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Reservoir characterization based on the Lambda-Mu-Rho method – case study

Charakterystyka złoża oparta na metodzie Lambda-Mu-Rho – przykład analizy

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ABSTRACT: The results of analyzes based on the Lambda-Mu-Rho method, allow us to understand how the properties of a formation are related to each other, identify lithological and petrophysical variability, recognise zones of saturation with hydrocarbons, and in the next stage, to integrate these results with seismic data. Consequently, various parameters of the deposit are considered (lithological, petrophysical, geochemical, geomechanical) and their waveform response whose interrelations can be observed in different scales of observation, giving the most reliable and coherent picture of the analyzed area. The aim of the article is to present the possibility of lithological and parametric identification using the LMR method, as well as attempt to determine the sweet spot for the shale reservoir interval. Lamé parameters ($\lambda\rho$ and $\mu\rho$) analysis supports the inference regarding relations between elastic moduli and individual parameters as well as lithology and fluid discrimination. Numerous publications have confirmed the validity of applying the LMR method due to the reliability of the obtained results. In our work, several relationships between velocity of compressional (V_p) and shear (V_s) waves, density, Lambda-Rho ($\lambda\rho$), Mu-Rho ($\mu\rho$), brittleness index (*BI*) and total organic content (*TOC*) were analyzed. The anonymous analyzing area covers five formations associated with limestones and shales rocks. This article concerns the general characteristic of these formations, including two of them which accumulate hydrocarbons from the same petroleum system. A number of dependencies between the analyzed elastic parameters as well as brittleness and organic matter content were determined, as well as a threshold value for the V_p/V_s ratio, defining the hydrocarbon accumulation zones. Finally, the analysis results were applied in the 3D model, locating the hydrocarbon accumulation zones within one of the analyzed formations.

Key words: LMR method, Lamé parameters, elastic modulus, modeling, crossplot analysis.

STRESZCZENIE: Celem artykułu jest przedstawienie możliwości identyfikacji zmienności litologicznej i parametrycznej, a także próba wyznaczenia interwału złożowego z wykorzystaniem metody Lambda-Mu-Rho. Parametry Lamégo (lambda-rho $\lambda\rho$ i mu-rho $\mu\rho$) wspomagają proces wnioskowania dotyczącego ogólnej charakterystyki złoża, ich zastosowanie pozwala też na określenie zróżnicowania litologicznego oraz identyfikację akumulacji poszczególnych rodzajów płynów złożowych. Liczne publikacje potwierdzają słuszność zastosowania tej metody z uwagi na wiarygodność uzyskiwanych wyników. W artykule przeanalizowano kilka z szeregu znanych zależności pomiędzy prędkością fal podłużnych (V_p) i fal poprzecznych (V_s), parametrami Lamégo, gęstością oraz indeksem kruchości (*BI*) i zawartością materii organicznej (*TOC*). Anonimowy obszar analizy dotyczy kilku formacji litologicznych związanych ze skałami węglanowymi i łupkowymi. Niniejszy artykuł odnosi się do ogólnej charakterystyki tychże formacji na podstawie wykresów krzyżowych (crossplotów), w tym dwóch formacji gromadzących węglowodory, pochodzące z jednego systemu naftowego. Określono szereg zależności pomiędzy analizowanymi parametrami sprężystymi oraz kruchością i zawartością materii organicznej, jak również wyznaczono wartość progową dla stosunku (V_p/V_s), określającego strefy akumulacji węglowodorów. Ostatecznie wyniki analizy zaaplikowano w modelu 3D, lokalizując strefy akumulacji węglowodorów w obrębie jednej z analizowanych formacji. Wyniki analiz opartych na metodzie Lambda-Mu-Rho pozwalają zrozumieć, jak właściwości formacji są ze sobą powiązane, identyfikować zmienność litologiczną i petrofizyczną, wskazywać strefy nasyceń węglowodorami, a w kolejnym etapie umożliwiają integrację tychże wyników z danymi sejsmicznymi. W konsekwencji uwzględnione zostają różne parametry złoża (litologiczne, petrofizyczne, geochemiczne, geomechaniczne) oraz ich odpowiedź w postaci obrazu falowego, których współzależności dają się zaobserwować w odmiennych skalach obserwacji, dając możliwie wiarygodny, spójny obraz analizowanego obszaru.

Słowa kluczowe: metoda LMR, parametry Lamégo, parametry elastyczne, modelowanie, wykres krzyżowy.

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Introduction

Rock physics creates a link between geophysical measurements and geological parameters (Fig. 1). It is an important part of the reservoir characterization process which describes a rock by its physical properties that will affect the physical way seismic waves travel through the rocks which helps to avoid biased interpretations. Many researchers have analyzed different types of reservoirs using rock physics solutions (Jarvie et al., 2007; Mavko et al., 2009; Bała and Waliczek, 2012; Sayers and Bachrach, 2014).

