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Application of multivariate statistical methods for characterizing heterolithic reservoirs based on wireline logs – example from the Carpathian Foredeep Basin (Middle Miocene, SE Poland)

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Principal Components Analysis (PCA) and Cluster Analysis (CA) were applied for well log data derived from heterolithic intervals drilled in two boreholes (Mrowla-1 and Cierpisz-2) in the Miocene fill of the Carpathian Foredeep. Both boreholes penetrated similar basement elevations conductive for structural trapping of hydrocarbons in an overlying thin-bedded heterolithic reservoir, which produces gas in commercial quantities in one borehole. The PCA was used to reduce data space preserving sufficient amounts of parameters for a differentiation between thin layers of sandstones and mudstones and between gas- and water-saturated horizons. In both boreholes, the number of logs was reduced to four significant principal components (PCs). Differences between gas-saturated and water-saturated layers were found. CA was used for the classification and grouping of data according to natural petrophysical features of the analysed rocks. The group corresponding to gas-saturated zones was found in the Cierpisz-2 borehole. It is concluded that PCA and CA can provide useful information for a more reliable identification of gas-saturated horizons.

Key words: well logs, Principal Components Analysis, Carpathian Foredeep, Miocene, heterolithic reservoir rock.

INTRODUCTION

The Carpathian Foredeep forms one of the most important petroleum provinces in Poland. Extensive geological research that began here in the middle of the last century resulted in documenting a number of accumulations of natural gas, located especially in the eastern part of the basin (Karnkowski, 1994). Gas occurs in the Middle Miocene siliciclastic succession, which attains locally 4000 m in thickness and is of a Badenian-Sarmatian age (Oszczypko et al., 2006). The succession is thought to have been deposited within submarine fan, shelf and fluvial-dominated deltaic settings (Maksym et al., 1997; Dziadzio, 2000; Porębski et al., 2002; Porębski and Warchoł, 2006; Lis and Wysocka, 2012). Gas, mostly microbial methane (Kotarba and Peryt, 2011), was documented in both structural and stratigraphic traps (e.g., Karnkowski, 1999; Krzywiec, 1999; Borys et al., 2000; Myśliwiec, 2004). Gas-bearing reservoir rocks are represented mainly by sandstones, but significant gas inflows were also recorded from heterolithic intervals that are typified by centimetre scale interbeds of sandstones and mudstones (Myśliwiec, 2004). It has ignited an interest in the methods of recognition of the nature of this peculiar, thin-bedded reservoir (e.g., Zorski, 2009). However, Miocene heteroliths reveal small differences in values of standard petrophysical parameters, like bulk density, resistivity, as well as P- and S-wave velocity, and the “zebra”-like interbedding of permeable and non-permeable lithologies makes it difficult, or sometimes impossible, to use standard well logging interpretation procedures for a proper characterization of reservoir properties (Jarzyna et al., 2013a). Moreover, the vertical resolution of conventional well logging tools is lower than bed thickness in heterolithic facies, and advanced, high-resolution imaging devices, such as Formation Microimager (FMI), have seldom, if ever, been used in the Carpathian Foredeep.

In our study, we have employed a set of statistical techniques, including principal components and cluster analysis, to well log data in order to better constrain the reservoir properties of Miocene heterolithic intervals. The analysis was performed on logs run in the Cierpisz-2 and Mrowla-1 boreholes (Fig. 1). They are located at the SW–NE seismic profile on the Trzciana-Cierpisz-Zaczernie seismic volume (Geofizyka Kraków, Ltd.; Fig. 2). Both boreholes abound in thick intervals of heterolithic facies and both are located above basement uplifts creating favourable conditions for the development of structural trapping mechanisms of gas accumulations (Fig. 2). However, gas inflow in commercial quantities was recorded from the

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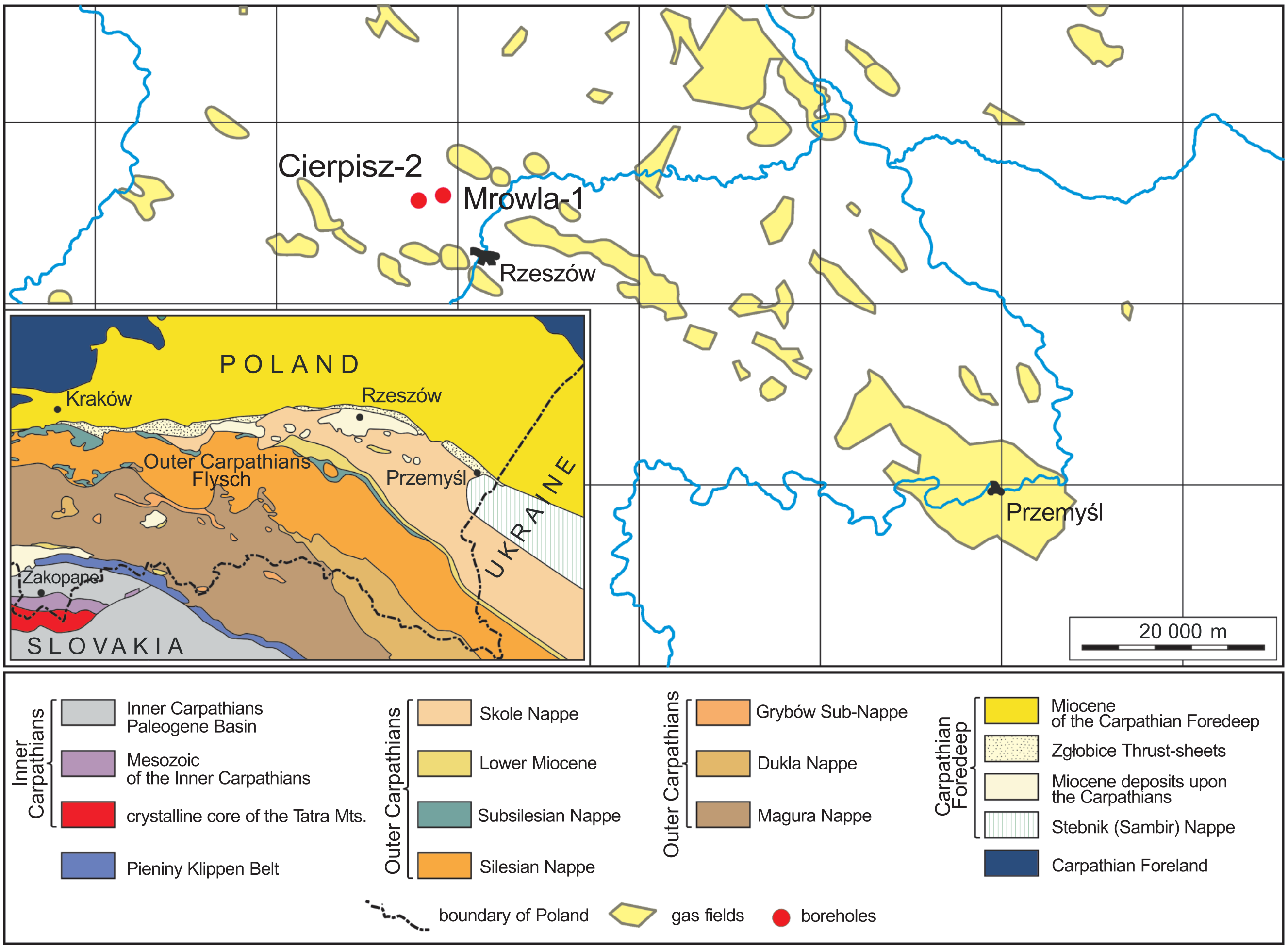

