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RESERVOIR AND BASIN MODELING RELATING GEO- AND ROCK PHYSICAL RESEARCH

New scientific achievements of PhD. Thesis

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1. INTRODUCTION & TOPIC RELEVANCE

Pore pressure prediction is a specialized field in earth science that aims to estimate the expected pressure within the pore spaces of sedimentary rocks. Accurate pore pressure prediction is crucial during the planning phase of drilling activities in hydrocarbon exploration and development projects due to the associated drilling risks.

During drilling, the borehole is filled with drilling mud, which serves as a lubricant for the drilling head and prevents pore fluids from entering the borehole. However, in exceptional circumstances, such as when the mud pressure is lower than the pore pressure, pore fluid may enter the borehole, or the borehole may deviate from its optimal round shape due to low permeability. Conversely, if the mud pressure exceeds the pore pressure, the mud filtrates into the pore space and builds up a mud cake. These technical issues can prolong the drilling process and increase costs. If the pore fluid enters the borehole without any control, it can result in a well blowout, endangering human life.

The issues mentioned above represent the main drilling risks and require the most accurate pore pressure prediction. Pore pressure increases with depth, and the gradient is dynamically changing, which makes prediction challenging. Predictions are based on petrophysical and reflectional seismic methods (Bowers, 1995; Eaton, 1975; Huffman, 2002), which use equations to describe the relationship between physical parameters and pore pressure values.

In his 2002 publication, Swarbrick highlighted limitations in velocity-based methods for pore pressure prediction (including petrophysical and seismic methods). These limitations fall into three categories:

- The main phenomenon neglected by the aforementioned methods is lateral transfer. In reservoirs with regional distribution and high permeability, pore pressure is equalized. This means that there may be overpressure in shallower basin parts and unexpected drops in pore pressure at the deepest subbasins (Nagy et al., 2019).
- Petrophysical and seismic methods rely on comparing normal compactional trends (i.e., hydrostatic conditions) with measured data. However, special geological conditions, such as erosion after uplifts, can result in the normal compactional part of the stratigraphic series being

removed. This makes it impossible to identify the normal compactional trend (NCT) and thus prevents the application of petrophysical and seismic methods. Another frequent problem is lithological heterogeneity, which can make it difficult to identify the NCT due to the heterogeneous nature of the rock material.

- Velocity-based pore pressure prediction methods only consider irreversible mechanical compaction as the trigger for porosity reduction. However, chemical processes, such as dissolution, precipitation, cementation, and mineral transformation, can modify the porosity values resulting from mechanical compaction. This means that velocity-based pore pressure prediction can be unreliable when chemical processes are present.

To manage the above limitations, there are two practical solutions: deliver several pore pressure predictions using independent methods and compare the results or choose a pore pressure prediction method that incorporates the above limitations. Basin modeling is a method developed to evaluate hydrocarbon generation, migration, and accumulation in sedimentary basins. It can simulate burial, compaction, hydrocarbon generation, and multi-phase fluid migration in a geological timeframe (Hantschel and Kauerauf, 2009).

The advantage of basin modeling lies in the fact that it provides an independent method for pore pressure prediction, allowing for an alternative prediction to be made. The goal is not to replace petrophysical or seismic methods in the field of pore pressure prediction, but to extend the existing toolkit. Basin modeling considers lateral transfer and chemical compaction as overpressure generation mechanisms and does not require a normal compactional trend as an input parameter.

According to the above, it is a capable method to manage the velocity-based pore pressure prediction method's limitations. The goal of the Author’s PhD research was to build up 2D and 3D pore and overpressure models of the Danube Tisza Interfluve area, identify the active overpressure generation mechanisms and evaluate the quantitative contribution of unique generation mechanisms to the complex pore pressure regime.

1.1. Research purpose & research conducted

The Author's research activities regarding basin modeling started in 2013 and shifted focus towards pore pressure prediction in 2017. The research had dual goals: to construct 2D and 3D basin models for understanding the physical changes occurring in sedimentary basins and to evaluate the overpressure generation mechanisms in the Pannonian Basin.

The Author developed a multidisciplinary approach, which involved identifying overpressure generation mechanisms, evaluating well logs, conducting rock mechanical measurements, and using stochastic basin modeling techniques. The research activities resulted in the following specific research objectives:

- Identifying lithostratigraphic units, which take part in overpressure generation by well logs.
- Conducting a reservoir mechanical measurement program in case of under sampled lithostratigraphic units and delivering reservoir mechanical trends.
- Managing limited calibration data issues in case of pressure data and developing quantitative calibration techniques, which can manage calibration of data ranges.
- Estimating the contribution of individual overpressure generation mechanisms to the subsurface pressure regime in the southern Pannonian basin.
- Developing stochastic pore pressure prediction methods, which were robustified, Monte Carlo simulation supported basin modeling.

The Author conducted lithology-sensitive well log evaluations to investigate individual lithological units and their role in overpressure development. Shale-rich series were delineated for further analysis, and overpressure generation mechanisms were evaluated using compressional wave velocity-depth and bulk density-compressional wave velocity cross plots. A combination of lithology and porosity-sensitive well log analysis proved to be a capable method for identifying depth intervals where overpressure could be present.