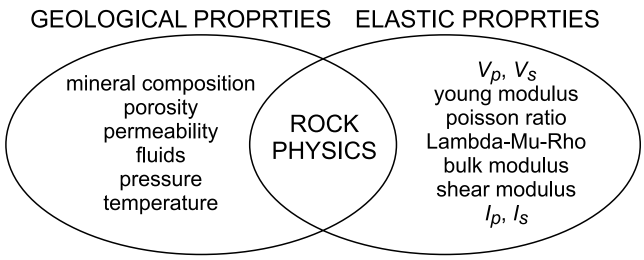


Fig. 1. Rock Physics as a quantitative link between elastic properties of the rock and the geological properties

Rys. 1. Dziedzina fizyki skał jako pomost pomiędzy analizą parametrów sprężystych a parametrami geologicznymi skał

Availability of P-wave velocity, S-wave velocity and density logs allow for the estimation of the range of elastic properties:
- Acoustic impedance;
- Shear impedance;
- V_p/V_s ratio;
- Poisson's ratio;
- Young's modulus;
- Lamé constant;
- Shear modulus;
- Lambda-Rho;
- Mu-Rho.

Calculation of these parameters in the isotropic media is uncomplicated and has been widely published in numerous papers. The challenge starts with taking into account the anisotropy of the media. Due to dependence on the direction of the force vector, values of parameters vary in particular directions.

In this article, well logs data was used to investigate the relations between different parameters on cross plots. The main idea was to use the observed relations and implement them in 3D model to present the spatial distribution of significant and reliable results. Eventually, the resulting model will guide seismic data during the process of well and seismic data integration, which will reduce the uncertainty of the obtained results (Udo et al., 2017).

The analyzed geological interval generally consists of limestone and mudstone formations (Fig. 2). The organic shale interval is one of the most prolific liquids-rich shale discoveries in this area. It is a source rock for the overlying limestone formation. It is divided into upper and lower units where the lower is characterized as the most organically rich.

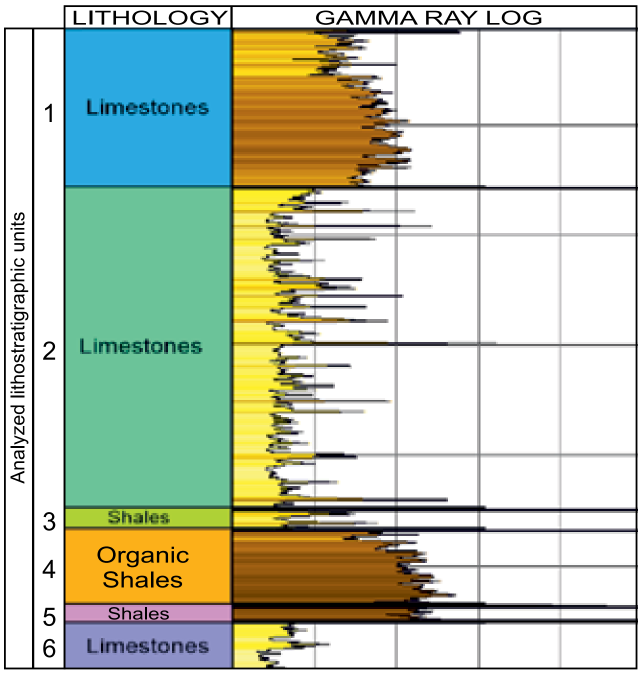


Fig. 2. Analyzed lithostratigraphic units combined with the gamma ray log

Rys. 2. Analizowane jednostki litostratygraficzne wraz z zapisem profilowania gamma

Methodology

In the analyzed case study, V_p, V_s, *GR*, density and *TOC* logs were available from four wells. Also, in one well, where mineral volumes were available, the brittleness index was calculated using two of the most popular mineralogical approaches (Jarvie et al., 2007). The goal was to prepare a set of logs which could be used in cross-plot analysis for lithology, *TOC*, *BI* and fluid discrimination.

The procedure of the analysis was as follows:
- Calculation of Lamé impedances based on V_p, V_s and density well logs;
- Calculation of the brittleness index *BI* in a single well;
- Identification of relationships between:
  - Lambda-Rho versus Mu-Rho,
  - Lambda-Rho versus V_p/V_s,

  and their relations to *TOC* values and *BI*;
- Hydrocarbon occurrence identification based on the Lambda-Mu-Rho (LMR) method;
- Sweet spots defining.

By intention, this approach should lead to results utilization at the stage of integration of well data and seismic data.

