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Geostatistics assisted well-logging inversion method developments

PhD THESIS

By

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SCIENTIFIC BACKGROUND AND AIMS

It matters what lies below the Earth's surface because it impacts geophysical and hydrogeological investigations, resource exploration, environmental sustainability, and infrastructure development. Borehole logging data inform us about the composition, structure, and fluid content of the subsurface, and they represent a key tool for unraveling these complexities. Yet the data are challenging to interpret (Bradley and Fayyad 1998). Traditional approaches, like K-means clustering and conventional inversion methods, often struggle to be trustworthy when confronted with noisy datasets, outliers, or complicated geologic formations (Szabó and Dobróka 2013). This can have the impact of giving rise to misunderstandings, clouding useful information on lithology, aquifer behavior, or reservoir characteristics (Mohammed et al. 2025). It is the intention of this thesis to overcome these difficulties by employing innovative techniques that improve the accuracy, lifetime, and reliability of subsurface characterization, thus providing a new insight into geophysical data interpretation.

At the heart of this research is the realization that traditional methods of borehole log data interpretation fall short in addressing the realities of complexity. For instance, K-means clustering is highly sensitive to outliers and noise, elements which can bias results and lead to incorrect classifications (Bradley and Fayyad 1998). Similarly, conventional inversion techniques used for the estimation of reservoir parameters tend to face issues regarding convergence stability and computational efficiency when applied to noisy datasets (Dobróka et al. 2016). These constraints emphasize the need for adaptive methodologies with the ability to handle the inherent uncertainties in geophysical data (Szabó and Dobróka 2013). The recent advancements in statistical methods and computational techniques form a foundation for the development of more robust and accurate interpretation tools (Dobróka and Szabó 2015).

A major advance in this field is the invention of the Most Frequent Value (MFV) algorithm, a statistical technique that is used to lessen the impacts of outliers and enhance the robustness of data analysis (Kemp and Steiner 1991). Integrating the MFV algorithm into cluster procedures results in more precise outcomes, particularly in the presence of noisy data. Furthermore, interval inversion techniques, which were initially meant for oil exploration, are more successful in parameter estimation when compared to conventional methods. The above techniques improve both precision and convergence stability, successfully dealing with the complexities involved in subsurface data. Building on these advances, the current research work introduces a set of new methodologies that integrate rigorous statistical methods with advanced inversion strategies, thus creating an integrated paradigm for accurate characterization of subsurface structures.

The primary thesis presupposes that the application of sophisticated statistical techniques, such as the MFV algorithm, coupled with developing inversion techniques, has the potential to enhance borehole log data analysis substantially. It is expected that the outlier suppression and centroid stabilization property of the MFV algorithm will enhance clustering performance, whereas hybrid inversion methods maximize parameter estimation by exploiting the strengths of various algorithms. Furthermore, it is expected that these techniques have universal applicability across a broad spectrum of geologic environments, ranging from groundwater aquifers to hydrocarbon reservoirs and geothermal systems, and therefore constitute versatile tools for subsurface exploration.

The research plan is to develop and test three main methods. The first method is an MFV-based clustering algorithm using Steiner-Cauchy weights, which reduces the effect of outliers and improves centroid estimation. This algorithm develops a novel distance metric, known as the Steiner distance, that helps to select the most appropriate range of data while removing noise caused by outliers. Utilization of the MFV for centroid update helps in achieving robust clustering results despite choosing random initialization points. The second method is a Damped Least Squares (DLSQ) and Singular Value Decomposition (SVD) hybrid inversion technique. This process adjusts damping factors in real-time to enhance performance, making it a superior and more accurate method than previous inversions. The third method is an automatic procedure that integrates Hurst analysis, interval inversion, and the Csókás method for total formation evaluation. This procedure applies Hurst analysis for making layer number predictions and depth location estimations, interval inversion for petrophysical parameter calculations, and the Csókás method for improving hydraulic conductivity estimation. Together, these protocols form an integrated system for effective subsurface characterization. What is novel in this research is the manner in which these techniques are combined in one system, solving the problems of the other methods.

