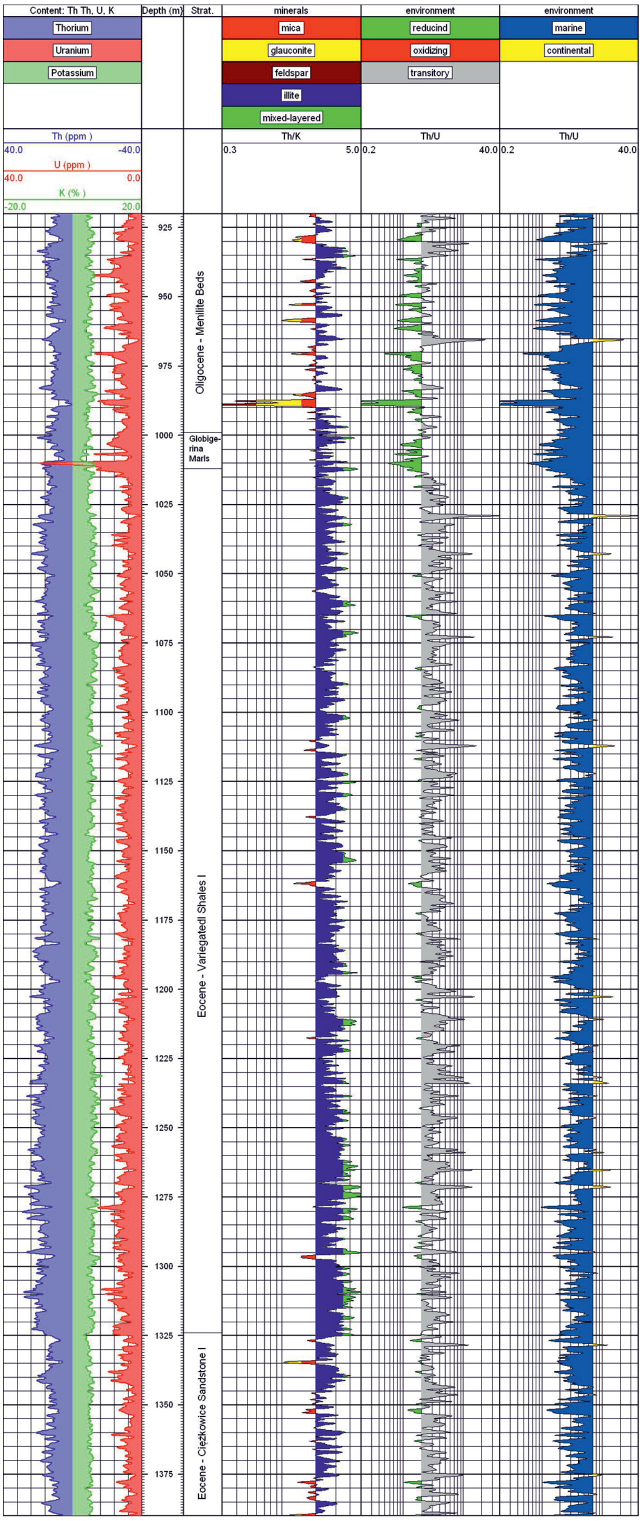

Fig. 4. Characteristics of sedentary conditions and evaluation of clay mineral types for borehole D-1

Clay content in boreholes D-1 and Z-8K

As mentioned above, the main advantage of SGR logging is its ability to determine the clay content in a more trustworthy manner, and therefore a correct evaluation of the reservoir conditions in the borehole data logs. The investigated intervals include: Menilite Beds, Globigerina Marls, Variegated Shales I (D-1, Fig. 6) and Jurassic deposits (Z-8K, Fig. 5). In the case of borehole Z-8K the application of standard gamma log resulted in too high clay content in the interval 3230÷3308 m in comparison with the uranium free curve output (Fig. 5). This