Calculation of Lamé impedances based on V_p, V_s and density well logs

Based on V_p, V_s and density logs, Lambda-Rho and Mu-Rho parameters (Lamé impedances) were estimated using the following equations (Goodway, 2001):

$$\lambda\rho = \rho(V_p^2) - 2(\rho V_s^2) \quad (1)$$

$$\mu\rho = \rho V_s^2 \quad (2)$$

where:
λ – Lamé 1st parameter – compressibility,
μ – Lamé 2nd parameter (shear moduli) – rigidity,
V_p – compressional wave velocity,
V_s – shear wave velocity,
ρ – bulk density.

Both parameters are crucial due to the sensitivity of λ to pore fluids and μ sensitivity to matrix connectivity (Goodway, 2001; Udo et al., 2017; Wilson et al., 2017) and combined together they are excellent lithological, parametrical and fluid zones discriminators.

Calculation of brittleness index *BI*

Jarvie and Wang (Jarvie et al., 2007; Wang and Gale, 2009) proposed *BI* definitions based on the mineral composition of the rock, dividing the most brittle minerals by the sum of the constituent minerals in the rock sample, considering quartz (and dolomite), in the case of Wang and Gale (2009) as the more brittle minerals:

Wang and Gale (2009):

$$BI = \frac{Q + Dol}{Q + Dol + Lim + Cl + TOC} \quad (3)$$

Jarvie et al. (2007):

$$BI = \frac{Q}{Q + C + Cl} \quad (4)$$

where:
Q – quartz,
Dol – dolomite,
Lim – limestones,
Cl – clays,
TOC – total organic carbon,
C – carbonates.

The relationship between *BI* estimates from these two approaches is presented on cross-plot showing the differences of estimation in particular lithostratigraphic units (Fig. 3).

Required data from one of the wells were collected and displayed on the well sections (Fig. 4).

Comparing the results of *BI* log calculations, the difference in the organic shale interval is easy to note. It is assumed that the presence of *TOC* reduces the brittleness of the rock, and because Jarvi's et al. (2007) equation does not take into account the content of *TOC*, which is abundantly present in the shales interval, we used the *BI* log calculated using Wang and Gale (2009) equation (3) in the further analysis.

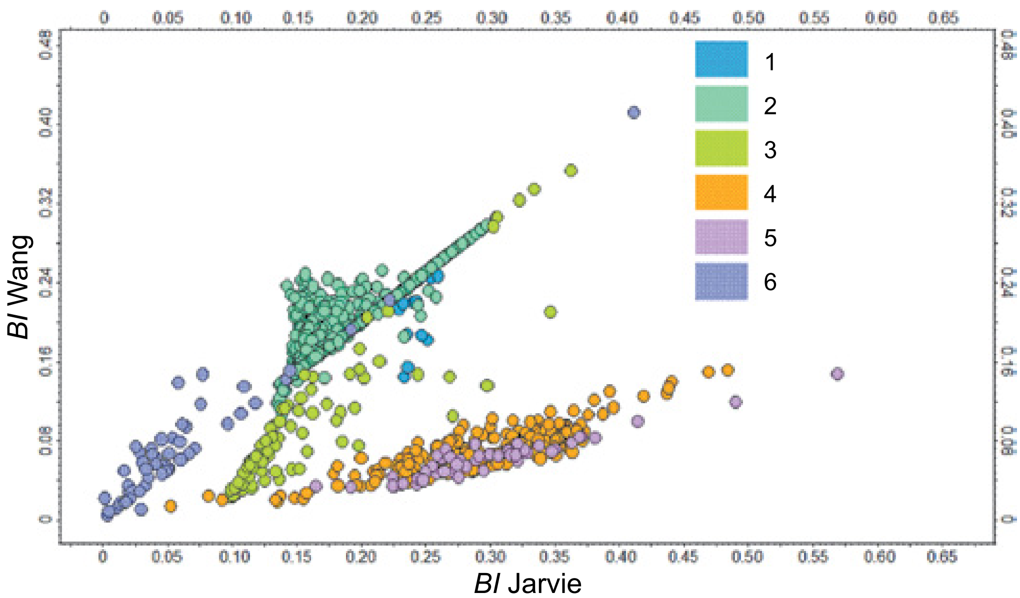


Fig. 3. Cross-plot showing the relation between the brittlenes index estimation calculated using Jarvie et al. (2007) equation (X axis) and Wang and Gale (2009) equation (Y axis); 1–6 – lithostratigraphic units (see Fig. 2)

Rys. 3. Wykres krzyżowy obrazujący relacje pomiędzy indeksem kruchości obliczonym metodą Jarviego et al. (2007) (oś X) oraz Wanga i Gale'a (2009); 1–6 – jednostki litostratygraficzne (patrz rysunek 2)