The MFV-based clustering algorithm introduces a new method of distance measurement and group center updating to make clustering stronger and more robust. The hybrid inversion method varies damping factors dynamically to accelerate the process, providing a better alternative to previous inversion techniques. The automated process employs Hurst analysis to determine rock type boundaries and interval inversion to obtain precise parameter estimates, providing a full solution for determining what lies beneath the surface. The motivation for this research is the need for accurate and efficient methods for interpreting complex geophysical data, particularly in the face of increasing environmental and resource challenges. Groundwater management, hydrocarbon exploration in complex reservoirs, and geothermal resource development require accurate subsurface characterization to inform decision-making and resource management. By developing methodologies that enhance the accuracy and efficiency of data interpretation, this research aims to contribute to geophysical and hydrogeological sciences. The contribution of the work extends beyond scientific research, offering practical tools for industry professionals and policymakers. The proposed methodologies can be used to improve aquifer property assessment, optimize hydrocarbon reservoir characterization, and maximize geothermal resource estimation. The workflows' automatic characteristic also reduces reliance on manual interpretation, minimizing subjectivity and improving reproducibility.

This PhD dissertation introduces a sequence of novel methodologies overcoming the drawbacks of conventional borehole logging data interpretation methods. This research uses advanced statistical methods, complex inversion techniques, and automatic procedures to develop a unique way of reading the subsurface. The results show that these kinds of techniques can revolutionize geophysical and hydrogeological research, yielding novel information about complex geological systems and helping to promote sustainable resource management. The development of such methods represents substantial progress in the discipline, with a wide range of applications in groundwater assessment, hydrocarbon exploration, and geothermal resource investigation. Through this work, I would like to provide the scientific community and professionals in the field with practical means to understand and manage the Earth's subsurface resources.

ACCOMPLISHED INVESTIGATION

In chapter one, I established the premise of this research by expressing the rationale for combining inversion methods with machine learning applications in geophysical interpretation. I highlighted their revolutionary potential, namely in terms of improving pattern recognition and parameter estimation, which are essential for accurate and effective interpretation of sophisticated well-logging data.

Chapter two is where I presented a new clustering algorithm intended to enhance lithological classification within geophysical data analysis. In this chapter, I applied the Most Frequent Value (MFV) algorithm with the purpose of addressing the common vulnerability of traditional clustering algorithms such as susceptibility to noise and dependence on initial centroids. With the addition of Steiner distances for weighted updates of centroids, I was successful in achieving improved accuracy and dependability. Through using the method on simulated well-log data with outliers and noise, I demonstrated the robustness of the method in maintaining cluster integrity and providing consistent output. Its application to real field data showcased its precise classification potential for aquifer quality, providing a high-resolution picture of subsurface layers augmented by analysis of core samples, thus constituting a milestone in geological data interpretation.

In chapter three, I examined the development of advanced techniques for enhancing the estimation of reservoir properties from well-logging data. I tackled the limitations usually associated with traditional methods, such as uncertainty and resolution issues, by suggesting advanced algorithms. I addressed how to deal with significant parameters like the damping factor, which is essential in stabilizing during estimation. By combining the Golden Section Search (GSS) with interval estimation methods, I established a more structured and effective methodology, best positioned for handling noisy data sets. I also proposed a hybrid approach combining Damped Least Squares (DLSQ) and Singular Value Decomposition (SVD), with an aim to increase computational efficiency. The methodology starts using SVD for optimal parameter tuning, then switches to DLSQ to optimize the solution as it nears completion. The validity of these methods was confirmed by their application to an Egyptian gas-bearing reservoir data, demonstrating the reservoir property heterogeneity and re-emphasizing the need for tailored assessment strategies.

Chapter four entailed showing a new approach to derive hidden patterns from geophysical data using the Hurst exponent—a measure of fractal analysis—combined with interval inversion. I began with factor analysis to reduce dimension and identify lithology-sensitive factors from well-log data. Applying the Hurst exponent analysis allowed me to define layer boundaries with depth-dependent metric, effectively capturing lithological variations. I demonstrated the effectiveness of the algorithm with synthetic data and real hydrogeophysical data from Hungary. The process also involves calculating hydraulic conductivity via the Csókás method, thus obtaining high-resolution aquifer quality information.