The reservoir mechanical properties database of MOL was evaluated, and underrepresented lithostratigraphic units were identified. Rock material for further measurements was obtained through core review and sampling, and the measurements were conducted at the Applied Earth Science Research Institute (AFKI). Reservoir mechanical trends were generated based on the emerging reservoir mechanical properties of MOL-AFKI. The reliability of the applied empirical equations was tested for the formation of the Pannonian Basin, and the uncertainties in the accepted trends were evaluated and described for the Middle Miocene and younger formations.

Despite the limited amount of available static pressure data, the research involved the use of different pore pressure proxies in the pressure calibration process. To handle the interval data associated with both proxies, a statistical algorithm was integrated into the model calibration process. In order to avoid endless calibration iterations, a stop criterion was built into the model as a trigger mechanism. As a result, the research activity led to a quantitative calibration process.

Calibrated pore pressure model considers every overpressure generation mechanism. However, the contribution of unique mechanisms has been evaluated by building simplified models. Simplified models were copied from the final model, but neglected one overpressure generation mechanism, so the contribution of the given mechanisms to the subsurface pressure regime has been estimated with a deductive method. Besides the overpressure generation mechanisms, the timing effect of sedimentation has been investigated.

During the Author's research, the sensitivity of pore pressure prediction to input reservoir mechanical trends was evaluated, and the uncertainty of these trends was quantitatively described. To handle input data uncertainty, a stochastic pore pressure prediction method was developed, and Monte Carlo simulation was integrated into the simulation process. To take non-Gaussian distributed error into account and make the prediction method more robust, the Most Frequent Value method was also integrated into the stochastic pore pressure prediction method.

2. NEW SCIENTIFIC ACHIEVEMENTS

Novel scientific results have been discovered during the research conducted and presented in the Ph.D. thesis. This chapter provides a summary of the scientific findings and presents the theses.

2.1. First thesis

Through well log data evaluation, the Author identified two overpressure generation mechanisms in the Danube Tisza Interfluve area. Integral gamma and acoustic travel time log evaluation identified the top of the overpressure zone at a depth of 2000m. The study showed that overpressure begins developing in the Algyő Formation in the deepest parts of the basin, and that undercompaction is an effective overpressure generation mechanism, supported by the compressional wave velocity-depth profiles. The analysis also revealed that fluid expansion mechanisms did not contribute to overpressure generation. The study further identified chemical compaction as the second overpressure generation mechanism, supported by bulk density-compressional wave velocity cross plots.

2.2. Second thesis

The Author developed a program to measure reservoir mechanics and applied it to non-hydrocarbon reservoirs in the Late Miocene. Low permeability rocks (10-2 - 10-8 mD) were tested using AFKI's instruments, and permeability values were specified. The priority-depth, porosity-effective stress, and porosity-permeability trends were established for the Middle Miocene and younger sediments in the Danube Tisza Interfluve area. The empirical relationships were proven to be capable of describing the basin-scale mechanical compaction of the Újfalu, Algyő, Szolnok Formations, and Nagykörű, Tótkomlós Members. The applicability of Ungerer's (1990) and Schlumberger's "Multipoint" models was evaluated. The Author pointed out that Ungerer's model is suitable for describing the porosity-permeability relationship of rocks with a lower permeability range (such as shale, siltstone, and marl), but Schlumberger's "Multipoint" model is more dependable in the case of reservoir lithofacies.

2.3. Third thesis

The pore pressure model calibration process relied on static pore pressure data, although this dataset was incomplete. To overcome this limitation, the

Author incorporated additional independent pore pressure proxies and developed a statistical calibration method. This method compared measured and derived data ranges with estimated pore pressure values and iteratively minimized the Gaussian sum of square values of measured and simulated parameters. The optimal simulation number was determined using a convergent method. Despite the incomplete data system, the Author was able to successfully calibrate the basin model and demonstrated the automation of thermal model calibration. However, for at least partial manual calibration, another parameter calibration (porosity or pore pressure) was deemed necessary.

2.4. Fourth thesis

The Author constructed 2D and 3D basin models to investigate the magnitude and variance of pore pressure over geological timeframes. These models were based on reservoir mechanical trends that fit core-based measured porosity and permeability data. According to the basin models, undercompaction was found to have the highest contribution to the subsurface pressure regime, which is present in the Middle Miocene and younger low permeable rocks. Simplified models, neglecting the 1-1 mechanism, were constructed to investigate chemical compaction, hydrocarbon generation, and faults' effects on overpressure generation. With the support of basin models, the lateral transfer mechanism was identified as an overpressure generation mechanism in the Pannonian Basin, resulting in the development of a regionally uniform pressure system. The relationship between overpressure development and sedimentation was investigated on a geological timeframe. The Author also quantitatively calculated the unique contribution of each overpressure generation mechanism to the subsurface pressure regime in the Danube Tisza Interfluve area.