Fig. 1. Map showing the location of the Cierpisz-2 and Mrowla-1 boreholes and the distribution of gas fields in Miocene sediments of the southeastern part of the Polish Carpathians Foredeep Basin (Jarzyna et al., 2013b, modified from Myśliwiec, 2004); inset map shows a tectonic sketch of the Polish Carpathian Foredeep Basin and adjacent Outer Flysch Carpathians (modified from Oszczypko et al., 2006)

Cierpisz-2 borehole only. The main issue addressed here is whether the results of statistical analysis of log-derived petrophysical parameters can provide indicators of gas saturation and be helpful in pinpointing those among the parameters that can discriminate best between gas and non-gas conditions in the Miocene heterolithic reservoir rocks. Statistical methods were used for improving standard logging interpretation.

DATABASE

In the 20–2000 m depth interval of the boreholes, the following records were gained: calliper log (CALI), acoustic log (DT – transit interval time), neutron log (NPHI – neutron porosity), density log (RHOB), resistivity logs (RXO – invaded zone resistivity, RT – virgin zone resistivity), photoelectric absorption effect log (PE), borehole-corrected natural radioactivity log (GRC), spectrometric natural radioactivity logs (POTA – potassium log, THOR – thorium log, URAN – uranium log, TURA – thorium/uranium ratio log, UPRA – uranium/potassium ratio log, TPRA – thorium/potassium ratio log). Results of the standard logs interpretation were also available. Total porosity (PHI), water saturation (in the virgin zone SW, and in the invaded zone – SXO), irreducible water saturation (SWI), permeability (K), volume of sandstone (VSAN, ss), volume of shale (VCL, sh) and volume of limestone (ls) were used for statistical analysis. The logging measurements and interpretation were performed by Geofizyka Kraków, Ltd., Poland.

A 100 m of thick interval that is correletable between both boreholes was chosen for the statistical analysis. The interval occurs at a depth of 810– 910 m in the Cierpisz-2 borehole, and 910–1010 m in the Mrowla-1 borehole, and yielded a commercial gas flow in the former borehole (Fig. 2). As seen in short and discontinuous cores, reservoir rocks in the studied sections are dominated by thin-bedded, wavy and lenticularly laminated heteroliths, which are attributed to distal delta-front and prodelta environments.

The results of well logging and standard logs interpretation (Figs. 3 and 4) reveal strong variations in the contents of sandstones and shale, porosity, saturation and permeability. A considerable variability in interval transit time (DT), bulk density (RHOB), neutron porosity (NPHI) and borehole-corrected natural gamma radioactivity (GRC) was also observed. However, these results do not reflect clearly the presence of gas saturation in the Cierpisz-2 borehole and its absence in the Mrowla-1 borehole.

METHODOLOGY

Principal Components Analysis is a mathematical method of reorganizing information in a data set of samples. PCA was

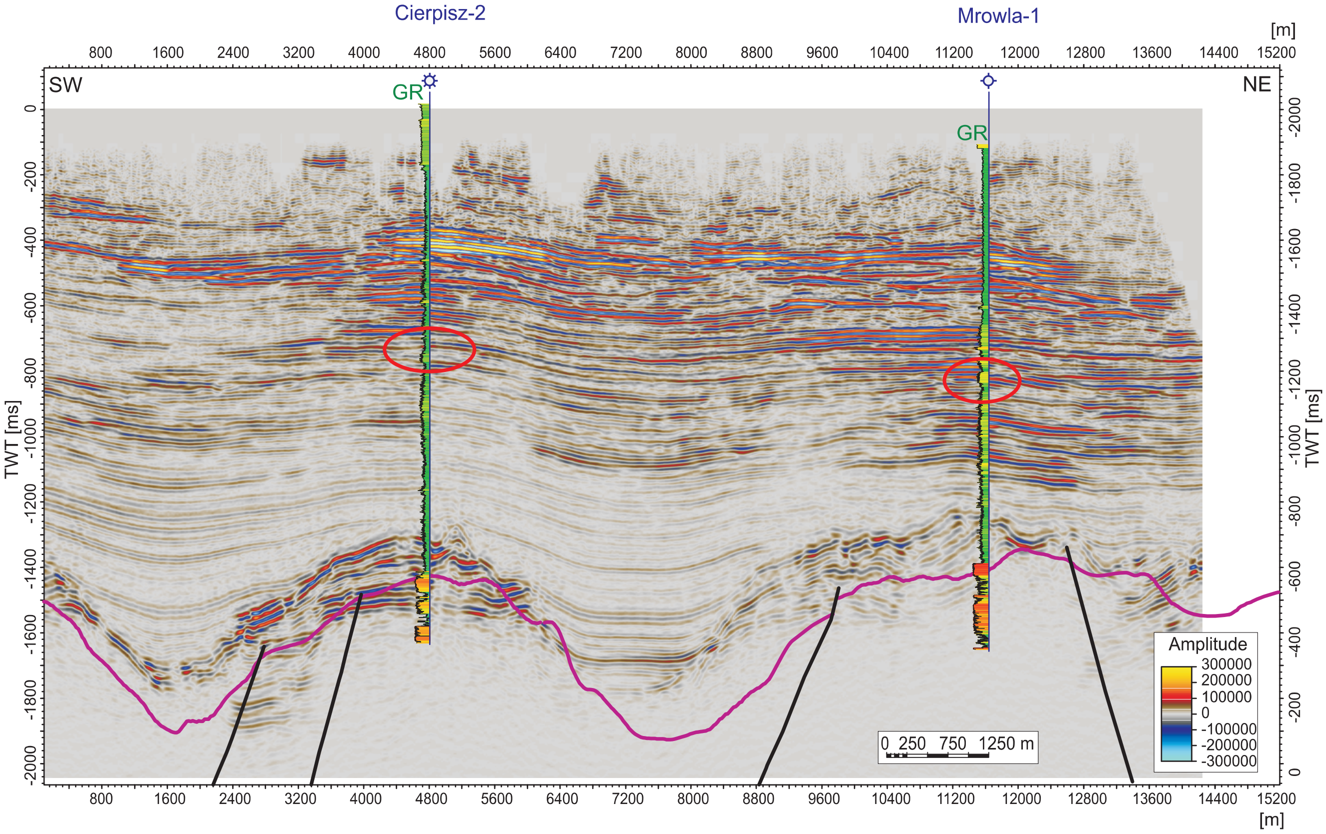

Fig. 2. Seismic cross-section between the Cierpisz-2 and Mrowla-1 boreholes

Ellipses mark intervals of interest (Pietsch et al., 2014); GR – natural gamma radioactivity