In the fifth chapter, I presented a refined algorithm aimed at petrophysical, zone, and geometrical parameter estimation from well log data. By combining MFV clustering with local inversion, I gained a more profound understanding of the static and dynamic properties of reservoirs. I illustrated the algorithm's versatility by increasing the number of unknowns to incorporate zone parameters such as shale density and cementation exponent. Synthetic modeling showed that it could simulate petrophysical as well as zone parameters simultaneously, proving its applicability in various geological settings. Validation with field measurements in a Hungarian oil field confirmed the algorithm's capability to predict petrophysical parameters under varying conditions of zones. I also developed an original technique integrating unsupervised pattern detection from data with interval analysis for effective determination of subsurface geological boundaries in terms of polynomial degree and thickness dependence.

Chapter six explains the new integration of unsupervised data pattern analysis and interval analysis to achieve precise delineation of underground geological boundaries. I addressed the problems brought about by polynomial degree and thickness dependency, providing a strict perception of subterranean attributes. My algorithm delineates boundaries under various levels of noise, being resistant to contamination up to 7%. Applied to data from Hungarian geothermal explorations to real-world applications, this approach was beneficial in practice, raising the level of confidence in subsurface analysis and resource estimation. With the advent of a new method of interpreting well-logging data through robust clustering and interval inversion techniques, I used machine learning to improve the accuracy of subsurface property estimation. This algorithmic method selects the best number of sub-intervals and dynamically adjusts polynomial orders for better computation of calculated and measured data fit. My sensitivity analysis highlighted the importance of parameters like the cementation exponent and tortuosity on the implementation of the algorithm on synthetic models and real-world datasets, including Egyptian gas reservoir ones. The technique improved petrophysical predictions more precisely and exhibited better convergence stability, resulting in successful delineation of distinct geological intervals.

NEW SCIENTIFIC RESULTS

Thesis Statement 1.

I have developed a robust cluster analysis method that can group well-logging data reliably by using the most frequent value (MFV) algorithm. The MFV-CA clustering algorithm can give the same cluster results with randomly chosen initial centroids. Besides that, the MFV-based clustering method effectively suppresses the outlying data during the classification of data objects. The optimal locations of the centroids are estimated by the MFV algorithm instead of the arithmetic mean of the cluster elements. I applied a weighting distance metric based on the Steiner weight function that so-called Steiner distance. I proved that Steiner distance can automatically identify the important range of the data, filtering out the noise caused by outliers. It retains the full scope of the dataset, ensuring all real data is preserved while minimizing distortion from extreme outlying values. In the latter case, I improved the results of rock typing in a Hungarian groundwater formation.

Thesis Statement 2.

I have developed two combined well logging inversion algorithms to improve reservoir parameter estimation. For achieving good convergence, hyperparameters, particularly the damping factor, must be accurately estimated. A comparison between GSS-based and DLSQ interval inversion methods showed the former has superior convergence smoothness and noise resistance. I suggested the first hybrid of DLSQ and SVD methods to achieve optimal computational efficiency. This composite inversion method uses SVD for automatic selection of the initial damping factor and DLSQ for improving convergence. When applied to the well-log data of an Egyptian gas reservoir, the algorithms yielded clear information about the reservoir. The error estimation showed that SVD gave very good results with smaller confidence intervals and lower values of parameter correlation. These results show the importance of having specific techniques for effective reservoir appraisal.

Thesis Statement 3.

I have developed a new integrated method based on the Hurst exponent and interval inversion for processing well logs. The conducted workflow consists of a series of innovative interpretation techniques that are used simultaneously to improve the evaluation of groundwater formations. The algorithm first extracts the first factor being a good lithology indicator. Then, Hurst analysis is applied to the first factor log to differentiate the lithology types. I proved that the scale and depth-dependent Hurst exponent exhibits a mean value of 0.5 at the exact location of the layers' boundaries with a decreasing pattern within the layers themselves. After the automated determination of the layer boundaries, interval inversion of the well logs provides the basic volumetric parameters such as porosity, shale volume and matrix volume. I proved the feasibility of the inversion algorithm using synthetic and field hydrogeophysical datasets. I extended the proposed algorithm to calculate the hydraulic conductivity using the Csókás method. I successfully validated the predicted petrophysical parameters using core laboratory measurements.

