UNIVERSITY OF MISKOLC
Faculty of Earth and Environmental Sciences and Engineering
Institute of Exploration Geosciences

WELL LOGGING METHOD DEVELOPMENT IN UNCONVENTIONAL HYDROCARBON RESERVOIRS

Theses of Doctoral Dissertation

by

Rafael Valadez Vergara

Scientific supervisor:

Prof. Dr. Norbert Péter Szabó

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES
Head of the Doctoral School: Prof. Dr. Péter Szűcs

Miskolc, 2025

Hungary

I. SCIENTIFIC BACKGROUND AND AIMS

Unconventional reservoirs have appeared as a significant aspect of the global energy landscape, presenting extensive opportunities for resource extraction and reshaping energy markets. Notably abundant in regions such as the United States of America and Canada, these reservoirs have produced deep economic and environmental changes. With daily production of natural gas and oil reaching unprecedented levels, they have facilitated a dramatic departure from coal, leading to reduced CO2 emissions and enhanced air quality (Kohli and Zoback, 2019a; Rezaee, 2022).

The unconventional oil and gas sector constitutes a fundamental element within the contemporary energy scene, marked by operational complexities and technological complexities. While North America has historically been at the vanguard of unconventional development, recent years have witnessed a growing interest in regions like China and Argentina (Kohli and Zoback, 2019a). The global potential for unconventional reservoirs extends far beyond current production hubs, with numerous countries poised to explore and exploit these resources to satisfy their energy needs.

The exploration and extraction of oil and gas resources demand a refinement comprehension of the geological complexities inherent within formations and basins. A fundamental aspect of this understanding lies in recognizing the layering within formations. Unlike traditional reservoirs, unconventional reservoirs possess distinct characteristics such as high organic content, low permeability, and intricate layering, which present both challenges and opportunities for extraction (Peters et al., 2016; Zee Ma, 2016; Kohli and Zoback, 2019a).

Organic-rich source rocks take a key function in the generation and accumulation of hydrocarbons within sedimentary basins. These source rocks are distributed all over the world (Dong et al., 2016), historically serving as migration pathways for hydrocarbons into conventional reservoirs. However, recent advancements in exploration and extraction techniques have shown the potential for directly targeting these source rocks for unconventional hydrocarbon development.

One prominent example highlighted is the Barnett Formation, located in the Fort Worth Basin (USA), which serves as a paradigmatic case of an organic-rich source rock. Within this formation, the organic material has undergone maturation, predominantly yielding gas. Despite its traditionally observed role as a source rock rather than a reservoir rock, improvements in extraction techniques, particularly hydraulic fracturing, have enabled economic production from such formations. Conversely, the Bakken Formation exemplifies a different aspect of unconventional resources, representing low-permeability reservoirs where extraction primarily relies on stimulating production through hydraulic fracturing. Additionally, there are layered plays characterized by fracking across various strata, encompassing both organic-rich and conventional reservoirs with low permeability (Peters et al., 2016; Kohli and Zoback, 2019a).

Furthermore, the compositional variability of rocks within formations adds another level of complexity to reservoir characterization. From carbonate-rich to clay-rich compositions, the diverse nature of rock compositions within a single well requires adaptable extraction strategies adapted to the specific geological context (Zee Ma, 2016). For instance, variations in mineralogical composition and maturity across different zones within a formation requires precise well placement and targeting. Thus, identifying zones with optimal mineralogical characteristics and maturity levels is crucial for maximizing resource recovery while minimizing operational costs and environmental impact.

Correlating maturation indicators with hydrocarbon production provides valuable insights for exploration and development activities. In regions such as the Fort Worth Basin, the alignment between indicators like vitrinite reflectance and actual gas production validates the reliability of these metrics in predicting hydrocarbon potential (Kohli and Zoback, 2019b). For this, various indicators, such as vitrinite reflectance, serve as proxy for assessing the maturity level of source rocks, where higher vitrinite reflectance values correspond to increased maturity, with specific thresholds indicating transitions in hydrocarbon composition—from oil to gas, and ultimately to inert carbon. Additionally, the type of gas produced, whether thermogenic or biogenic, is influenced by depth and temperature regime.