invented by Pearson (1901) and developed subsequently by Hotelling (1933), Karhunen (1947) and Loève (1948). Owing to its application versatility, PCA has been used in many disciplines, including engineering, geology and geophysics (Kaźmierczuk and Jarzyna, 2006). Principal Components Analysis is a multivariate statistical method, which is generally used to reduce multidimensional data sets into lower dimensions and to extract unobservable quantities hidden in the original measurements. The rules for computing new variables called principal components (PCs) are quite simple, but the mathematics involved is quite complex.

The method focuses on explaining and summarizing the underlying variance (covariance) structure of a large set of variables through a few linear combinations of these variables. The first principal component – PC1, is the direction through the data set that explains the most variability in the data (Fig. 5). The second and subsequent – PC2, must be orthogonal to PC1 and describes the maximum amount of the remaining variability. The use of a few principal components results in some loss of information, but at the same time, it re-arranges groups of data and reveals internal relationships between them. The final number of the principal components can be established by using the Kaiser criterion, or the scree test (Kaiser, 1960). According to this criterion, principal components with eigenvalues greater than 1 can be used (Fig. 6). The scree test is a graphical method that relies on finding a characteristic point on the plot of decreasing eigenvalues. To the right of this point, the eigenvalues rapidly increase, and to the left – a scree is observed (Fig. 6). The results of principal component analysis are commonly used as inputs to regression and cluster analyses. Principal Components Analysis of various logging data types generates a new log that correlates with the shale content, porosity and saturation contents, among others (Szabó, 2011).

The purpose of cluster analysis is to assemble observations into relatively homogeneous groups (clusters). The members of clusters are at once alike and at the same time unlike members of groups. There is no analytical solution to this problem, which is common to all areas of classification. For the discussed data sets, cluster analysis was performed by Ward's method (Ward, 1963) using a variance approach to evaluate distances between clusters. Results of the hierarchical clustering method were confirmed by using the nonhierarchical K-means methods (MacQueen, 1967). K-mean clustering aims to partition observations into clusters, in which each observation belongs to the cluster with the nearest centroids. When the objects are assigned, the positions of centroids are recalculated. The procedure is repeated until the centroids no longer move. Cluster analysis was applied to the calculated principal components and well logs.

RESULTS

BASIC STATISTICS AND CLAY TYPING

Logs were sampled in depth at 0.1 m spacing, thus, the obtained populations are sufficiently numerous for the statistical analysis. Despite a strong internal differentiation and the gas saturation in the Cierpisz-2 borehole, the variability coeffi-

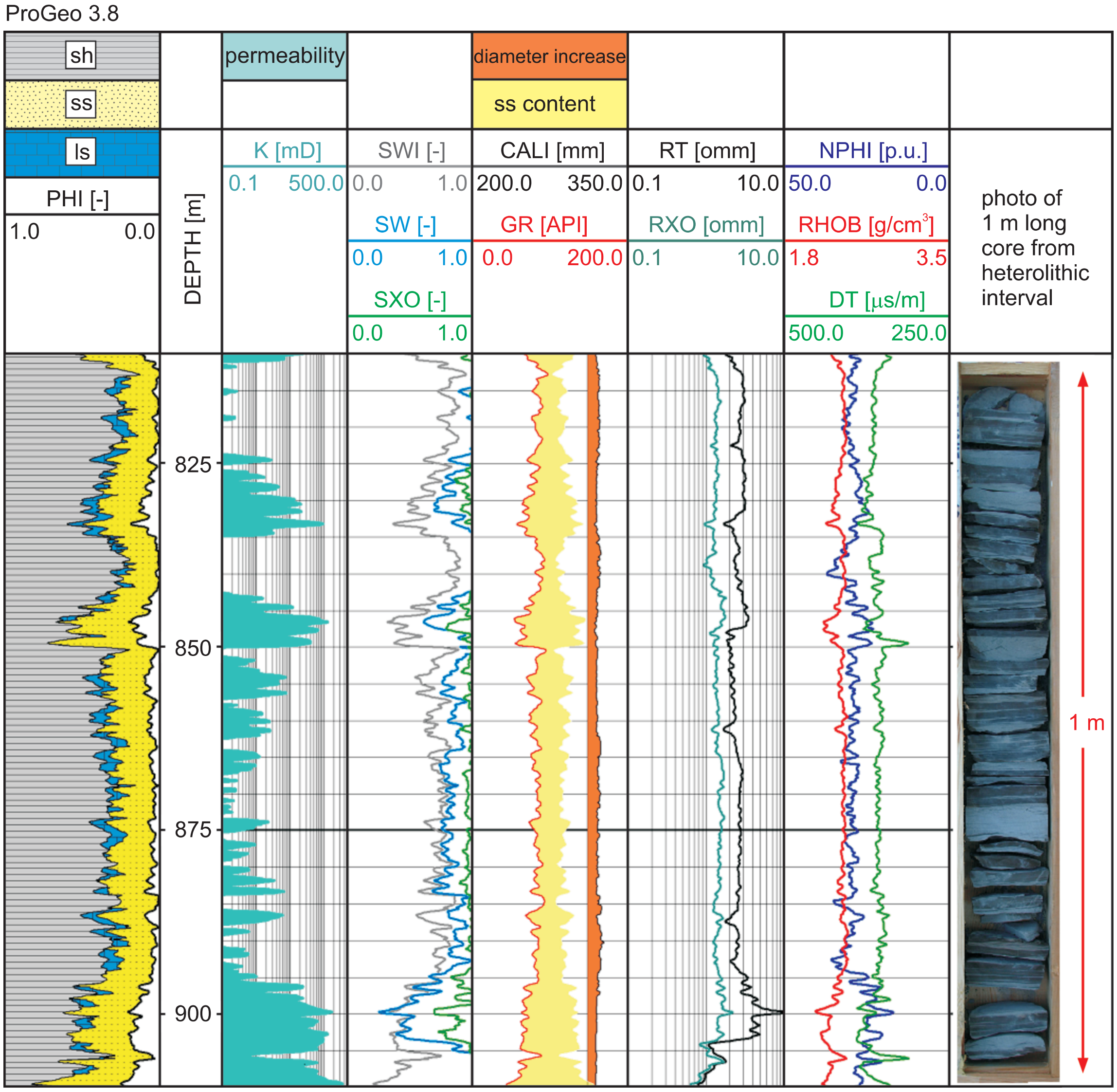

Fig. 3. Results of the measurements and comprehensive interpretation of logs in the Cierpisz-2 borehole