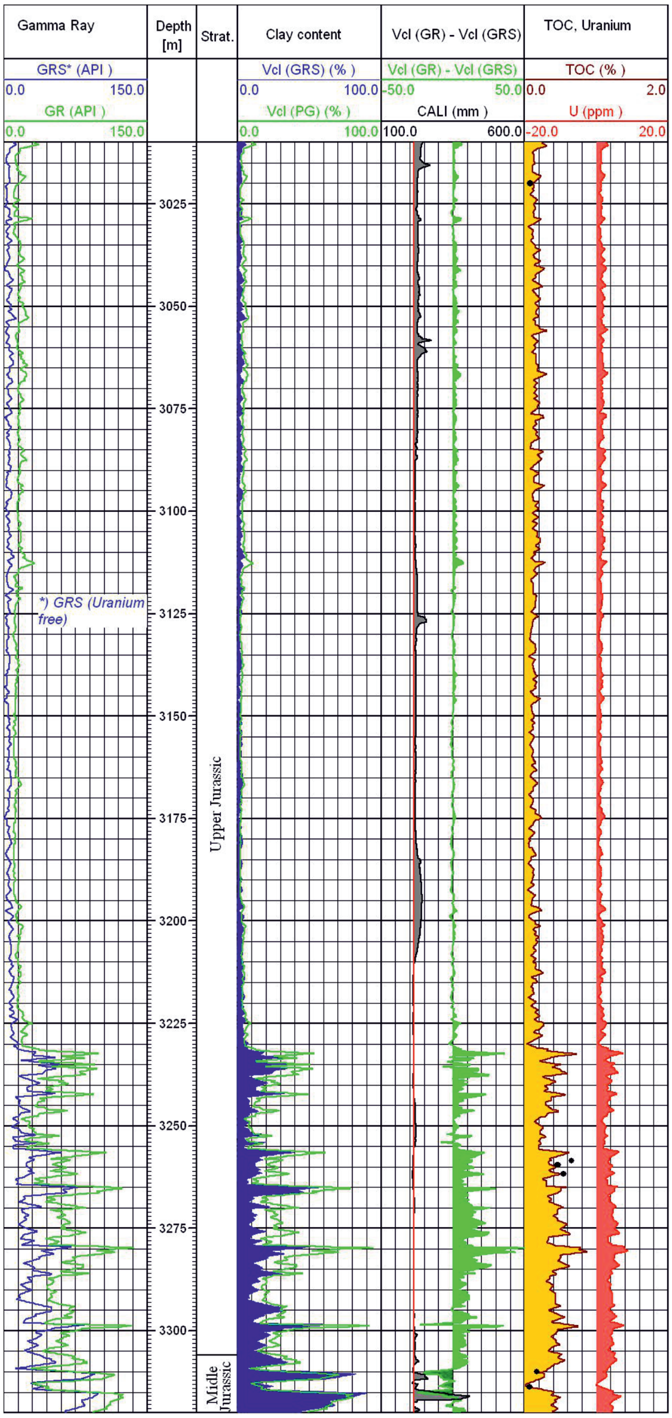

Fig. 5. Determination of the clay content and organic matter content in borehole Z-8K

is linked to the presence of organic matter which influences the increase in gamma radiation.

In the case of borehole D-1 likewise in Z-8K well the clay content determined on the basis of gamma log is higher when compared with the clay content determined by the GRS uranium-free curve. This result may also be explained by the presence of organic matter (Fig. 6).