Geological layering holds particular significance in petroleum engineering, especially concerning hydraulic fracturing operations (Kohli and Zoback, 2019b). Geological formations like the Eagle Ford and Barnett exhibit distinct layering patterns that profoundly influence rock composition and properties. Variations in Total Organic Carbon (TOC) content within these layers significantly impact the efficacy of hydraulic fracturing activities. Zones characterized by elevated TOC levels introduce complexities in terms of rock porosity, permeability, and mechanical properties (elastic moduli), posing both challenges and opportunities for hydraulic fracturing operations (Zee Ma, 2016; Kohli and Zoback, 2019b).

Hence, in drilling operations, understanding the mineralogical content and maturity of formations is indispensable for optimizing extraction strategies. Also, a comprehensive modeling approach is imperative to reveal stress variations, TOC fluctuations, and their impact on fracture behavior. Integrating geological, geomechanical, and engineering knowledge is essential for developing fracturing strategies designed to the specific characteristics of layered formations (Kohli and Zoback, 2019b).

Therefore, in my doctoral thesis, the primary objectives revolved around enhancing our understanding of reservoir properties and applying advanced petrophysical techniques to address challenges in petroleum geology, with a specific focus on TOC estimation, factor analysis of wireline logs, interval inversion methodology, and thermal maturity assessment in unconventional hydrocarbon reservoirs.

Moreover, this research delved into the complexities of deep and multi-mineral formations, where the number of applied logging tools is often limited, and more unknowns are explored. These intricate geological settings introduce additional noise and uncertainties into the inversion procedures, necessitating robust and adaptive formation evaluation techniques. Hence, this study addressed these challenges, enabling more reliable and precise characterization of reservoir properties, even in the face of limited data and increased geological complexities.

II. ACCOMPLISHED INVESTIGATION

This doctoral work focused on the quantitative analysis of reservoir properties and the application of advanced petrophysical techniques to address challenges in petroleum geology, particularly emphasizing Total Organic Carbon (TOC) estimation, factor analysis interpretation of wireline logs, interval inversion methodologies, and the assessment of thermal maturity in unconventional hydrocarbon reservoirs. By meticulously addressing the ideas outlined in each thesis, this research has not only achieved significant goals but has also paved the way for future advancements in hydrocarbon exploration and reservoir characterization.

The theories presented in Thesis I were diligently analyzed, leading to the development of a comprehensive understanding of simulated annealing as an optimization method for enhancing TOC estimation accuracy. Through comparative analyses with traditional linear estimation techniques, the efficacy of simulated annealing in improving precision and reducing computational requirements was demonstrated. Practical recommendations for researchers and industry professionals were provided, guiding the selection and application of linear estimation methods for TOC prediction in geological studies. The integration of simulated annealing represents a significant step forward in TOC estimation accuracy and reliability, promising enhanced decision-making capabilities in hydrocarbon exploration efforts.

Thesis II addressed the complex task of interpreting wireline logs and estimating organic matter content in unconventional reservoirs through factor analysis. By carefully addressing each point, a novel statistical method and algorithm were developed, demonstrating its effectiveness across diverse geological contexts. The feasibility and reliability of this method were highlighted through comprehensive analyses and validations, laying a solid foundation for its practical application in reservoir characterization problems. The insights gained from Thesis II not only enhance our understanding of unconventional reservoirs but also offer practical solutions for industry professionals seeking to optimize reservoir evaluation processes.

Our research in Thesis III has significantly advanced the field of well logging data inversion for unconventional hydrocarbon reservoirs by exploring into the critical aspect of analysis. This contributes to enhancing the accuracy and reliability of reservoir characterization, supporting informed decision-making in hydrocarbon exploration and production activities. Through synthetic case studies and field tests, we have validated the effectiveness and adaptability of this approach across diverse geological settings. Moving forward, our work sets the stage for further research in refining computational algorithms and extending the applicability of interval inversion to more complex geological scenarios.

The exploration of thermal maturity estimation presented in Thesis IV offers valuable insights into the assessment of hydrocarbon reservoirs. By introducing the innovative approach of interval inversion, linked with simulated annealing-based LOM estimation, this research addresses critical challenges in reservoir evaluation. The methodology's ability to derive in situ estimates of LOM without the need for costly laboratory measurements represents a significant advancement in reservoir characterization. Moreover, the study's future directions offer promising opportunities for further research, including the extension of interval inversion techniques to the evaluation of other reservoir properties related to thermal maturity.

