Assessing Thermal Maturity Levels in Unconventional Hydrocarbon Reservoirs through Interval Inversion and Simulated Annealing.

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Summary

A new methodology has been developed to estimate the level of maturity (LOM) of reservoirs, which is critical for assessing potential organic shale gas deposits. LOM affects factors like porosity, pore size, type, and volume, and is usually determined through vitrinite reflectance laboratory analysis. The new method involves estimating LOM using interval inversion to approximate total organic carbon (TOC) values, followed by the application of a metaheuristic global optimization method called simulated annealing. The method establishes a cost function based on the mathematical expression proposed by Passey et al. (1990) which relates LOM and TOC, allowing for the approximation of LOM values without the need for core samples or vitrine reflectance measurements. Interval inversion assumes petrophysical parameters as functions of depth, while simulated annealing is a global optimization method based on the physical annealing process of metals. Passey's method uses a linear relationship between sonic travel time and true formation resistivity log curves and TOC content to estimate TOC as a function of delta log R distance and LOM.

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Introduction

Although, when assessing potential organic shale gas deposits, total organic carbon (TOC) content is a crucial indicator of hydrocarbon resources. The level of maturity (LOM) of the reservoir plays an important role on the evaluation since while high TOC concentration indicates that the source rock is viable, the organic matter must undergo a lengthy process of thermal maturation before it can be converted into hydrocarbons (Passey et al., 2010, Zee Ma, 2016).

Furthermore, LOM is a critical input for basin and petroleum system modelling because it affects several relevant factors, such as porosity, pore size, type, and volume, all of which change progressively as thermal maturity increases (Pommer, 2014; Zhang et al., 2020; Dong and Harris, 2020). Moreover, LOM can be used to predict porosity on a regional scale as a function of thermal maturity, demonstrating that it is possible to empirically correlate the level of organic matter metamorphism or maturity with changes in porosity. As a result, basin models can simulate porosity evolution because it is influenced by lithology and thermal maturity (Schmoker, 1984; Osborne and Volk, 2020).

Nevertheless, LOM is critical for the evaluation of organic shale gas deposits, the predominant method for determining it, it is still relegated to mostly vitrinite reflectance laboratory analysis. Therefore, to simplify the determination of LOM and reduce the dependence on laboratory measurements, we have developed a novel methodology presented in this study. Our approach involves estimating LOM using interval inversion to approximate TOC values, followed by the application of a metaheuristic global optimization method called simulated annealing. This method allows us to establish a cost function based on the mathematical expression proposed by Passey et al. (1990) which relates LOM and TOC. By using this method, we can approximate LOM values without the need for core samples or vitrine reflectance measurements, making our methodology simple and straightforward.

Method and Theory

Interval Inversion

The interval inversion method is a technique that combines all available data from a logging interval and inverts it at once, leading to a highly overdetermined inverse problem and a less sensitive interpretation process (Dobróka and Szabó, 2001). This method has been previously shown to improve estimation accuracy for conventional hydrocarbon deposits. Recent studies demonstrate that the interval inversion method can also accurately assess multi-mineral structures and unconventional formations, such as shaly sand sequences, carbonate and metamorphic reservoirs, and shale gas formations (Szabó and Dobróka, 2020; Szabó et al., 2022).

In this method, petrophysical parameters are assumed to be functions of depth and are represented as a series of expansion coefficients using basis functions, $m_i(z) = \sum_{q=1}^{Q_i} B_q^i \Psi_q(z)$, where B_q^i represents the q-th series of expansion coefficient, and Ψ represents the q-th basis function. The objective function is optimized for fitting the estimated data, $d_s^{(c)}(z) = g_s[z, B_1^{(1)}, \ldots, B_{Q1}^{(1)}, \ldots, B_1^{(M)}, \ldots, B_{QM}^{(M)}]^T$, to the measured data by reducing the relative data distance between them in order to approximate the expansion coefficients (B_q^i). The nonlinear inverse problem is reduced to a series of linear problems using the Marquardt iterative procedure to compute the vector of model correction $B = \left(\bar{\bar{G}}^T \bar{\bar{G}} + \epsilon^2 \bar{\bar{I}}\right)^{-1} \bar{\bar{G}}^T \, \delta \vec{d}^m$, where $\bar{\bar{G}}$ is a linear operator, called Jacobian matrix, I is the identity matrix, and ϵ is a properly chosen small positive constant to numerically stabilize the inversion procedure. Finally, the depth variation of petrophysical characteristics can be deduced by assuming that the previously estimated expansion coefficients are a solution when there is no significant change in the fit between the measured and computed data.