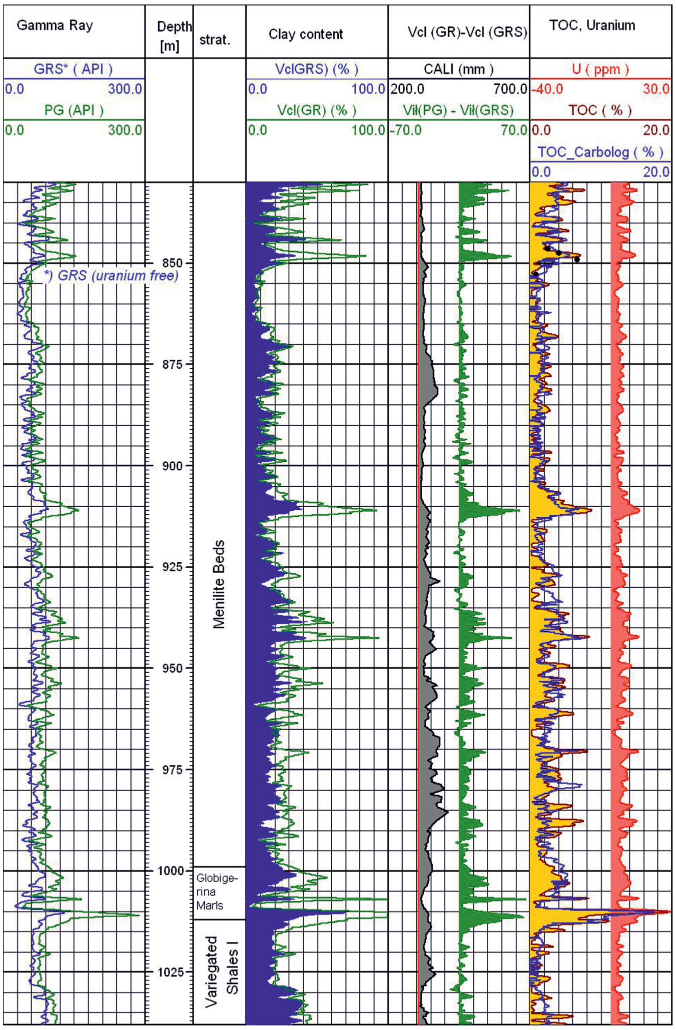

Fig. 6. Determination of the clay content and organic matter content in borehole D-1

Organic matter content in boreholes Ż-8, D-1 and Z-8K

The organic matter content was determined both qualitatively (Ż-8) and quantitatively (D-1). The following ratio curves were used for qualitative interpretation:

- thorium/uranium,
- uranium/potassium.

Increase in the U/K curve values with simultaneous decrease in the Th/U values is caused by an increase of the uranium content combined with organic matter in the case of borehole Ż-8. The presence of this substance in borehole Ż-8 is clearly pronounced in the interval with Menilite Beds (Fig. 7).