In the pursuit of a deeper understanding of petroleum geology, this doctoral thesis has explored various methods and techniques to estimate Total Organic Carbon (TOC) content and assess the Level of Maturity (LOM) in unconventional hydrocarbon reservoirs. Through thorough research, careful experimentation, and collaboration, significant progress has been made in improving our ability to predict and understand these vital aspects of oil and gas exploration.

III. NEW SCIENTIFIC RESULTS

Thesis 1

I compared two classical well logging methods, the clay indictor (**I_{cl}**) and Bibor-Szabó (**I_{cl}-BS**) methods and further developed the latter to improve the estimation of Total Organic Carbon (TOC) content in hydrocarbon formations.

The proposed **I_{cl}-BS-SA** method integrates Simulated Annealing into the nonlinear regression framework, a global optimum search method, to avoid the limitations of local optimization methods. To achieve optimal parameter estimation, the energy function was introduced utilizing normalized root mean squared error minimization.

This key addition led to significant advancements in parameter estimation, showcasing significant decreases in both relative data distance (91.5% improvement) and RMSE compared to its predecessors - the $\mathbf{I_{cl}}$ (86.6% improvement) and $\mathbf{I_{cl}}$**-BS** methods (60.6% improvement) - when tested in real well-log data collected from North Sea Central Graben, Norway.

Thesis 2

I proposed a new alternative methodology to the estimation of total organic content in unconventional hydrocarbon reservoirs based on the factor analysis. By extracting the statistical factors from well logging data, I corroborated that Factor 1 (F_1) correlates significantly to shale volume, and I identified Factor 2 log (F_2) as the "organic factor" linked to TOC.

Through synthetic modeling experiments and field tests, I demonstrated the feasibility of the proposed FA-TOC method. F_2 log, particularly, showed strong correlation with TOC, enabling reliable estimations of organic richness within different unconventional formations.

Furthermore, by parallelly interpreting F_1 and F_2, I successfully identified sweet spots and refined quantitative log interpretations, setting a more accurate and effective approach to assess organic content in unconventional reservoirs, providing a reliable means of in situ estimating TOC in unconventional reservoirs across diverse geological formations.

Thesis 3

I implemented a series expansion-based inversion method, traditionally used in conventional reservoirs, for evaluating complex multimineral scenarios in unconventional reservoirs. I estimated the volume of several matrix components and the kerogen volume, that is an important parameter, simultaneously in a joint inversion procedure.

The study assumed a multimineral formation, encompassing 11 mineral species alongside organic matter (kerogen) and two fluid types. Employing an interval inversion approach, I conducted calculations for several numbers of layers —up to 20—involving a substantial petrophysical parameters, reaching up to 11. This process involved accounting for different noise levels in log readings. Utilizing a layer-wise homogeneous model, the methodology enabled accurate estimation of volumetric parameters, including Total Organic Carbon (TOC), ensuring stability in the process and accuracy in the inversion results.

A field case study was conducted to give a better understanding of the inversion methodology, showing an improvement (around 20 %) in TOC estimation based on volume of kerogen inversion compared to classical linear inversion.

Thesis 4

I proposed an innovative methodology that combines Interval Inversion and Simulated Annealing techniques to estimate the Level of Maturity (LOM) of geological formations by assessing Total Organic Carbon (TOC) content. By reducing reliance on expensive geochemical data and improving accessibility, my methodology offers a robust and reliable means of LOM estimation, particularly for unconventional reservoirs.

The proposed method centers on increasing the available TOC data by deriving it from kerogen volume (V_k) via Interval Inversion. This expanded data then serves as the foundation for minimizing the RMSE based objective function for LOM values from the Passey's equation, employing randomness within the search process, specifically Simulated Annealing. The feasibility of this method constitutes its primary strengths, allowing not only accurate approximations of LOM values, typically showing a deviation of less than ±1 LOM unit. Furthermore, it offers an automated solution for this zone parameter in the $\Delta \log R$ equation compared to arbitrarily selected LOM values.