The depth interval from 810 to 910 m consists only of heterolithic facies with confirmed gas saturation; the photograph shows 1 m long core from heterolithic interval; for other explanations see text

cients, means and standard deviations display similar values in both boreholes. The histograms for selected variables (Fig. 7) show similar shapes, which approach normal distribution for the majority of variables. The highest differences were observed for the potassium and thorium contents. In the Cierpisz-2 borehole, the highest potassium (average 2.8%) and the lowest thorium (average 6.1 ppm) contents were measured. In the Mrowla-1 borehole, an opposite situation takes place: i.e., the lowest potassium (average 2.1%) and high thorium (average 8 ppm) contents. In both boreholes, the same type of drilling mud was used and the influence of potassium contained in mud was similar in both boreholes. Based on these results, only the TPRA logs completely separate data from the analysed boreholes (Fig. 7D).

Variations of the relative amounts of potassium and thorium are associated with clay minerals. Different potassium and thorium contents in the Cierpisz-2 and Mrowla-1 boreholes can be caused by different clay types present in deposits. The thorium vs. potassium cross-plot is one of the methods of visual identification of clay minerals (Schlumberger Log interpretation charts, 1985). Based on potassium and thorium logs, the cross-plots were constructed in both boreholes (Fig. 8). Gamma ray log, GRC, was used as a reference log. According to these plots, in the Cierpisz-2 borehole, potassium is contained in illite and micas (Fig. 8A), whereas in the Mrowla-1 borehole, the clay minerals are montmorillonite, mixed minerals and illite (Fig. 8B). In both boreholes, there is no correlation with depth. We can observe (Fig. 8) alternate layers with high contents of different clay types.

PRINCIPAL COMPONENT ANALYSIS

The use of multivariate statistical analysis was effective in both data re-arrangement and the reduction of the number of logs. Well log data were treated as random variables. In order to

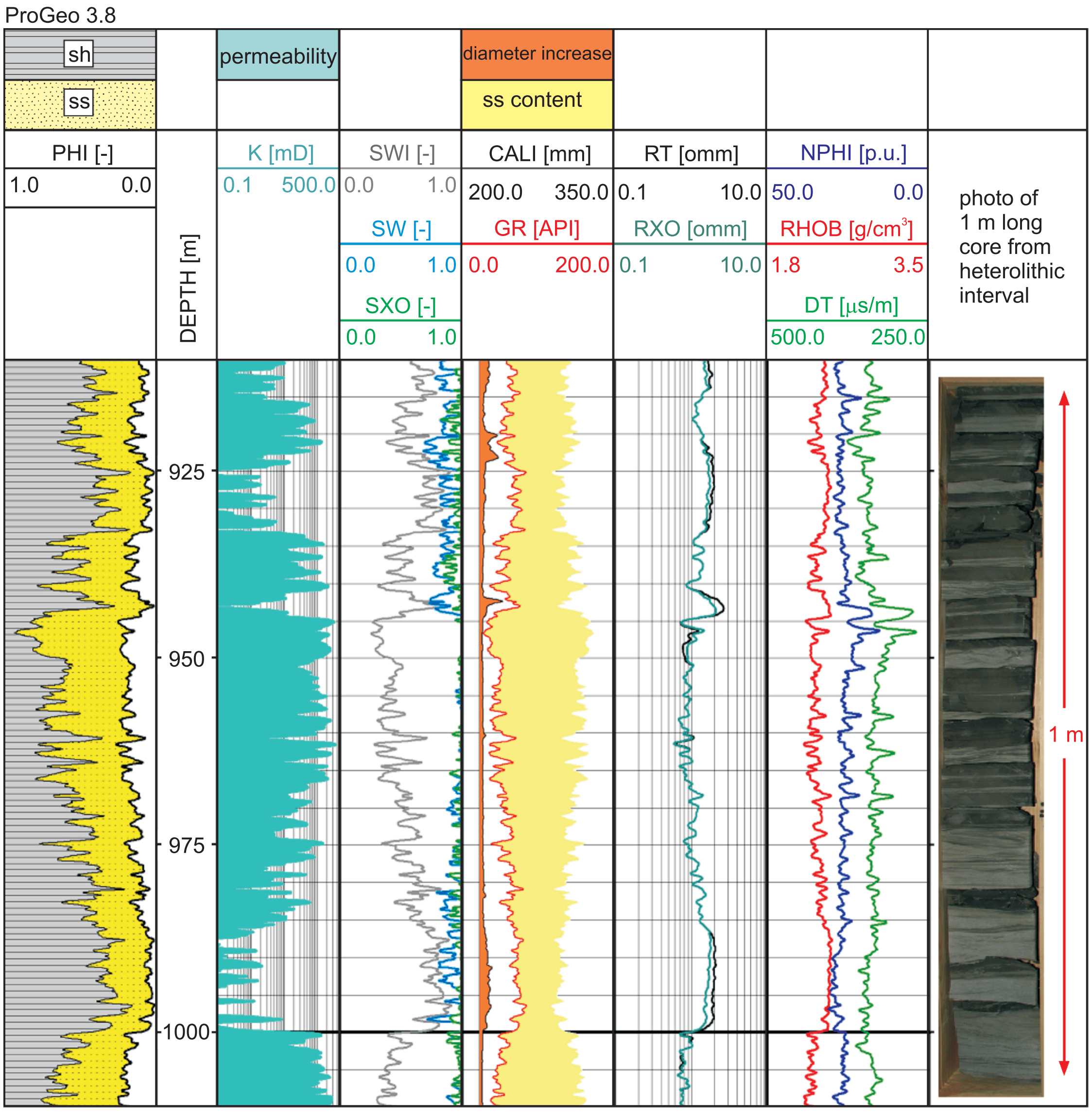

Fig. 4. Results of the measurements and comprehensive interpretation of logs in the Mrowla-1 borehole

The presented depth interval from 910 to 1010 m comprises only heterolithic facies, showing no significant gas saturation, the depth range corresponds to that from the Cierpisz-2 borehole (Fig. 2); photograph depicts 1 m long core from heterolithic interval; for other explanations see text

make the results of well logging of different petrophysical parameters comparable, the log data were standardized before carrying out the PCA. Table 1 shows eigenvalues for the calculated PCs and information on the data variability, which they explain. In both boreholes, the first four components have eigenvalues 1 (Table 1) and, in accordance with Kaiser's criterion, they were subjected to further analysis. The results of scree test also prove this observation (Fig. 6). The calculated PC correlation coefficients, based on 11 initial logs, are given in Table 2.