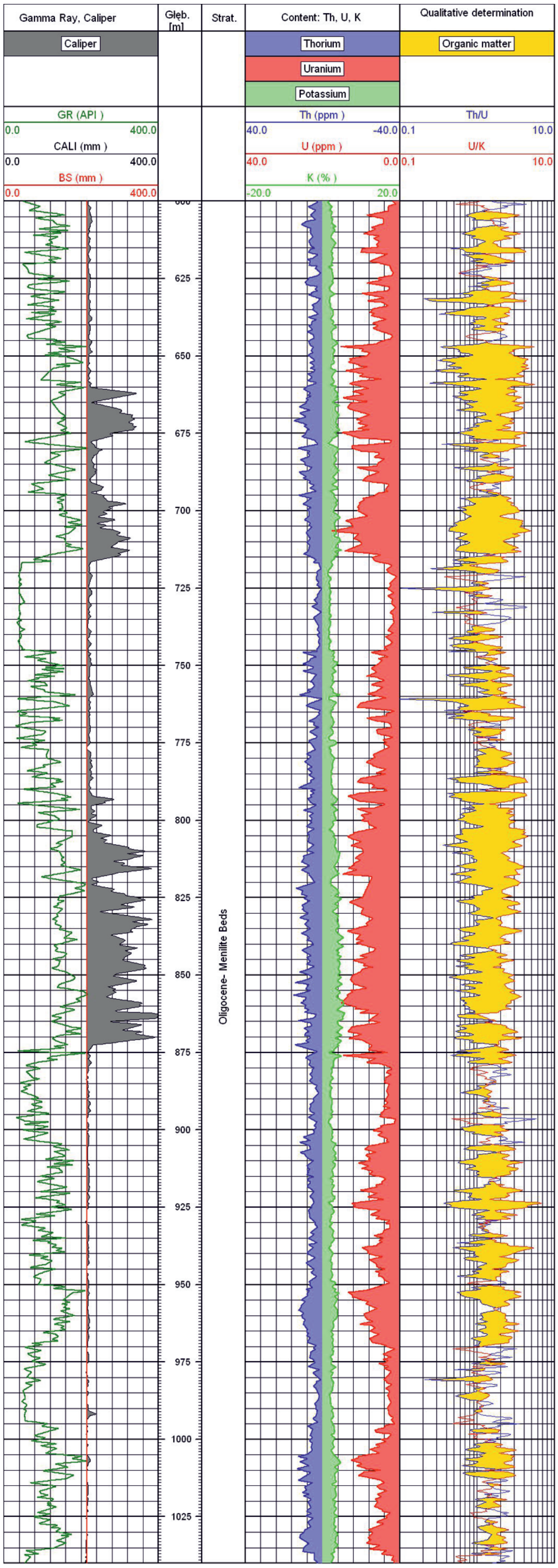

Fig. 7. Qualitative information of organic matter in borehole Ż-8

Quantitative interpretation was conducted for borehole D-1. The CARBOLOG method, developed in the French Oil Institute in 1989 [3] was applied. The method has been commonly used by the Oil and Gas Institute – National Research Institute, Poland in the interpretation of geophysical logging with regards to the quantitative evaluation of the TOC content [9]. CARBOLOG software was developed by the Department of Drilling Geophysics of the Oil and Gas Institute – National Research Institute; it allows a continuous record of the organic carbon content in the borehole log. The method is based on two conventional logs: acoustic (PAdt) and electrical resistivity (PO) and on basic interpretation models of Wyllie and Archie describing physical phenomena taking place in the rock medium. A cross-plot: $1/\sqrt{Rt} = f(\Delta T)$ based on data from well logging is used to determined the TOC content, where Rt is the rock electrical resistivity, and ΔT is the transit time interval of the acoustic wave in the rock. Points with coordinates representing pure rock components (water, rock skeleton, clay, organic matter) are marked on the plot; parameters of formation water are usually known, whereas the rock skeleton and the organic matter parameters should be determined. A straight line is drawn between points representing the rocks with the lowest volumetric organic matter content V_{TOC}, which crosses the PAdt axis at point $PAdt_{sz}$. The line with a tangent characteristic of the stratigraphic series in a sedimentary basin represents the beginning of the scale used for the volumetric content V_{TOC} calculation. Determination of the interval time $PAdt_{TOC}$ (at 100% content of organic matter) requires calibration, based on laboratory measurements. Therefore the calculation of TOC parameter using CARBOLOG software is based on a theoretical equation with only three parameters: transit time interval of the organic matter ($PAdt_{TOC}$), transit time interval of the rock skeleton ($PAdt_{sz}$) and tangent of the zero line corresponding to organic matter. The curve drawn (TOC_carbolog) allows to trace the change in the organic matter content with depth in particular lithostratigraphic units, which has been presented in Figure 6.

SGR logs were used to evaluate the organic matter content. In this case the relationship between the uranium content (ppm) determined from SGR logs and the TOC content determined from pyrolytic analyses were applied [14, 16]:

- for borehole D-1 (Fig. 8):

Table 3. Geochemical data [15] with GRS measurements for borehole Z-8K

No.	Sample depth [m]	Lithostratigraphy	Degree of thermal alteration T_{max} [ºC]	Vitrinite reflectance R_o [%]	TOC content [%]	U content [ppm]
Upper Jurassic – Astartian						
1	2560.0	limestone			0.02	0.35
2	2598.1	limestone			0.02	0.42
3	2610.0	limestone			0.03	0.48
4	2635.0	limestone			0.05	0.68
5	2660.0	limestone			0.05	0.85
Upper Jurassic – Raurakian						
6	2730.0	limestone			0.15	1.55
7	2749.4	limestone + clay	432		0.10	0.85
8	2754.5	siltstone	422		0.12	0.88
9	2822.5	siltstone + limestone			0.14	1.05
10	2823.9	siltstone + limestone			0.12	0.92
11	2825.6	siltstone + limestone			0.12	0.98
12	2830.0	limestone	301		0.05	0.71
13	2840.0	limestone			0.08	0.48
14	2880.0	limestone			0.02	0.45
15	2900.0	limestone			0.05	0.68
16	3020.0	limestone			0.08	1.20
17	3258.5	siltstone	431		0.65	5.90
18	3259.5	siltstone	431		0.45	3.20
19	3261.7	siltstone + dolomite	427		0.54	4.66
20	3300.0	limestone	421		0.21	4.00