For validating the well log analysis results, field tests were conducted in both Norway and Alaska, where I have demonstrated the effectiveness and applicability of this methodology across diverse geological contexts.

IV. PRACTICAL APPLICATION OF THE RESULTS

The culmination of this doctoral work captures the interdisciplinary nature of reservoir evaluation and development. By exposing the complexities of reservoir quality assessment, completion quality, and thermal maturity estimation, this research contributes to a holistic understanding of hydrocarbon reservoirs. The proposed methodologies not only streamline the prospecting phase but also offer practical implications for operational efficiency and cost reduction. Moreover, the study's future directions highlight the ongoing commitment to advancing reservoir characterization methodologies and fostering a more sustainable approach to hydrocarbon exploration.

This doctoral work focused on the quantitative analysis of reservoir properties and the application of advanced petrophysical techniques to address challenges in petroleum geology, particularly emphasizing Total Organic Carbon (TOC) estimation, factor analysis interpretation of wireline logs, interval inversion methodologies, and the assessment of thermal maturity in unconventional hydrocarbon reservoirs. By meticulously addressing the ideas outlined in each thesis, this research has not only achieved significant goals but has also paved the way for future advancements in hydrocarbon exploration and reservoir characterization.

In the pursuit of a deeper understanding of petroleum geology, this doctoral thesis has explored various methods and techniques to estimate Total Organic Carbon (TOC) content and assess the Level of Maturity (LOM) in unconventional hydrocarbon reservoirs. Through thorough research, careful experimentation, and collaboration, significant progress has been made in improving our ability to predict and understand these vital aspects of oil and gas exploration.

Finally, there exist abundant opportunities for enhancing and implementing these methodologies further. It is imperative that academia, industry, and government stakeholders collaborate closely to propel these advancements and guarantee the sustainable exploration and utilization of energy resources. By improving our ability to estimate TOC content and assess reservoir maturity, we are better equipped to make informed decisions in oil and gas exploration. As we persist in refining and deploying these techniques, we edge closer to realizing a future characterized by sustainable and efficient energy practices.

V. BIBLIOGRAPHY CITED IN THE BOOKLET

Dong, Z., Holditch, S.A., John Lee, W., 2016. Chapter 2 - World Recoverable Unconventional Gas Resources Assessment, in: Ma, Y.Z., Holditch, S.A. (Eds.), Unconventional Oil and Gas Resources Handbook. Gulf Professional Publishing, Boston, pp. 53–70. https://doi.org/10.1016/B978-0-12-802238-2.00002-X

Kohli, A.H., Zoback, M.D. (Eds.), 2019a. Composition, Fabric, Elastic Properties and Anisotropy, in: Unconventional Reservoir Geomechanics: Shale Gas, Tight Oil, and Induced Seismicity. Cambridge University Press, Cambridge, pp. 31–64. https://doi.org/10.1017/9781316091869.003

Kohli, A.H., Zoback, M.D. (Eds.), 2019b. Introduction, in: Unconventional Reservoir Geomechanics: Shale Gas, Tight Oil, and Induced Seismicity. Cambridge University Press, Cambridge, pp. 3–30. https://doi.org/10.1017/9781316091869.002

Peters, K.E., Xia, X., Pomerantz, A.E., Mullins, O.C., 2016. Chapter 3 - Geochemistry Applied to Evaluation of Unconventional Resources, in: Ma, Y.Z., Holditch, S.A. (Eds.), Unconventional Oil and Gas Resources Handbook. Gulf Professional Publishing, Boston, pp. 71–126. https://doi.org/10.1016/B978-0-12-802238-2.00003-1

Rezaee, R., 2022. Editorial on Special Issues of Development of Unconventional Reservoirs. Energies 15, 2617. https://doi.org/10.3390/en15072617

Zee Ma, Y. (2016). Chapter 1—Unconventional Resources from Exploration to Production. In Y. Z. Ma and S. A. Holditch (Eds.), Unconventional Oil and Gas Resources Handbook (pp. 3–52). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-12-802238-2.00001-8

VI. LIST OF PUBLICATIONS AND PRESENTATIONS

JOURNALS ARTICLES

Valadez Vergara, R., Szabó, N.P., 2024. Level of thermal maturity estimation in unconventional reservoirs using interval inversion and simulating annealing method. Acta Geophys. https://doi.org/10.1007/s11600-024-01413-4

Szabó, N.P., Valadez-Vergara, R., Tapdigli, S., Ugochukwu, A., Szabó, I., Dobróka, M., 2021. Factor Analysis of Well Logs for Total Organic Carbon Estimation in Unconventional Reservoirs. Energies 14, 5978. https://doi.org/10.3390/en14185978

Valadez Vergara, Rafael. "Well-log based TOC estimation using linear approximation methods." Geosciences and engineering: a publication of the University of Miskolc, ISSN 2063-6997 (8. évf.) 13. sz. 2020.