Thesis Statement 4.

I present an automated inversion scheme utilizing MFV clustering and point-by-point inversion to predict geometrical and petrophysical parameters, improving log data interpretation. The initial algorithm assumes known zone parameters, while the advanced version handles unknown parameters, both constant and varying across layers. Validation with synthetic data sets showed robust clustering into lithological groups. Application to a Hungarian dataset, as depicted in the figure, demonstrates classification into rock types and parameter estimation, with bulk volume around 0.5, fluid volume 0.1, shale resistivity up to 6 ohmm, and cementation exponent ranging from 1.8 to 2.6. This approach enhances reservoir characterization by integrating layer-specific volumetric and zone parameters, aligning with calculated saturation profiles and advancing static reservoir modeling.

Thesis Statement 5.

The dissertation introduces a novel method in petrophysical parameter prediction using a strongly overdetermined interval inversion process where zone parameters such as cementation exponent, tortuosity, and shale properties are optimized. It automated layer boundary identification and was field tested with synthetic data at noise levels of 2%, 5%, and 7%. Applied to northeast Hungarian hydrogeophysics data, it was found to be able to identify six distinct subzones and to rightly establish geological boundaries. Validation on an Egyptian hydrocarbon dataset showed successful classification of rock interfaces and estimation of parameters, with bulk volumes around 0.5, water saturation around 0.5, and fluid volume with a peak of 0.2. The machine-learning-based inversion gave a reduced data misfit of 7.5%, with improved convergence stability significantly. Zone parameters, including varying cementation exponent values, were estimated correctly, providing robust reservoir characterization.

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LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

JOURNAL ARTICLE

1. Szabó, N. P., B. A. Braun, M. M.G. Abdelrahman, and M Dobróka. 2021. "Improved Well Logs Clustering Algorithm for Shale Gas Identification and Formation Evaluation." *Acta Geodaetica et Geophysica* 56 (4): 711–29. https://doi.org/10.1007/s40328-021-00358-0.
2. Abdelrahman, M. M.G., N. P. Szabó, and M. Dobróka. 2021. "Petrophysical Parameters Estimation Using Levenberg-Marquardt and Singular Value Decomposition Inversion Schemes." *Multidiszciplináris Tudományok* 11 (5): 24–38. https://doi.org/10.35925/j.multi.2021.5.3.

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4. Abdelrahman, Moataz Mohamed Gomaa, Norbert Péter Szabó, and Mihály Dobróka. 2022. "Meta-Algorithm Assisted Interval Inversion for Petrophysical Properties Prediction." *Multidiszciplináris tudományok* 12(4): 242–60.

5. Abdelrahman, M. M.G., and H. A. A. Hassan. 2022. "Optimal Regularization for 1-D Local Inversion for Borehole Geophysical Data." *University of Miskolc, Faculty of Earth Sciences and Engineering, Miskolc-Egyetemváros, Hungary* (9789633582695): 165–72. https://www.researchgate.net/publication/369859837_Optimal_Regularization_for_1-D_Local_Inversion_for_Borehole_Geophysical_Data.

CONFERENCE PROCEEDINGS PAPERS (SHORT AND EXTENDED ABSTRACT)

1. Vergara, R. Valadez, M. M. Abdelrahman, and N.P. Szabó. 2023. "Improving Toc Estimation Accuracy Using Simulated Annealing Algorithm: A Data Science Approach." In , edited by Fifth EAGE Conference on Petroleum Geostatistics, 1–5. European Association of Geoscientists & Engineers. https://doi.org/https://doi.org/10.3997/2214-4609.202335010.

2. Abdelrahman, M. M.G., and N. P. Szabó. 2024. "A Case Study of Petrophysical Prediction Using Machine Learning Integrated with Interval Inversion in a Tight Sand Reservoir in Egypt."