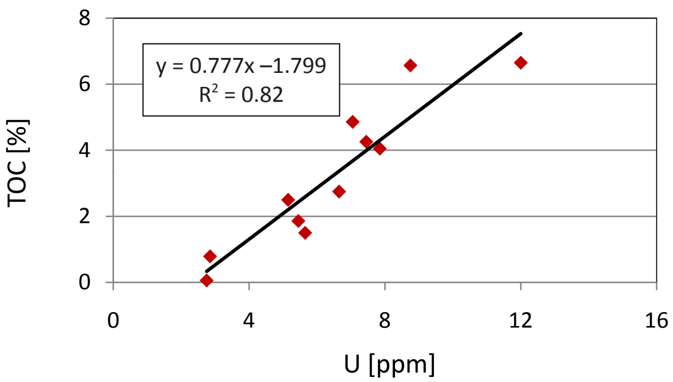

Fig. 8. Relationship between the TOC content and the uranium content in borehole D-1

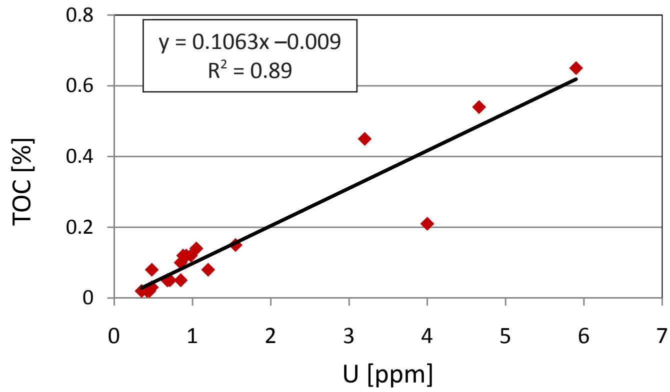

Fig. 9. Relationship between the TOC content and the uranium content in borehole Z-8K

Table 4. Geochemical data [16] with GRS measurements for borehole D-1

No.	Sample depth [m]	Lithostratigraphy	Degree of thermal alteration T_{max} [°C]	Vitrinite reflectance R_o [%]	TOC content [%]	U content [ppm]
Upper Jurassic – Oxfordian						
1	465.5	siltstone	427		2.75	6.65
2	466.3	siltstone + claystone	428		4.26	7.45
3	468.5	siltstone + claystone	423		6.57	8.75
4	846.5	siltstone	432		2.50	5.15
5	847.5	siltstone	423		4.05	7.85
6	849.1	siltstone	424		6.65	12.00
7	852.7	sandstone	428		0.79	2.85
Eocene – shales + sandstones						
8	1194.0	siltstone + sandstone	432		1.86	5.45
9	1330.5	siltstone + sandstone	421	0.32	4.86	7.05
10	1334.3	siltstone	427		0.06	2.75
11	1447.8	siltstone	436	0.64	1.50	5.65

$$TOC(\%) = 0.777U – 1.799;\ R^2 = 0.86 \qquad (4)$$

- for borehole Z-8K (Fig. 9):

$$TOC(\%) = 0.1063U – 0.009;\ R^2 = 0.89 \qquad (5)$$

The match of obtained curves (TOC and TOC_carbolog) is not ideal (Fig. 6). There are intervals where the curves agree better or worse with one another. However, a general trend is maintained, which indicates that the simplified method of TOC determination may be used, as a tool for the qualitative evaluation of the organic matter content.