Simulated Annealing

The simulated annealing (SA) method is a global optimization method based on the physical annealing process of metals. It generates two solutions and evaluates them using an objective function, accepting improving solutions and sometimes allowing inferior solutions to escape local optima. A Metropolis scheme of SA was used in this study. The energy function or cost function of the model is calculated and compared at each iteration step. The new model's acceptance probability is determined by the Metropolis criteria, and the cooling schedule affects the pace of convergence (Metropolis, et al., 1953).

Passey's method and LOM

Passey et al. (1990) proposed that a linear relationship exists between the distance separation of the sonic travel time and true formation resistivity log curves and TOC content, particularly evident in organic-rich intervals. They suggested a mathematical expression to estimate TOC as a function of delta log R distance (ΔlogR) and LOM, $\mathrm{TOC} = (\Delta \log R) \times 10^{(2.297-0.1688 \times LOM)}$. The ΔlogR distance is measured as follows, $\Delta logR = \log_{10}(R/R_{baseline}) + 0.02 \cdot (\Delta \mathrm{t} - \Delta \mathrm{t}_{\mathrm{baseline}})$, where $R_{baseline}$ is the resistivity corresponding to the $\Delta \mathrm{t}_{\mathrm{baseline}}$ value when the curves are baselined in a fine-grained non-source, clay-rich rocks.

LOM estimation based on Interval Inversion and Simulated Annealing

The LOM can be approximated using the TOC-Δlog$R$ diagram proposed by Passey et al. (1990) by fitting a best-fitting straight line to the data. However, this technique requires a fair amount of TOC values from geochemistry data to calibrate the linear model. As geochemistry data is scarce and expensive, the proposed methodology combines interval inversion and the global optimization method of S.A. to estimate the volume of kerogen (V_k) from which TOC content can be derived, $TOC = \frac{\rho_k}{k\rho_b} V_k$, where ρ_k is kerogen density $(\frac{g}{cm^3})$, k is a constant, varying from 1.18 to 1.48, and ρ_b is the density log (Herron and Letendre, 1990). The predicted TOC data is then used to minimize the following energy function, $\mathrm{E} = \left(\frac{1}{\mathrm{NS}} \sum_{i=1}^{NS} \left(TOC_i^{(m)} - TOC_i^{(c)}\right)^2\right)^{\frac{1}{2}}$, to calculate the LOM, implied in Passey equation.

Case study 1

The dataset analysed is from a well drilled in the Norwegian Continental Shelf in the North Sea, which is a productive hydrocarbon province. The Upper Jurassic marine shales are the most important source rocks in this province.

The inversion procedure used four borehole logs (Gamma Ray, Density, Neutron Porosity, and Deep Resistivity) as inputs and divided the well into four layers based on gamma ray intensity changes. The procedure involved 20 iterations over the four layers, with an initial model set at 0.5 water saturation, 0.1 porosity, clay, quartz, and carbonate content, and 0.01 kerogen and pyrite content. Seven model parameters were considered in the inversion procedure. The average data distance at the last iteration for was 1.13 %. The estimated data is considered good based on Figure 1.

Valadez Vergara (2020) calculated the ΔlogR distance (Figure 1), establishing the baseline interval at approximately 480 m depth using resistivity and sonic logs with baseline values of 1.9928 ohm-m and 81.0727 µsec/ft, respectively. The TOC content was then determined using the V_k obtained from the inversion procedure, considering $\rho_k = 1.0$ $(\frac{g}{cm^3})$, $k = 1.2$, and ρ_b from the density log. Figure 2 shows that the TOC log obtained from the inversion procedure is consistent with previous estimations. The root mean squared deviation of the TOC inversion is 0.91, while the result from Passey method yielded a value of 1.36 (Valadez Vergara, 2020).