In the Cierpisz-2 borehole, four principal components were determined and these explain about 85% of the data variability (Table 1). Correlation coefficient values, calculated based on correlation between principal components and standardized logs, are shown in Table 2. The first principal component – PC1, contains information about petrophysical properties of rock, like porosity and lithology. This is indicated by high correlation with NPHI and RHOB – two “porosity logs”, and high correlation with PE – photoelectric absorption index log, related to mineral/element composition. PC1 carries also information about the shale volume and the type of clay minerals (GRC, POTA, THOR). The PC1 dependence on PE, GRC, THOR and POTA reflects a substantial influence on lithological composition of heteroliths and their overall shaliness in both boreholes. The high correlation coefficient for GRC in both boreholes indicates that shaliness plays indeed an important role, but the different coefficients for POTA point to differences in clay mineral composition. The second principal component – PC2, provides information about the presence of moveable hydrocarbons. This is indicated by the high values of correlation coefficient between PC2 and RT and RXO. The odd values of correlation coefficients for PC2 and RT and RXO in the Cierpisz-2 borehole, in contrast to positive values of correlation coefficients for PC1 and RT and RXO, reflect a difference in the saturation, which is

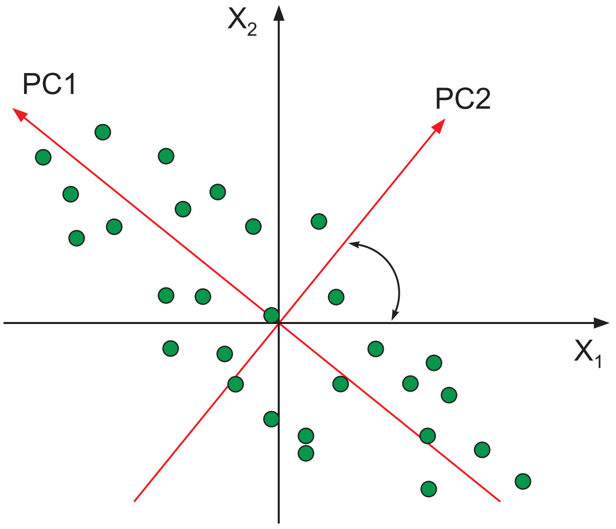

Fig. 5. New variable, first and second principal components PC1 and PC2

PC1 is the direction of the greatest variability of old variables X_1 and X_2

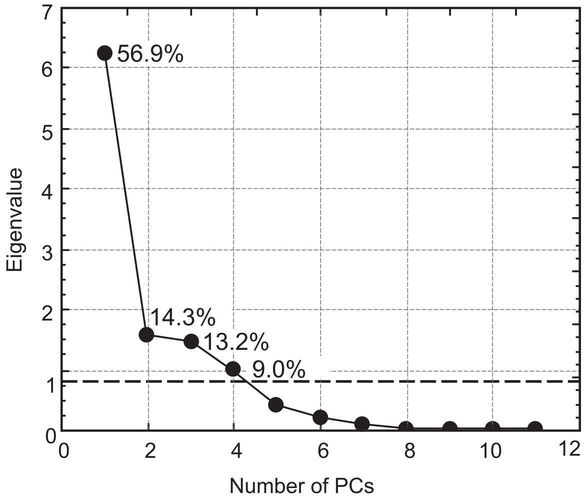

Fig. 6. Scree test for the selected interval in the Mrowla-1 borehole, for the first four PCs, percentages of total variance are given

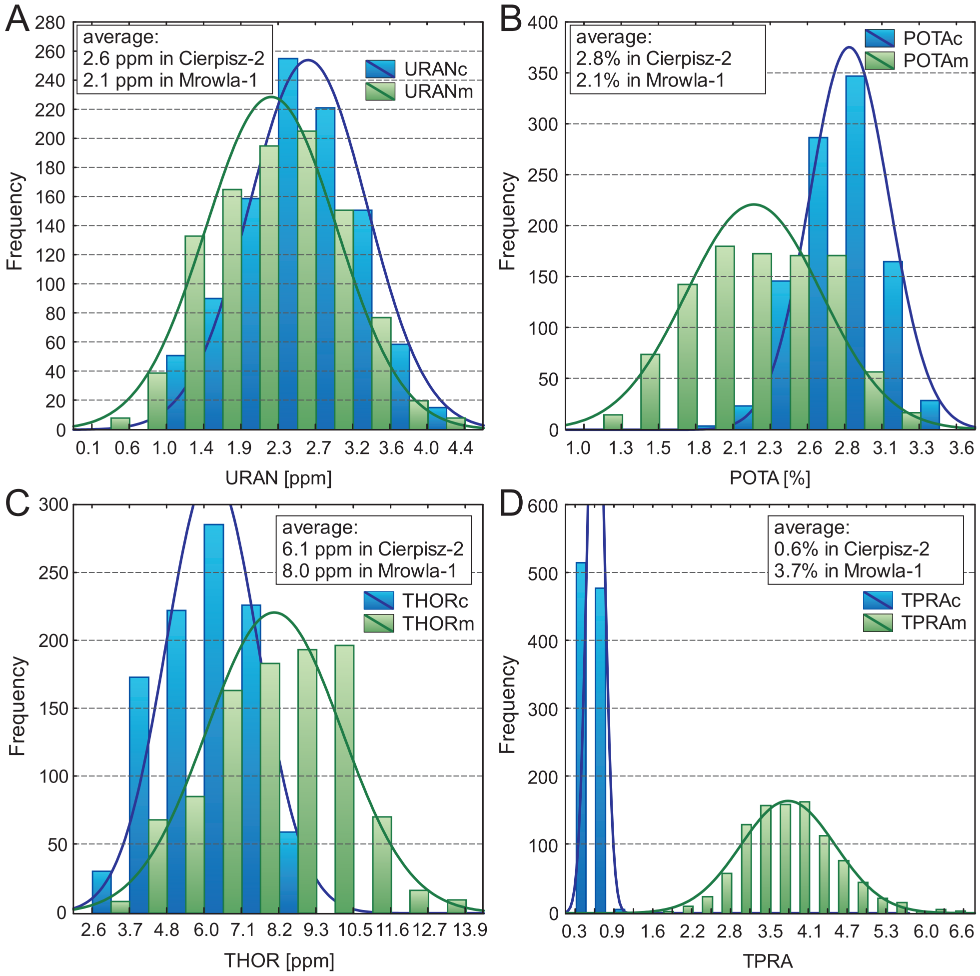

Fig. 7. Distribution of the uranium (A), potassium (B) and thorium contents (C), and the thorium/potassium ratio (D) in the studied boreholes

Data from Cierpisz-2 and Mrowla-1 are shown in blue and green, respectively gas in the Cierpisz-2 borehole, and water in the Mrowla-1 borehole. The third principal component – PC3, contains information about organic matter concentration as indicated by a high correlation with URAN. The highest correlation of PC4 is with the DT, which corresponds to porosity and velocity.