PROCEEDING OF INTERNATIONAL CONFERENCES

Valadez Vergara, R., Gomaa Abdelrahman, M.M., Szabó, N.P., 2023. Improving TOC Estimation Accuracy Using Simulated Annealing Algorithm: A Data Science Approach 2023, 1–5. https://doi.org/10.3997/2214-4609.20233501

Abdelrahman, M., Valadez, R., Szabo, N., 2023. Automated Prediction of Geometrical, Zone, and Petrophysical Parameters for a Gas-Bearing Reservoir 2023, 1–5. https://doi.org/10.3997/2214-4609.20233500

Valadez Vergara, R., & Szabó, N. P. (2023). Assessing Thermal Maturity Levels in Unconventional Hydrocarbon Reservoirs through Interval Inversion and Simulated Annealing. 2023(1), 1–5. https://doi.org/10.3997/2214-4609.202320055

PROCEEDINGS OF DOMESTIC CONFERENCES

Valadez-Vergara, R. 2023. Metropolis Algorithm Driven Total Organic Carbon Content Estimation. New results in Earth and Environmental Sciences 2023. Miskolc, Hungary

Valadez Vergara, Rafael (2022). Zone Parameter Selection for Well-logging Inversion to Evaluate Unconventional Hydrocarbons Plays: A Műszaki

Földtudományi Kar konferencia kiadványa. pp. 203-212. ISBN 978-963-358-269-5

INTERNATIONAL CONFERENCE PRESENTATIONS

Improving TOC Estimation Accuracy Using Simulated Annealing Algorithm: A Data Science Approach. Fifth EAGE Conference on Petroleum Geostatistics. Nov 2023. Porto, Portugal.

Assessing Thermal Maturity Levels in Unconventional Hydrocarbon Reservoirs through Interval Inversion and Simulated Annealing. NSG2023, 29th European Meeting of Environmental and Engineering Geophysics. Sep 2023. Edinburgh, UK.

DOMESTIC CONFERENCES PRESENTATIONS

Insights into Total Organic Carbon Content Estimation using a Stochastic Optimization Algorithm. Doktoranduszok fóruma conferencia. Nov 2023. Miskolc, Hungary

Alternative approach for assessing Thermal Maturity on unconventional hydrocarbon reservoirs. Youth Performers Day 2023. May 24, 2023. University of Miskolc, Hungary.

Utilization of Advanced Inversion Tools for Analyzing Unconventional Hydrocarbon Reservoirs. 26th Spring Wind Conference (DOSZ), University of Miskolc, Hungary. 2023, May 5th.

Modern Inversion Tools for Evaluating Unconventional Hydrocarbon Reservoirs . LVII Meeting of Young Geoscientists. March 31, 2023. Nagybörzsöny, Hungary.

Well-logging interval inversion and sensitivity analysis for zone parameters estimation of unconventional hydrocarbon reservoirs. Inverziós Ankét 2022. MTA- Miskolci Akadémiai Bizottság. Nov 14, 2022. Miskolc, Hungary.

Sensitivity analysis in inversion of well logging data. Ifjúságu Elödói Nap 2022. May 25, 2022. Miskolc, Hungary.

Quantification of TOC content from well logs using linear approximation methods, Doktoranduszok Fóruma. November 19, 2020. University of Miskolc (Online), Hungary.

Well-log based TOC estimation using linear approximation methods, Inverziós Ankét. November 2–3, 2020. . University of Miskolc (Online), Hungary.

Quantification of Source Rock Potential Using Wireline Logs, Raw Material University Day – EIT Raw Materials Academy. October 20, 2020. . University of Miskolc (Online), Hungary.