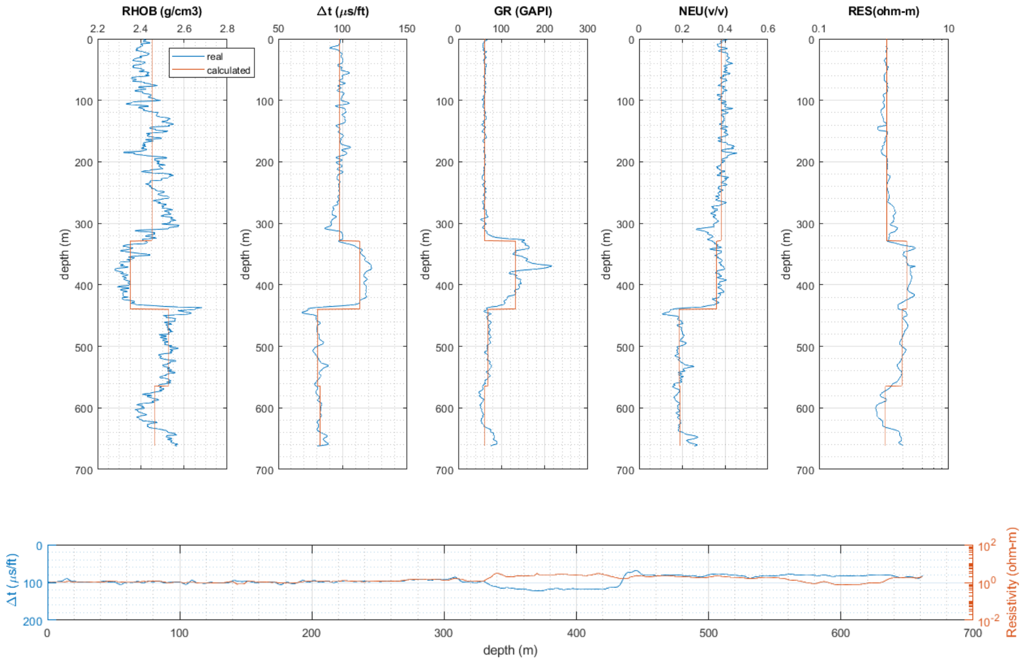

***Figure 1** Upper picture: In blue the measured boreholes are displayed, in red the estimated by interval inversion. Bottom picture: the overlay sonic and resistivity log, the separation of the curve indicates the source rock zone (Modified from Valadez Vergara, 2020).*

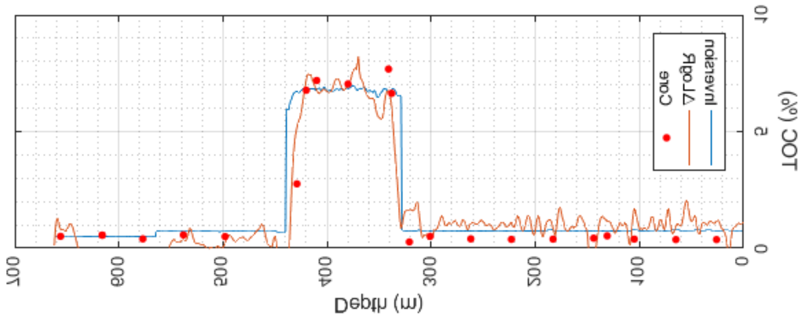

***Figure 2** Total organic carbon content logs. In blue, the inverted TOC log. In red, the TOC obtain by Passey method by Valadez Vergara (2020). And the red dots indicate the core TOC values.*

Conclusions

This study proposes a new method for evaluating the level of maturity and assessing the potential of unconventional hydrocarbon reservoirs. The method utilizes the interval inversion tool and the global optimization method of simulated annealing to estimate the LOM without the need for laboratory measurements from core samples. Also, the study shows that the interval inversion technique accurately estimates various petrophysical variables including TOC, fractional volumes of pore spaces, water, hydrocarbon, and mineral composition of unconventional formations, since the estimated results correlate well with existing literature on the area (Worden H., et al., 2020, Storebø, 2021). The results from the SA procedure confirm the correlation with the Vitrinite reflectance gradients for the Norwegian sectors of the Central Graben in the North Sea (Petersen et al., 2013). Therefore, the proposed method for predicting LOM provides a straightforward estimation of LOM independent of core data.

Acknowledgements

The research was carried out in the Project No. K-135323 supported by the National Research, Development, and Innovation Office (NKFIH), Hungary.

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