Four principal components were determined in the Mrowla-1 borehole, and it explains over 93% of the data variability (Table 1). In this borehole, any high gas saturation has not been proven. In PC1, the highest correlation coefficient was observed for GRC, POTA, THOR, RHOB, PE, RT and RXO logs. These logs provide information on porosity, bulk density and shale content. Information from RT and RXO was not separated as in the Cierpisz-2 borehole, but was added to PC1 in this case. In the absence of hydrocarbons, these logs reflect either increased sand content in the heterolithic rock, or increased permeability of sandstone layers. PC2, in turn, provides hints about porosity and acoustic velocity. The third and fourth PCs give clues to organic matter content and clay admix-

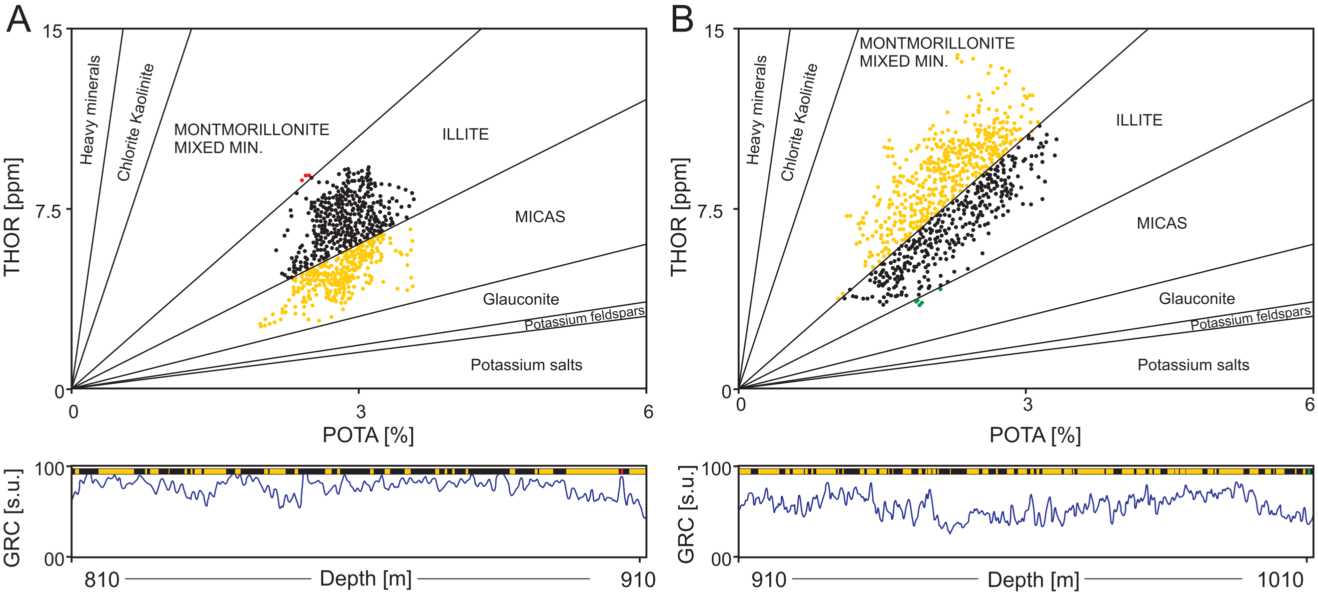

Fig. 8. Cross-plots of thorium/potassium in the Cierpisz-2 borehole (A) and Mrowla-1 borehole (B)

Table 1

Eigenvalues of principal components (marked in blue first four PCs chosen for further analysis)

No. of PC	Cierpisz-2 (depth interval 810–910 m)				Mrowla-1 (depth interval 910–1010 m)			
	Eigenvalue	Total variance [%]	Cumulative eigenvalue	Cumulative variance [%]	Eigenvalue	Total variance [%]	Cumulative eigenvalue	Cumulative variance [%]
1	4.5	41.2	4.5	41.2	6.3	56.9	6.3	56.9
2	1.9	16.8	6.4	58.0	1.6	14.3	7.8	71.2
3	1.8	16.5	8.2	74.5	1.5	13.2	9.3	84.4
4	1.1	10.1	9.3	84.6	1.0	9.0	10.3	93.4
5	0.7	6.6	10.0	91.2	0.4	3.8	10.7	97.2
6	0.3	2.8	10.3	94.0	0.2	1.6	10.9	98.8
7	0.3	2.5	10.6	96.6	0.1	0.6	10.9	99.4
8	0.2	1.9	10.8	98.4	0.0	0.3	11.0	99.8
9	0.1	1.2	11.0	99.7	0.0	0.1	11.0	99.9
10	0.0	0.3	11.0	100.0	0.0	0.1	11.0	100.0
11	0.0	0.0	11.0	100.0	0.0	0.0	11.0	100.0

Table 2

Principal component analysis results for selected interval in the Cierpisz-2 and Mrowla-1 boreholes (marked in colours the highest correlation between logs and each PCs)

	Cierpisz-2				Mrowla-1			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
DT	–0.40	–0.16	0.13	0.69	0.34	–0.81	0.11	0.02
NPHI	0.77	0.35	–0.26	0.20	0.59	–0.69	0.15	0.01
RHOB	0.88	0.00	–0.35	–0.16	0.89	0.35	–0.13	–0.10
PE	0.82	–0.18	–0.34	–0.04	0.96	–0.02	–0.08	–0.08
RT	–0.21	–0.89	0.01	0.06	0.89	0.25	–0.23	–0.09
RX0	0.04	–0.88	–0.11	–0.31	0.87	0.30	–0.25	–0.10
GRC	0.92	–0.19	0.15	0.20	0.93	0.02	0.24	0.27
POTA	0.55	–0.23	–0.22	0.58	0.85	–0.06	–0.11	0.49
THOR	0.83	–0.07	0.49	–0.01	0.84	0.08	0.52	0.04
URAN	0.00	0.05	–0.89	–0.14	0.44	–0.35	–0.50	–0.63
TPRA	0.17	0.16	0.82	–0.49	0.18	0.17	0.83	–0.50

ture. In the water-saturated intervals of the Mrowla-1 borehole, PCA provides more uniformly spread and better fitting results than those derived from the gas saturated zones in the Cierpisz-2 borehole. In the latter borehole, relationships between the data are more complex, and PCs interpretation is neither simple nor unambiguous.

CLUSTER ANALYSIS

Cluster analysis was done based on logs data and principal components. In both boreholes, two clustering methods were applied. Results of Ward's hierarchical methods and non-hierarchical K-means methods are in general the same. Figure 9 shows the tree diagram with the cut-off level. Above the cut-offs, the quantity of clusters was determined. In the Cierpisz-2 borehole, three clusters were distinguished, and two in the Mrowla-1 borehole. The third group in Cierpisz-2 correlates with the presence of gas. In the analysis below, group SS comprises data attributable to a higher sandstone content and high water saturation, group SSG embraces those showing high sandstone content and high gas saturation, whereas group SH is a "shaly" cluster, where high clay volume was observed.