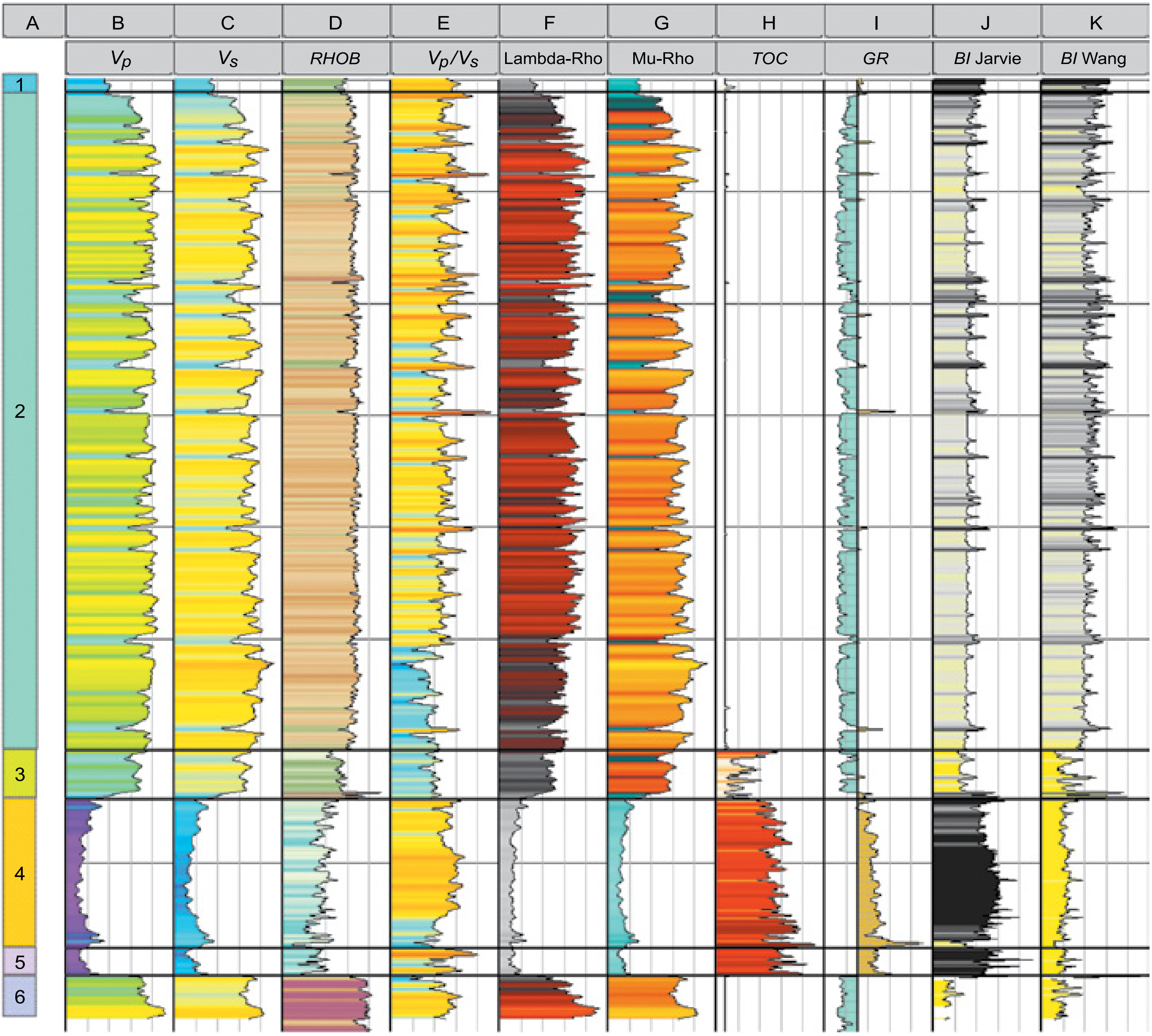


Fig. 4. Collection of well data available in one of the wells: A – Lithostratigraphic units, B – V_p, C – V_s, D – *RHOB* (density), E – V_p/V_s ratio, F – Lambda-Rho, G – Mu-Rho, H – *TOC*, I – *GR* (gamma ray), J – *BI* according to Jarvi's et al. equation, K – *BI* according to Wang and Gale equation

Rys. 4. Zestawienie danych wejściowych w profilu jednego z otworów: A – jednostki litostratygraficzne, B – V_p, C – V_s, D – *RHOB* (gęstość), E – współczynnik V_p/V_s, F – Lambda-Rho, G – Mu-Rho, H – *TOC*, I – *GR*, J – *BI* obliczone metodą Jarviego et al, K – *BI* obliczone metodą Wanga i Gale'a

Relation identification

There are well-known rock physics' rules, widely discussed in numerous publications (Goodway, 2001; Jarvie et al., 2007; Wang and Gale, 2009; Udo et al., 2017) which are taken into account during the analysis:

- λ is sensitive to fluid (values decrease in contact with hydrocarbons);
- μ is sensitive to the rock matrix;
- $\lambda\rho$ low values indicate hydrocarbons accumulations and favorable petrophysical properties of the reservoir;
- V_p/V_s ratio as well as $\lambda\rho$ versus $\mu\rho$ are remarkable lithology indicators;
- low values of V_p/V_s identify good quality hydrocarbon reservoir zones;
- $\lambda\rho$ versus $\mu\rho$ shows fluid discrimination within the reservoir interval.

