Doctoral School of Geosciences

SPATIAL CHARACTERISATION OF THE FRACTURED MEZŐSAS-W (PANNONIAN BASIN) BURIED HILL METAMORPHIC RESERVOIR USING MULTIVARIATE EVALUATION OF WELL-LOGS

Thesis of the PhD Dissertation

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1.0 Introduction and Aims

The Pannonian Basin is known for its complex and complicated structure because of multiple overthrusting events due to the Alpine orogeny and basin formation during the Neogene (Tari et al., 1999; Haas & Péró, 2004). The complex structural evolution complicates the interpretation of geological events, including determining lithology sequences (Horváth and Tari, 1999). The Mezősas-West hydrocarbon field is located in the northern part of the Békés Basin, one of the subbasins in the Pannonian Basin (Selmeczi, 2018). The basement reservoir consists of pre-Alpine metamorphic rocks, different gneiss varieties, mica-schist and amphibolite (Szabó et al., 2022). These metamorphic rocks are also known for their significant roles in providing migration pathways and storing fluids due to their fractured characteristics (Tari et al., 1999; Schubert et al., 2007). Three main rock bodies have been proven to make up the basement reservoir. Orthogneiss (OG block) dominates the lowermost zone, followed by garnet- and sillimanite-bearing paragneiss (SG block), and finally, an amphibolite and amphibole biotite gneiss dominated (AG block) occurs on the topmost section (Molnár et al., 2015a; Molnár et al., 2015b; M. Tóth et al., 2021).

Understanding the fractured basement metamorphic reservoir is essential, and some of the most common data sources to analyse reservoir characteristics are conventional well-logs, core samples, image logs and seismic data (Sebtosheikh & Salehi, 2015). Nonetheless, there are some challenges regarding old and deep hydrocarbon fields. For instance, core samples are critical when analysing the lithology and fracture characteristics. However, some wells do not have this crucial information due to problems such as a failed retrieving process, and bad quality of the core samples gathered (Lyu et al., 2016; Hu et al., 2023). Also, image logs are very common when analysing fractured reservoirs; however, most old wells do not have this valuable information. It is also reported that image logs and core samples sometimes take a lot of time, the cost of retrieving cores and image logs is high, and it has been reported that not all

companies will opt for this option for every single well that they drill (Tang & White, 2008; Li et al., 2021; Tanaka et al., 2024).

Due to these problems, it is derived that, in most cases, conventional well-logs are the most widely available data from the exploration wells. Hence, leveraging this advantage, conventional well-logs were chosen as the primary input data for this PhD work analysis. This PhD work's focus is twofold; one is to investigate lithology, and another one is to analyse the fracture property. Given the situation in which several fracture properties can be studied, only fracture density was chosen to be investigated along with the conventional well-logs.

2.0 Applied Methods

In evaluating fractured fluid reservoirs, lithology identification and fractured rock characteristics analysis are expected in previous studies. Much of the research attempts to analyse these two study areas by utilising the advantages of statistical methods and machine learning algorithms. This study aims to use limited sources of information to maximise the results for future applications with minimum uncertainties. This research used the available conventional well-log as the limited source of information to predict lithology and fracture density (results) using statistical and machine learning methods. The applied techniques are briefly explained below.

1) *Discriminant function analysis*. Discriminant function analysis (DFA) or discriminant analysis (DA) is a statistical method used to predict group membership of undetermined individuals and their probability classification based on several independent predictor variables (Teh et al., 2012; Iduseri & Osemwenkhae, 2015). This study used DFA to group undetermined individual well-log points into certain lithology groups. DFA was also used to validate the predicted results of fracture density predictions.
2) *Multiple linear regression*. Multiple linear regression (MLR) can analyse and establish the relationship between a single dependent variable and several independent variables (Ajona et al., 2022; Cai

et al., 2023). The primary purpose of MLR is to use the known values of independent variables to predict the single dependent value (Hernández-Fernández, 2020; Ismail et al., 2023). This study employed MLR to establish a relationship between conventional well-log data (independent variables) and fracture density (dependent variable).