In borehole D-1, the Menilitic Beds are characterized by a higher content of organic matter (TOC within 0.25÷19.5%) in comparison with the Variegated Shales (TOC within 0.25÷5.93%), and thus represent a better source of hydrocarbon generation (Fig. 6).

The calculated indicator of TOC changes with depth for the lithostratigraphic units from borehole Z-8K, which allows to distinguish two separate levels. The first interval at 3126÷3230 m is characterized by decreased TOC values (TOC Є 0.01÷0.27%), and the second at 3230÷3308 m has much higher values of TOC (TOC Є 0.14÷0.87%), which is associated mainly with the high clay content (Fig. 5).

Radiogenic heat determination

The value of radiogenic heat was calculated for borehole P-29 by using RADIOLOG software.

A continuous record of changes of the determined parameter with depth was obtained and, allowed to observe the building of the heat field within the following lithostratigraphic units: Variegated Shales II, Ciężkowice Sandstones II, Variegated Shales III and Istebna Beds (Fig. 10). The largest differences of the generated radiogenic heat A occur in the Eocene layer (Ciężkowice Sandstones II) developed as sandstones (A = 1.22 μW/m^3) intercalated with clay shales (A = 4.03 μW/m^3).

The values of radiogenic heat characterizing the remaining units are as follows:

- Variegated Shales II: A € 2.64÷4.69 μW/m^3,
- Variegated Shales III: A € 3.27÷4.48 μW/m^3,
- Istebna Beds: A € 1.60÷4.62 μW/m^3.

Analysis of the interpretation results (Fig. 10) indicates the relationship between the heat value and the clay content: the value of the heat emitted by rocks is proportional to the clay content.