We first checked, if identified lithostratigraphy zones separate on the $\lambda\rho$ versus $\mu\rho$ cross-plot according to one of the rock physics rules, in contrast to V_s versus V_s cross-plot.

Lambda-Rho versus Mu-Rho

The relation of these two parameters (Fig. 5), clearly indicate the range in which each lithology appears, especially in regards to separate organic shales from other lithology types. The V_s versus V_s crossplot, on the other hand, shows more linear relations, which testified to its insensitivity to the rock quality. In order to investigate conclusions from this relation, the *TOC* and *BI* color table were placed on the cross-plot as a third variable (Z) (Fig. 6).

In general, the lowest values of both $\lambda\rho$ and $\mu\rho$ parameters indicate the highest (>2%) *TOC* content. In the case of *BI*, the highest values of this parameter are related with limestone formation, and they are connected more with the lowest values of $\lambda\rho$. The arrows on LMR cross-plots (Fig. 6) indicate general trends of values increased for both *TOC* and *BI* parameters.

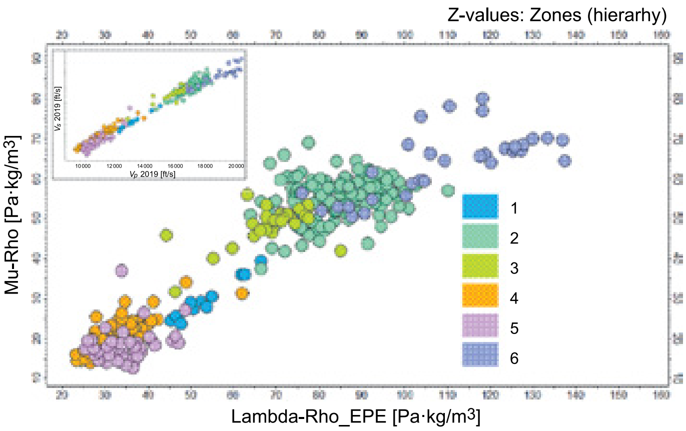


Fig. 5. $\lambda\rho$ (X axis) versus $\mu\rho$ (Y axis) cross-plot separating the lithologies within the analyzed area together with the V_p vs V_s cross-plot (left top corner); 1–6 – llithostratigraphic units (see Fig. 2)

Fig. 5. Wykres krzyżowy parametrów $\lambda\rho$ (oś X) versus $\mu\rho$ (oś Y) wydzielający interwały litologiczne w zasięgu analizowanego obszaru, wraz z wykresem krzyżowym pomiędzy V_p i V_s w lewym górnym rogu; 1–6 – jednostki litostratygraficzne (patrz rysunek 2)

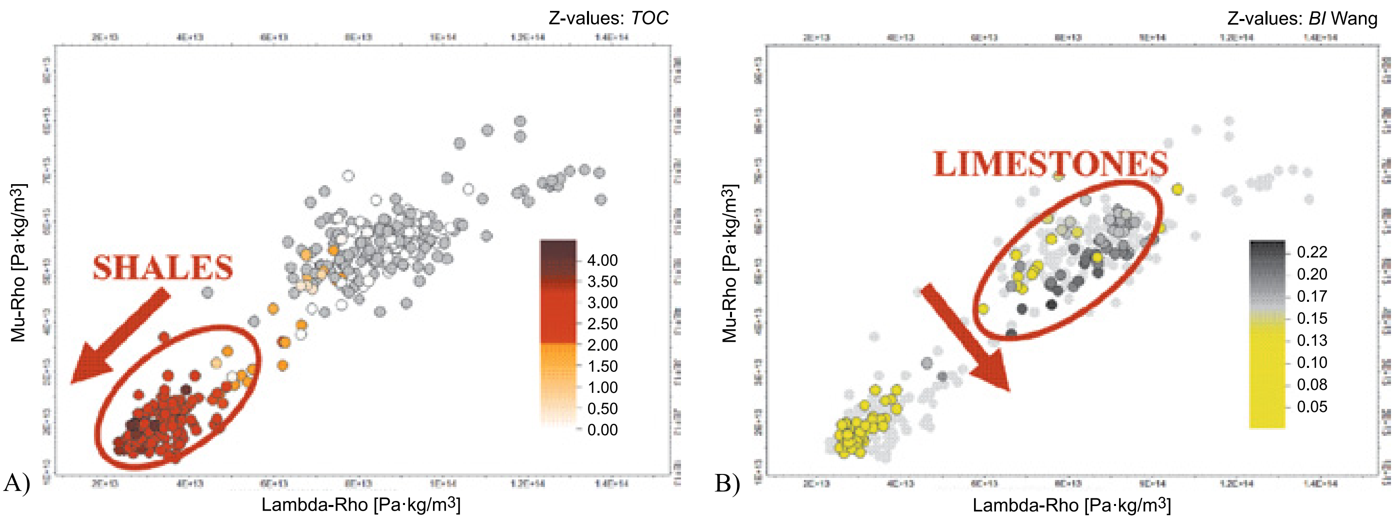


Fig. 6. $\lambda\rho$ (X axis) vs $\mu\rho$ (Y axis) crossplot and: A) vs *TOC*, B) vs *BI* (Z-axis) and general direction of values increasing (arrow) of Z-axis variable