3) *Principal component analysis*. Principal component analysis (PCA) is a dimension reduction statistical approach to transform a set of probably correlated into uncorrelated data (Teh et al., 2012). The newly transformed data or variables are called principal components (PC), and since each PC is uncorrelated, it is advantageous to explain one PC without referring it to another (Tiryaki, 2008; Konaté et al., 2015). This study applied PCA to conventional well-log data to transform the data into much simpler PCs.
4) *Gene expression programming*. Gene expression programming is a machine learning method developed by Ferreira by combining genetic algorithm (GA) and genetic programming (GP) (Ferreira, 2001; Khandelwal et al., 2016). These three methods are based on or inspired by the biological evolution process, which means that these methods all started with the random creation of the initial population of chromosomes (Algaifi et al., 2021; Afrasiabian and Eftekhari, 2022; Aydogan et al., 2023). The application of GEP to petroleum engineering and geoscience studies is minimal, primarily related to fracture characteristics evaluation. Hence, this is one of the earliest studies that employ this method for fracture density predictions.

3.0 New Scientific Results

T1: Using well-logs information and statistical analysis, the previously known AG rock body can further differentiate into amphibolite-rich (AG) and amphibole-biotite gneiss (AG2) blocks. In the previous research, amphibole–biotite gneiss and amphibolite were regarded as one lithology based on core sample data and well-log interpretation. However, the DFA and cross plots could differentiate these two lithologies based on their petrophysical characteristics. Upon

implementation of cross plots and generated DFA functions, the characteristics of AG2 are different from those of SG. Hence, further investigation was conducted to confirm that AG2 differed from SG. Eqs. (1) and (2) differentiate AG and AG2 perfectly. The spectral GR regarding uranium and potassium content data were good predictors.

$$D(1) = 0.723*K + 0.868*U - 1.114*D + 0.082*N + 0.203*S - 12.451 \quad (1)$$

$$D(2) = 0.045*GR + 5.017*R + 1.302*D + 0.136*N + 0.153*S - 17.781 \quad (2)$$

T2: The different types of metamorphic rocks can be grouped using discriminant function analysis and cross-plot methods. The fundamental idea of the first part of this PhD research work was to interpret, classify and determine the complex metamorphic rock lithology based on well-logs information. As mentioned earlier and based on much previous research, metamorphic rocks determination and interpretation using well-logs are difficult, especially when core samples are unavailable or insufficient. The well-logs data of confirmed lithology was trained using the DFA method and cross-plots. To discriminate between AG and SG rock bodies, Well 22 was selected as the teaching well, while Well 27 was chosen as the teaching well to separate SG and OG. The undetermined lithology was successfully classified based on generated DFA functions. Cross-plot results clearly show that all four lithologies can be discriminated based on their physical properties. For instance, AG has a higher bulk density than AG2, SG, and OG. It also has low potassium and uranium contents, and hence, the GR value for amphibolite is relatively lower than the GR values of other rock types. OG generally has lower density values than the SG body, per the density porosity. Also, the spectral GR results show that the potassium and uranium contents of OG are generally lower than those of the SG rock.

T3: The previously reported AG-SG-OG layers sequence is confirmed by constructing one-dimensional lithostratigraphic columns and extending the spatial range of the predicted lithology. After all lithologies from all available wells had been determined, the well-to-well correlation was done to extend the results spatially. As per

the previous research, the ideal rock column was validated, and SG covered the OG. AG and AG2 are the topmost layers of the basement rocks, and they lie over the SG. AG and AG2 clearly define independent rock bodies with AG on the top.

T4: The structural evolution of the Mezősas-West area was defined, and low-angle thrust fault zones and younger normal faults were determined. Low-angle thrust and normal faults are fundamental in the study area since these structures define migration pathways for the hydrocarbon to flow and could act as storage volumes for the hydrocarbons. This information is valuable for predicting hydrocarbon accumulation and could help determine well placement for future exploration. The normal faults were deemed appropriate based on the spatially correlated lithological model. The evolution of the Pannonian Basin as a part of the Cretaceous nappe activity contributed to the structural evolution of the area, including the formation of low-angle thrust zones that are common in the Pannonian Basin.