In the Cierpisz-2 borehole, clusters SS and SSG differ from cluster SH in terms of lithology (Fig. 10). The sandstone content (Fig. 10C) is greater in cluster SS and SSG (more than 30%) than in cluster SH (average 20%). In the shaly SH cluster, the clay content averages 65%. Permeability in clusters SS and SSG is similar and higher than in cluster SH (Fig. 10D). The best data separation was achieved on PCs. PC1 (connected with the lithology in PCA) differentiates cluster SH from cluster SS and cluster SSG (Fig. 10E). Data belonging to cluster SH display mainly a positive PC1 value. PC2 (connected with the saturation in PCA) differentiates the data set according to gas

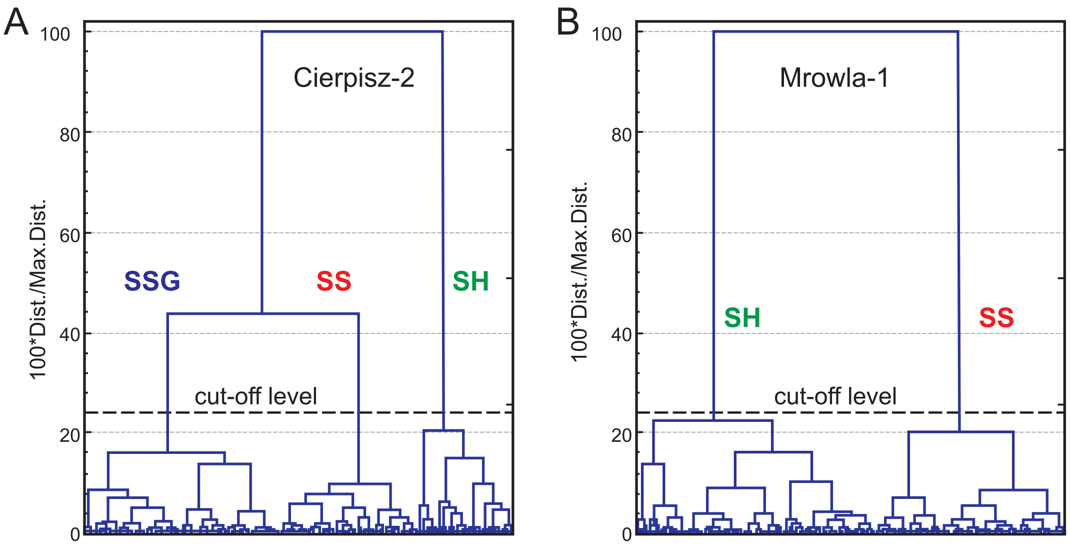

Fig. 9. Tree diagram obtained from Ward's method applied to first four PCs data in both boreholes

SS – group with higher sandstone content, SH – group with higher shale content,
SSG – sandstone group with high gas saturation

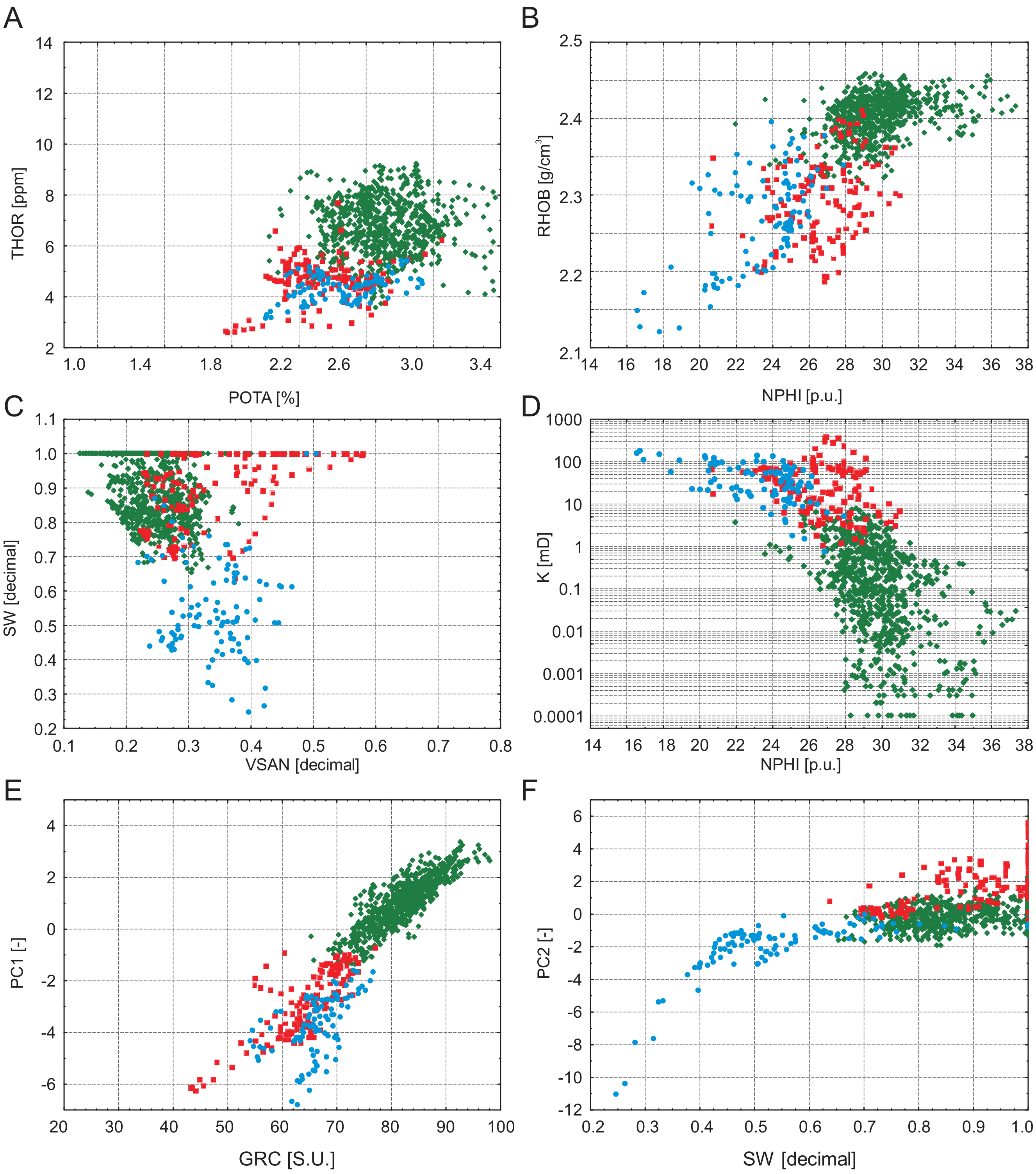

Fig. 10. Scatter plots for: A – THOR vs. POTA logs, B – RHOB vs. NPHI logs, C – SW vs. VSAN, D – K vs. NPHI log, E – PC1 vs. GRC log, F – PC2 vs. SW in the Cierpisz-2 borehole