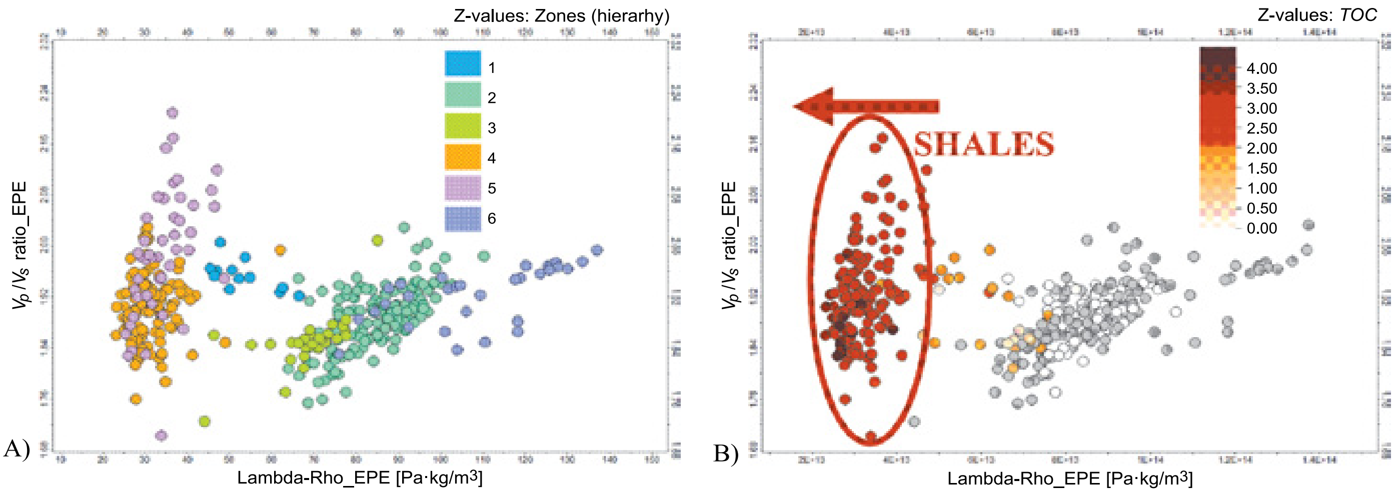
Rys. 6. Wykres krzyżowy parametrów $\lambda\rho$ (oś X) i $\mu\rho$ (oś Y) w funkcji (oś Z): A) zawartości materii organicznej *TOC* oraz B) wartości indeksu kruchości wraz z głównym kierunkiem wzrostu ich wartości

Lambda-Rho versus V_p/V_s

Another way to look at the data for the purpose of reservoir characterization in the clasterization context is to compare the V_p/V_s ratio with $\lambda\rho$. It is a reliable lithology indicator (Fig. 7A) but also it point out of the highest *TOC* content by the lowest $\lambda\rho$ values (Fig. 7B), while relatively high V_p/V_s ratio and $\lambda\rho$ values (Fig. 7C) within limestone formation indicate the highest brittleness index.

To identify hydrocarbons occurring in zones with favorable porosity and permeability properties that have not been analyzed on cross-plots due to the lack of fluid saturation interpretation logs, Lamé parameters were used on well sections.

Following Goodway (2001) $\lambda\rho$ and $\mu\rho$ logs can designate gas zones by log crossovering (when $\lambda\rho < \mu\rho$). The larger the distance between the logs, the higher the values of porosity and permeability we can expect. Due to the aforementioned facts, *AI*, *Is*, $\lambda\rho$, $\mu\rho$, as well as V_p/V_s ratio have been compiled in Figure 8.