T5: This PhD successfully implemented and employed the GEP method to predict FD (fracture density) using well-logs data. Based on the comprehensive literature studies, GEP is not widely used in the field of petroleum engineering or geoscience studies, and this work is one of the earliest studies that explore GEP to predict fracture density for metamorphic basement rocks, specifically amphibolite and amphibole biotite gneiss type of lithology. The method predicts the FD with R2 values above 0.86 based on the findings.

T6: The nonlinear GEP method gave better results in predicting fracture density values than the linear MLR method. This statement is based on comparing the MLR with the GEP method. The result of GEP gives a better predictive model since most well-log input parameters are nonlinear, and nonlinear approaches are better for tackling nonlinear problems. GEP predicted the best fracture density with $R^2 > 0.86$, while the MLR method predicted FD values with R2 around 0.75.

T7: Different log responses concerning FD were established and evaluated, and the findings are consistent with those published previously for other metamorphic terranes. In many cases of previous studies relating to predicting FD using statistical or machine learning methods, most authors tend to discuss the results focusing only on the developed models and very rarely the discussion trying to explain the significance of well-logs parameters to their models. However, in this study, the methods were evaluated in terms of their validity, and the most crucial part, the relationship between FD and well-logs parameters, was also discussed. For instance, some results explain why flushed zone resistivity played an essential role in FD. This is because in the zones with high FD, the flushed zone resistivity readings tended to be lower, and it is observed in the models produced. As predicted, gamma-ray alone did not contribute substantially to the FD prediction, and it is showcased in all of the GEP models for OG, SG, and AG (including AG2). However, as observed in the literature, SGR is beneficial since the individual component of the gamma-ray could be analysed appropriately. Thorium and uranium content, for example, tended to contribute the most in predicting FD. Porosity logs also influenced the prediction of FD, wherein bulk density showed the most effects on the FD, followed by neutron porosity.

T8: SG and OG rock bodies of the Mezősas-West field exhibit similar fracture density patterns. The results from GEP modelling show that the fracture density prediction between SG and OG rock bodies has no significant difference regarding the well-log responses. The considerable parameters for SG are spectral gamma ray, resistivity (flushed zone and deep) and bulk density. In contrast, the significant parameters for OG are spectral gamma ray, resistivity (flushed zone and deep) and neutron porosity. In addition, the comparisons of the relative contribution of input parameters and the plot of fracture density frequency distribution show that these rocks yielded similar results and patterns. It is safe to assume that both gneiss types act similarly in providing the fluid migration pathways or storing fluid capacity.

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List of Publications

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Hasan, M. L., & M. Tóth, T. (2023). Localization of potential migration pathways inside a fractured metamorphic hydrocarbon reservoir using well log evaluation (Mezősas field, Pannonian Basin). Geoenergy Science and Engineering, 211710. https://doi.org/10.1016/j.geoen.2023.211710

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Co-author Statements

I, Tivadar M. Tóth, hereby declare that the role of the doctoral candidate in the publication of

Hasan, M. L., & M. Tóth, T. (2023). Localization of potential migration pathways inside a fractured metamorphic hydrocarbon reservoir using well log evaluation (Mezősas field, Pannonian Basin). Geoenergy Science and Engineering, 211710. https://doi.org/10.1016/j.geoen.2023.211710

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was decisive that I did not use it to obtain a scientific degree and will not do so in the future.

Szeged, 23 April 2024

Tivadar M. Tóth

Declaration of the Supervisor

I, Tivadar M. Tóth, hereby confirm that the content of the dissertation is based on the independent work of the doctoral candidate and that he has contributed decisively to the results through his independent creative activity. I consider the entire dissertation to be eligible for support from a professional and academic point of view and recommend its acceptance.

Szeged, 23 April 2024

Tivadar M. Tóth