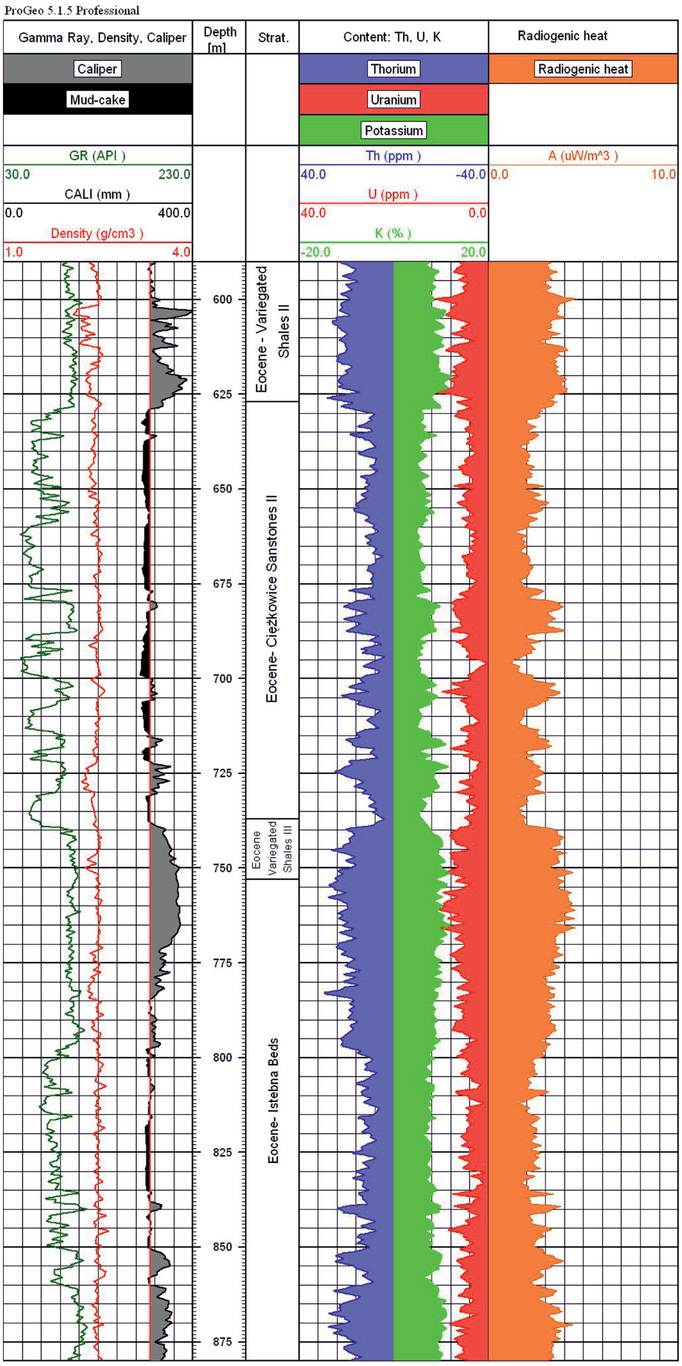

Fig. 10. Determination of radiogenic heat based on the Rybach formula for borehole P-29

Sedimentary environment observed in geological profiles of boreholes D-1 and Ł-20

In the case of borehole D-1, the interpretation was focused on the depth interval within 920÷1390 m comprising: Menilite Beds, Globigerina Marls, Variegated Shales I and Ciężkowice Sandstones I. The curve showing the Th/U ratio was used for the analysis; according to which the deposits mostly represented marine environments (Fig. 4). A small influence of the continental setting was recorded at 920÷1390 m. The subdivision into reducing and oxidizing environments was much more complicated. Three zones characterized by diverse sedimentary conditions can be distinguished in the lithostratigraphic succession. The first (920÷1012 m) (Menilite Beds and Globigerina Marls) is characterized by a dominating influence of the reducing environment. In Eocene strata (Ciężkowice Sandstones I, Variegated Shales I), the reducing environment has much lower influence and oxygen influx is observed, which may point to slightly oxidized sedimentary conditions. The obtained results are confirmed by geochemical studies, in which marine organic matter in the Menilite Beds is confirmed by the low-particle hydrocarbon maximum. In turn, the pristane (Pr)/phytane (Ph) indicator points to the presence of low-oxygen conditions in the sedimentary environment (Pr/Ph – 1.44) [14]. In the case of Eocene deposits, the distribution of n-alkanes and isoprenoids is distinctly dominated by pristane, where its ratio to phytane is between 5.43÷6.77 and points to oxygenizing conditions in the sedimentary environment [14].

In borehole Ł-20 the interpretation was focused on Jurassic sediments deposited in a deep marine setting without oxygen (reducing environment). The results of this interpretation are presented in Fig. 11.

Fissure zones identification in Upper Jurassic carbonate rocks for borehole Ł-20

The interpretation was focused on the Malmian carbonate rocks drilled at 1400÷1675 m in borehole Ł-20. Fissure identification was based on comparison of the Th/U and U/K curves, presented in Fig. 11. In reducing conditions, in which the studied deposits were formed, formation waters or hydrothermal waters circulation may cause precipitation of uranium salts in the fissures, thanks to which the presence of fissures may be detected by increased uranium content. The Th/U and U/K ratios were calibrated to enhance variability in the uranium content. The curves are inversely proportional to each other and therefore changes in the uranium content result in their dips in opposite directions. In the log this fact is shown as an enhancement marked yellow, indicating zones with increased