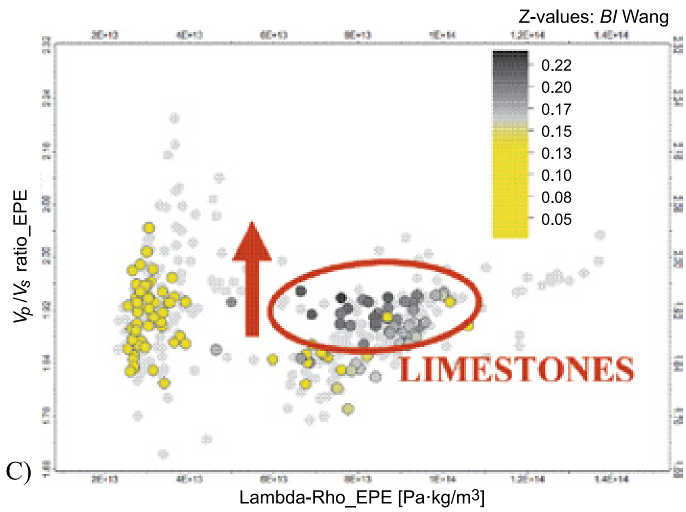


Fig. 7. *μρ* (X axis) vs V_p/V_s (Y axis) cross-plot and:
A) vs lithostratigraphy (1–6); B) vs *TOC*; C) vs *BI* and general direction of values increasing (arrow) of Z-axis variable

Rys. 7. Wykres krzyżowy współczynnika *μρ* (oś X) i V_p/V_s (oś Y) w funkcji (oś Z): A) wydzieleń litologicznych (1–6); B) *TOC*; C) indeksu kruchości wraz z kierunkiem wzrostu wartości tych parametrów

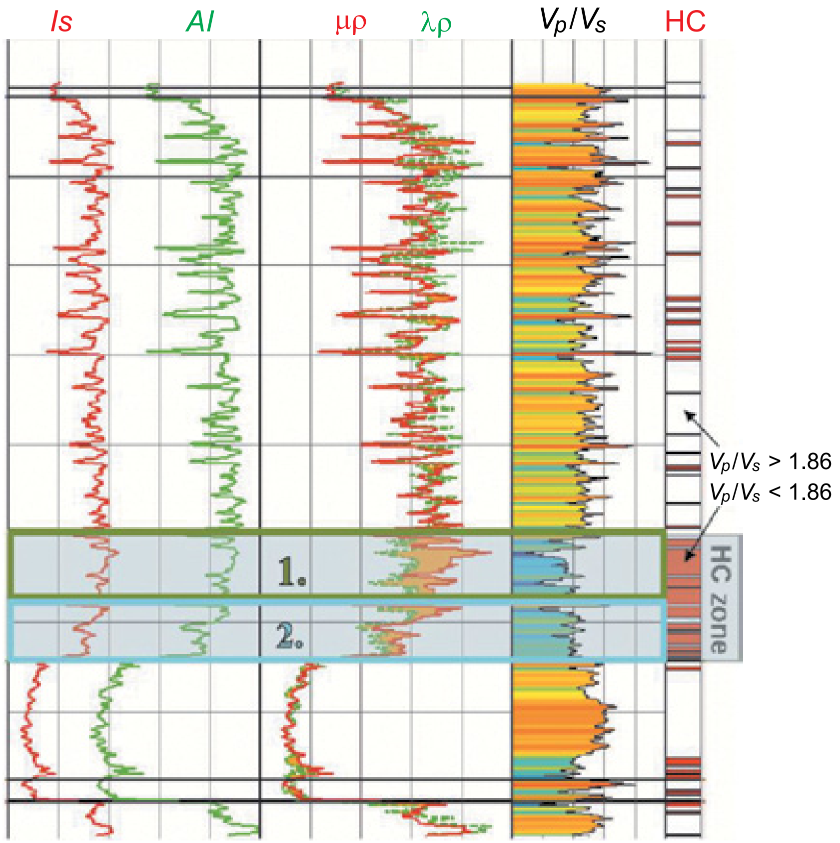


Fig. 8. Hydrocarbon zone identification based on *λρ μρ* logs crossover combined with *Is*, *AI* and V_p/V_s ratio logs: 1 – zone with more, 2 – less favorable poro-perm properties

Fig. 8. Identyfikacja stref nasycenia węglowodorami na podstawie krzywych *λρ* i *μρ* w zestawieniu z krzywymi *Is*, *AI* i współczynnikiem V_p/V_s: strefa 1 – mająca bardziej sprzyjające porowatości i przepuszczalności i strefa 2 z o nieco słabszych własnościach

The analysis of separate *Is* and *AI* does not contribute as much as $\lambda\rho$ and $\mu\rho$ put together. The crossovering curves are noticeable right above the shale formations with high *TOC* content, from where hydrocarbons have been migrated to overlying fractured limestones. Crossovering intervals are characterized by V_p/V_s ratios lower than 1.86. Based on this fact, a discrete log of potential hydrocarbon saturation has been created, which is present on the last track.

According to the already made conclusions concerning hydrocarbon accumulation and its relation to V_p and V_s and its derivatives, the V_p vs V_p vs V_p/V_s crossplot showing all significant outcomes has been created (Fig. 9). That kind of classification can be directly integrated with seismic data for the purpose of spatial discrimination of identifying sweet spots (Fig. 10).