2.5. Fifth thesis

The Author utilized Monte Carlo simulation to estimate the uncertainty of 2D pore pressure models based on the error of measured permeability data. Different input parameters, such as porosity-permeability trends and depth maps, were modeled using various probability distributions. A statistical method was developed to determine the error of pore pressure models, and the Most Frequent Value (MFV) method was used to robustify the results. The Author then developed a stochastic pore pressure prediction method for the Pannonian basin, which takes into account error propagation in model parameter estimation.

3. POTENTIAL APPLICATION

The developed pore pressure models have enabled a better understanding of the unique overpressure generation mechanisms in the southern Pannonian basin. For instance, the lateral transfer and its pore pressure homogenization behaviour explain mud losses in deeper basin parts and unexpected gas kicks above basement highs. Reservoir mechanical trends could prove useful in section restoration or palinspastic restoration, where sediment compaction is usually neglected. Paleo water depth values of delta systems are often estimated based on the seismic clinoform high, which also neglects sediment compaction. As a result, the paleo water depth values are underestimated, which can be eliminated by incorporating compactional trends into the calculation.

Additionally, a new robust and independent method has been added to the existing pore pressure prediction toolkit. This method can provide pore pressure predictions during the exploration phase, which can be used as an input parameter for well planning. Moreover, 2D simulations can be completed in 1-2 hours, enabling the monitoring of pore pressure during drilling. I believe that the simultaneous real-time application of porosity-sensitive log-based prediction (logging while drilling - LWD) and basin modeling could save a significant amount of time and money.

4. PUBLICATIONS PRESENTED IN THE THESIS' TOPIC

4.1. Articles and proceedings

Nagy, Zs., Baracza, M.K., Szabó, N.P., (2019): Pore Pressure Prediction In Pannonian Hydrocarbon Reservoir Systems Using An Integrated Interpretation Approach. GEOSCIENCES AND ENGINEERING: A PUBLICATION OF THE UNIVERSITY OF MISKOLC, Vol. 7 (12), pp. 105-115.

Nagy, Zs., Baracza, M.K., Szabó, N.P. (2019): Integrated Pore Pressure Prediction with 3D Basin Modeling, In: Second EAGE Workshop on Pore Pressure Prediction, pp. 1-5. DOI: https://doi.org/10.3997/2214-4609.201900513

Nagy, Zs., Kiss, K., Baracza, M.K., Szabó, N.P. (2020): Subsurface Pressure Regime Evaluation with 2D Basin Modeling: A Case Study of Two Subbasins from Hungary, In: Third EAGE Workshop on Pore Pressure Prediction, pp. 1-6. DOI: https://doi.org/10.3997/2214-4609.202038013

Nagy, Zs., Baracza, MK., Szabó, NP. (2021): Magnitude Estimation of Overpressure Generation Mechanisms Using Quantitative Stochastic 2D Basin Models: A Case Study from the Danube-Tisza Interfluve Area in Hungary, APPLIED SCIENCES, 11, 6, p. 2841. DOI:10.3390/app11062841

4.2. Conference presentations

Basin model of the western part of the Hungarian Paleogene Basin, Meeting of Young Geoscientists (ISZA), Sopron, 27-28 March, 2015

Salt effects on thermal regime and maturity in 2D basin models – a case study from North Kazakhstan, Meeting of Young Geoscientists (ISZA), Kaposvár, 31 March - 1 April, 2017

Pore pressure prediction in hydrocarbon reservoir systems using an integrated interpretation approach, III. Innovatív Technológiák a Fluidumbányászatban, Miskolc, 25 October, 2018

Integrated Pore Pressure Prediction with 3D Basin Modeling, Second EAGE Workshop on Pore Pressure Prediction, Amsterdam, 19-21 May 2019

Application of Artificial Neural Networks (ANN) in geosciences – A case study from Central Hungary, Ifjú Szakemberek Ankétja, Ráckeve, 29 – 30 March, 2019

Subsurface Pressure Regime Evaluation with 2D Basin Modeling: A Case Study of Two Subbasins from Hungary, Third EAGE Workshop on Pore Pressure Prediction, Amsterdam, 14-16 December, 2020

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Eaton B. A. (1975): The equation for geopressure prediction from well logs. Society of Petroleum Engineers of AIME, Texas, SPE 5544.

Hantschel T. és Kauerauf A.I. (2009): Pore Pressure, Compaction and Tectonics. In: Fundamentals of Basin and Petroleum Systems Modeling. Springer, Berlin, Heidelberg, XVI, 476, pp. 31-101.

Huffman A.R. (2002): The future of pore-pressure prediction using geophysical methods. The Leading Edge 21, pp. 199-205.

Nagy Z., Baracza M.K. és Szabó N.P. (2019): Pore Pressure Prediction In Pannonian Hydrocarbon Reservoir Systems Using An Integrated Interpretation Approach. Geosciences And Engineering: A Publication Of The University Of Miskolc 7, 12, pp. 105-115.

Swarbrick R.E. (2002): Challenges Of Porosity-Based Pore Pressure Prediction. Society of Exploration Geophysicists. 27, 7, pp. 75-77