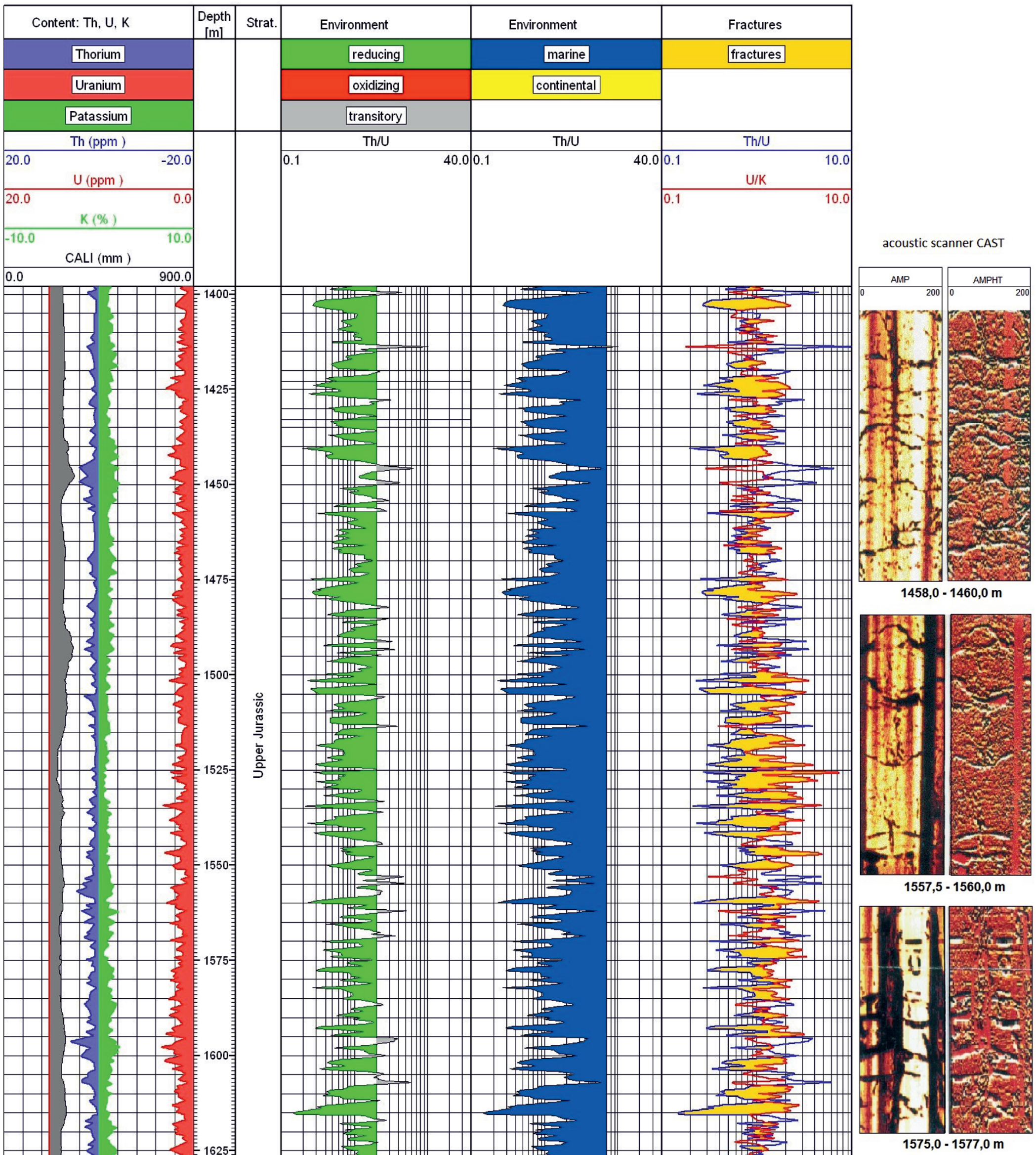

Fig. 11. Identification of fissure zones and analysis of sedimentary conditions for borehole Ł-20

uranium concentration. To confirm the presence of fissures, the results of measurements with an acoustic scanner CAST have been shown (Fig. 11); CAST allows a continuous, digital record of the amplitude and time of the wave reflected from the borehole wall. Based on processed amplitude and time images, type, density and distribution of fissures can be determined.

Remarks and conclusions

1. The advantage of spectral gamma ray SGR application is a significant improvement in the clay content evaluation, and therefore determination of the rock reservoir properties. In extreme cases, the lack of this measurement may cause omission of a productive level.
2. There is a good match between the organic matter content determined in laboratory and that calculated on the basis of the uranium curve. The usage of TOC(U) as an organic matter indicator has been confirmed by results obtained independently with the CARBOLOG method.

3. SGR log allows to determine fissuring, an important parameter that influences the presence of the reservoir layer in carbonate rocks.
4. Application of SGR logging allows to determine the value of radiogenic heat produced during the decay of radioactive elements. This is an important parameter used in the analysis of sedimentary basins when simulating processes of organic matter transformation into hydrocarbons.

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