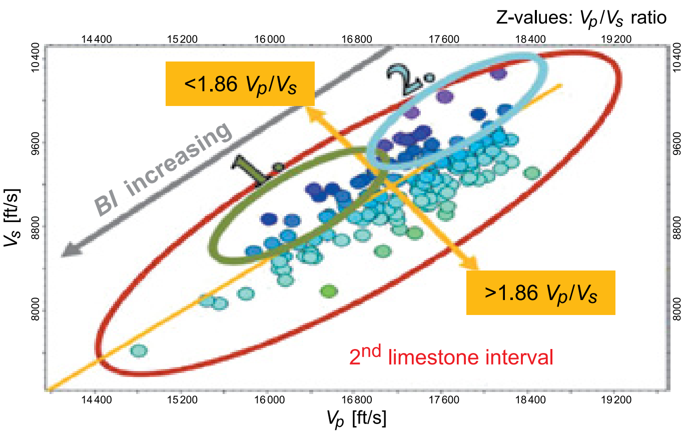


Fig. 9. Relation between V_p vs V_s vs V_p/V_s in the second limestone interval together with the boundary ranges of **1** and **2** HC zones

Rys. 9. Zależność pomiędzy V_p, V_s i współczynnikiem V_p/V_s w interwale węglanowym nr **1** i **2** wraz z wyznaczonymi strefami nasycenia węglowodorami

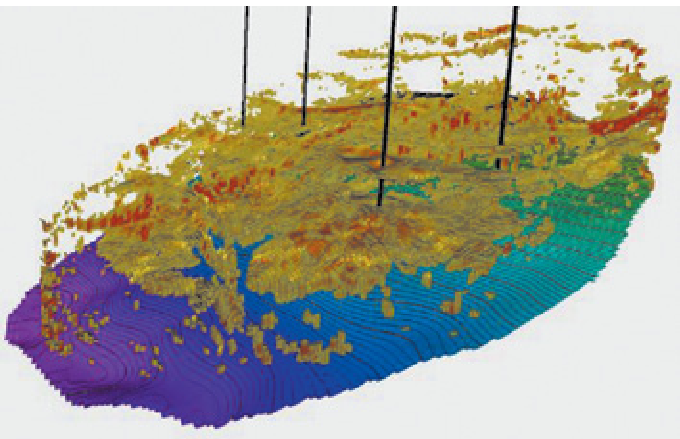


Fig. 10. V_p/V_s model with filtered cells within 2nd limestone interval (cut-off > 1.86) which meet the condition of $\lambda\rho < \mu\rho$. The warmer colors indicate higher hydrocarbon accumulation potential

Fig. 10. Model przestrzenny współczynnika V_p/V_s z wyfiltrowanymi komórkami spełniającymi warunek $V_p/V_s > 1{,}86$ oraz $\lambda\rho < \mu\rho$ wyznaczającymi strefy nasycenia węglowodorami. Im cieplejsze kolory komórek grida tym wyższe nasycenie węglowodorami

Conclusions

This paper has described how elastic properties are controlled by a wide range of different factors, including lithology, *TOC*, and *BI*.

A cross-plot analysis of the presented elastic parameters compiled with other parameters supports the process leading to an understanding of the reservoir. The analysis presented here, when supported by interpretations of particular fluid saturation, gives us better reservoir understanding and unambiguous conclusions. However, the lack of this data does not hinder defining the clusters that differentiate the favorable from unfavorable values of properties as well as hydrocarbon saturation intervals based on Lamé parameters: $\lambda\rho$, $\mu\rho$. The presented analysis has led to concrete conclusions (presented collectively in Figure 9). Based on the V_p versus V_s cross-plot together with V_p/V_s ratio and *BI* as well as the principle of $\lambda\rho < \mu\rho$ defining hydrocarbons zones, it was possible to define favorable values of properties (values within cluster 1 in Figure 9) for its implementation in spatial models leading to determining sweet spots. Nevertheless, because the scales of petrophysical, geophysics and seismic measurements are different, the challenge in further spatial analysis, will be to determine the appropriate model grid resolution, which will show the most accurate relationship between the measurements. To conclude, rock physics analysis, linking elastic with geological properties, helps to:

- understand how rock properties are related to each other;
- distinguish different types of lithologies;
- discriminate sets of similar values of particular reservoir properties;
- identify fluid substitution indicators;
- define cluster patterns at known wells which can be further implemented;
- avoid certain ambiguities in seismic interpretation;
- designate sets of relations describing a given reservoir as reliably as possible.

However, for the purpose of complex rock physics analysis connecting all data in the most reliable 3D reservoir model which shows how seismic properties and well log data are controlled by different factors, comprehensive petrophysical well logs interpretation, fluid saturation, elastic modulus calculations which take anisotropy into account is necessary.

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