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3. Abdelrahman, M. M., and Norbert Péter Szabó. 2023. “Unsupervised Machine Learning Assisted Hydrogeophysical Borehole Logging Inversion for Robust Aquifer Characterization.” In , edited by NSG2023 2nd Conference on Hydrogeophysics, 1–5. European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202320013.
4. Abdelrahman, M. M., R. Valadez Vergara, and N.P. Szabó. 2023. “Automated Prediction of Geometrical, Zone, and Petrophysical Parameters for a Gas-Bearing Reservoir.” In , edited by Fifth EAGE Conference on Petroleum Geostatistics, 1–5. European Association of Geoscientists & Engineers. https://doi.org/https://doi.org/10.3997/2214-4609.202335006.

INTERNATIONAL CONFERENCE PRESENTATION

1. Speaker at The First Scientific Research Symposium of Faculty of Science conference, Cairo (Egypt), "Gas sand prediction using Bayesian classification of el Obayied field, Western Desert, Egypt", December 27th, 2018.
2. Speaker at The First Scientific Congress of Junior Geoscientists in Egypt (SCJGE-1) held at Sohag University, "Geological Reservoir Modeling of the Lower Safa Member at El-Obaiyed Field, Northwestern Desert, Egypt", February 3rd, 2019.
3. Speaker at the XXIII Conference of PhD Students and Young Scientists “A case study of petrophysical prediction using machine learning integrated with interval inversion in a tight sand reservoir in Egypt” (June 2023).

4. Speaker at NSG2023 2nd Conference on Hydrogeophysics, European Association of Geoscientists & Engineers “Unsupervised Machine Learning Assisted Hydrogeophysical Borehole Logging Inversion for Robust Aquifer Characterization” (September 2023).
5. Speaker at Fifth EAGE Conference on Petroleum Geostatistics, European Association of Geoscientists & Engineers “Automated Prediction of Geometrical, Zone, and Petrophysical Parameters for a Gas-Bearing Reservoir” (November 2023).

DOMESTIC CONFERENCE PRESENTATIONS

1. Speaker at the Ph.D. Forum, organized by the University of Miskolc, "Gas sand prediction using Bayesian classification of El Obayied field, Western Desert, Egypt" (October 2020).
2. Speaker at the ISZA conference “Borehole Geophysical Inversion Using Levenberg Marquardt and Singular Value Decomposition Schemes for Petrophysical Parameters Estimation” (September 2021)
3. Speaker at the Ph.D. Forum, organized by the University of Miskolc, "Modified Interval Inversion Methods for Petrophysical Parameters and Layers’ Boundaries Prediction" (November 2021).
4. Speaker at the micoCAD conference, organized by the University of Miskolc “Petrophysical Parameters Estimation using Levenberg-Marquardt and Singular Value Decomposition Inversion Schemes” (September 2021).
5. Speaker at the Youth Performers Day 2021, organized by the department of geophysics “GEOPHYSICAL INVERSION VERSUS MACHINE LEARNING” (May 2021).

6. Speaker at the GeoMATES 2022 conference, “Unsupervised Machine Learning Assisted Borehole Geophysical Inversion for Robust Reservoir Characterization” (September 2021).
7. Speaker at the Inversion Conference 2022, organized by the MTA Miskolci Területi Bizottságának Földtudományi Munkabizottsága és Geoinformatikai és Térinformatikai Munkabizottsága “Integrated workflow for evaluating groundwater formations using the Hurst exponent and interval inversion” (November 2022).
8. Speaker at the Ph.D. Forum, organized by the University of Miskolc, " Prediction of layers’ thickness and petrophysical parameters using Hurst exponent and interval inversion" (November 2022).
9. Speaker at the micoCAD conference, organized by the University of Miskolc “Meta-Algorithm Assisted Interval Inversion for Petrophysical Properties Prediction” (September 2022).
10. Speaker at the ISZA conference “A robust clustering technique assisted interval inversion of well-logging data for automatic determination of formation boundaries” (April 2023)
11. Speaker at the Ph.D. Forum, organized by the University of Miskolc, " Fully automated algorithm for petrophysical, zone, and geometrical parameters prediction" (November 2023)