Data from clusters SS, SSG and SH are shown in red, blue and green, respectively

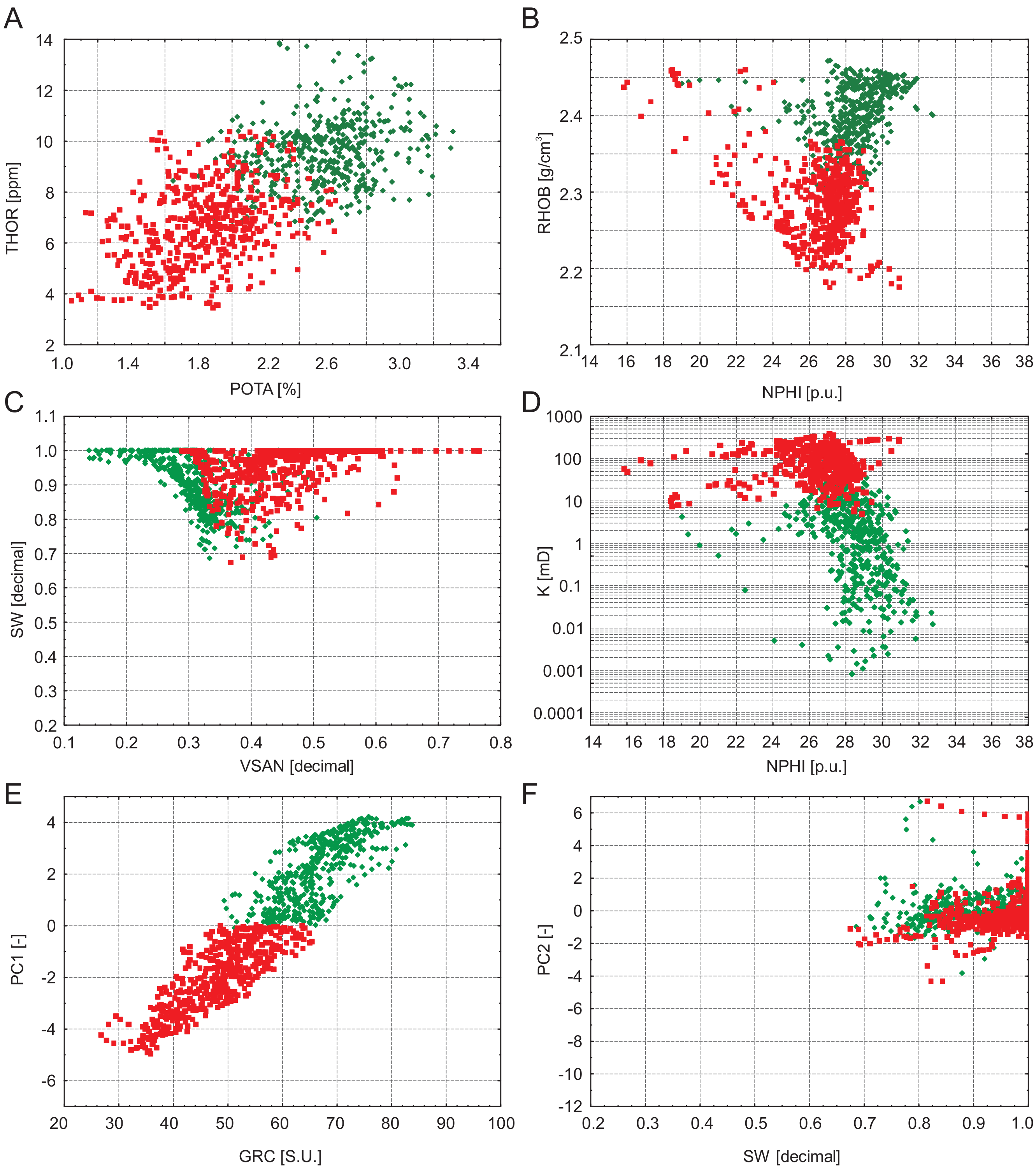

Fig. 11. Scatter plots for: A – THOR vs. POTA logs, B – RHOB vs. NPHI logs, C – SW vs. VSAN, D – K vs. NPHI log, E – PC1 vs. GRC log, F – PC2 vs. SW in the Mrowla-1 borehole

Data from SS and SH clusters are shown in red and green, respectively saturation. Figure 10F depicts the SSG cluster separation from the data set. In cluster SSG, average gas saturation is 60%, and PC2 in that group displays the smallest, negative values. Both PCA and cluster analyses separate effectively gas-bearing beds from the gas-free host.

In the Mrowla-1 borehole, only clusters SS and SH separate off the whole data set and the separation can be traced to lithological changes (Fig. 11). There is no indication of significant gas saturation (average 10%) in the analysed interval compared to the equivalent interval in the Cierpisz-2 borehole (average 60% in cluster SSG). Differences in lithology are also shown in the permeability of the formation (Fig. 11D). Group SS displays high permeability (>5 mD) compared to that in group SH (5 mD). There is no correlation between PC2 and saturation (Fig. 11F). Both PCA and cluster analyses separate effectively the lithological changes.

CONCLUSIONS

The most important role of the Principal Components Analysis lies in the reduction of data amount. In the analysed boreholes, the number of well logs was reduced to four significant PCs. PCs combine internally some properties and enable to take a new look at the reservoir formation. The calculated basic statistics, together with the PCs and cluster analysis results, have confirmed that shaliness is one of the most important parameter controlling reservoir properties in the Miocene gas-bearing sediments. Moreover, mineralogical differentiation of the shale, reflected in the different potassium and thorium contents, may have played a significant role.

The use of Principal Components Analysis provides the lowest number of variability without loss of information contained in the input logs. For the Cierpisz-2 borehole, the first two PCs confirmed the presence of gas. For the Mrowla-1 borehole, all PCs appear to reflect shaliness and lithology. There was no separate component linked to saturation. The PCA and cluster analysis for logs in the analysed interval yielded mutually consistent outcomes. The cluster analysis confirmed the results of PCA. In the Cierpisz-2 borehole, the clustering resulted in three groups, one of them reflecting the presence of gas.

It is very difficult to recognize and trace the mutual relations concerning various geological events on the basis of anomalies on well logs only. Statistical analysis offers an additional tool to petrophysicists and log analysts for improving description of complex rock formations. As exemplified here, the use of principal component and cluster analyses has turned out to be helpful for successful differentiation between thin layers of sandstones and mudstones, and between gas- and water-saturated horizons.

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