Doctoral School of Geosciences

A MICRO- TO LABORATORY-SCALE INVESTIGATION OF PHYSICAL CLOGGING PROCESSES DURING GEOTHERMAL TAIL WATER REINJECTION IN THE PANNONIAN BASIN

Theses of the Doctoral Dissertation

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2024

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Theses Booklet

I. Introduction and Aims of the Study

Geothermal energy is increasingly recognized as essential in sustainable development strategies worldwide. It provides reliable, continuous, and environmentally friendly energy. Unlike solar or wind energy, which are intermittent and weather-dependent, geothermal energy is available 24/7. This availability makes it crucial for meeting base-load power demands. Its consistency and minimal environmental footprint position geothermal energy as a key resource in the transition to a low-carbon economy (Lund & Toth, 2021; Sowiżdżał et al., 2017). The global focus on reducing greenhouse gas emissions and mitigating climate change further highlights the importance of geothermal energy as a renewable resource (Adams et al., 2015; Harrouz et al., 2018).

The Pannonian Basin, located in Central Europe, is one of the most promising regions for geothermal energy exploitation. The basin is characterized by favorable geothermal conditions, including a high geothermal gradient and significant heat flow densities. These features make the basin ideal for geothermal energy production (Dövényi & Horváth, 1988; Kovács et al., 2007). The basin's geological history has been shaped by complex tectonic interactions and sedimentary processes. This history has resulted in extensive sedimentary deposits, primarily sandstones, clays, and marls. These formations, particularly those within the Dunántúl Group (DG), are known for their porosity and permeability. These attributes enhance their suitability for geothermal energy production (Horváth et al., 2015; Nádor et al., 2020).

The DG, which comprises the Zagyva and Újfalu Formations, represents a significant geothermal resource within the Pannonian Basin. These formations consist of deltaic and turbiditic sandstones deposited during the Late Miocene. They are crucial aquifers for geothermal energy extraction (Koroncz et al., 2022; Szanyi & Kovács, 2010; Willems et al., 2021). The region's unique geological setting, with its high geothermal gradients and heat flow densities, further boosts its geothermal potential. The geothermal gradient in the Pannonian Basin, which ranges from 45 to 50 °C per kilometer, is among the highest in Europe. This makes the basin particularly attractive for geothermal development (Lenkey et al., 2021; Szanyi et al., 2021).

Despite the promising geothermal potential of the Pannonian Basin, the sustainable exploitation of these resources faces significant challenges. One of the primary issues is the reinjection of geothermal fluids into the reservoir after heat extraction. Reinjection is critical for geothermal energy production. It helps maintain reservoir pressure, which is essential for the long-term sustainability of the system (Choudhary et al., 2021; Tut Haklıdır, 2020). However, reinjection processes can be hampered by clogging, which can severely reduce the efficiency of geothermal wells. In extreme cases, it can lead to the premature shutdown of wells (Bálint & Szanyi, 2015; Szanyi & Kovács, 2010).

Clogging in geothermal reservoirs is a complex issue. It is influenced by various physical, chemical, and biological factors. Physical clogging, the primary focus of this dissertation, involves the reduction in permeability due to the accumulation of suspended particles, fines migration, and partially mineral precipitation within the reservoir rock (Haonan et al., 2022a; 2022b; Li et al., 2021).

This process is particularly problematic in sandstone formations, where the pore structure and connectivity play critical roles in fluid flow and heat transfer efficiency (Xia et al., 2023; Yu et al., 2022). When particles accumulate in the pores, permeability decreases significantly. This reduction makes it challenging to reinject geothermal fluids at the desired rates (Mustapic et al., 2018; Szanyi et al., 2015). In addition to particles in the reinjection fluid, this reduction in permeability is compounded by chemical interactions between injected fluids and reservoir minerals, leading to further clogging due to mineral precipitation (Markó et al., 2021). Biological clogging caused by microbial activity, though less common, can also exacerbate this problem (Osvald et al., 2017).

Understanding the mechanisms that lead to clogging is crucial for developing effective strategies to mitigate this issue and ensure the sustainable operation of geothermal systems. This is essential for maximizing the efficiency and longevity of geothermal operations (Chai et al., 2022; Liu et al., 2022; Stober & Bucher, 2021).

My PhD research investigates the physical clogging processes during geothermal fluid reinjection in the sandstone formations of the Pannonian Basin. It integrates micro-scale and laboratory-scale investigations to uncover the mechanisms behind clogging, combining traditional petrophysical methods with advanced imaging techniques for a comprehensive assessment of reservoir properties. Particular attention is given to the integration of high-resolution X-ray micro-Computed Tomography (μ-CT) imaging with Digital Rock Physics (DRP) simulations, which allow for a detailed examination of pore structures and their influence on clogging behavior (Halisch et al., 2016; Linden et al., 2015; Schmitt et al., 2016). One of the key methodologies involves applying μ-CT to characterize pore structures in the sandstone formation. Additionally, an experimental design is developed to validate setups that simulate in-situ geothermal conditions. The research also models fluid flow and particle transport within the reservoirs using digital simulations. The ultimate goal is to develop strategies that mitigate clogging, optimize geothermal production, and ensure the sustainability of energy resources in the Pannonian Basin.

The samples used in this research were categorized into four distinct groups based on their actual field performance and experimental relevance: Poor Reinjection Samples, Good Porosity and Permeability Samples with Clogging Issues, Good Reinjection Samples, and Artificial and Digital Samples. These categories offer a comprehensive framework for understanding the variability in reinjection success across the Pannonian Basin's sandstone formations. By examining both natural and artificially manufactured samples, this research provides insights into the mechanisms of clogging and helps develop targeted strategies for reinjection processes, ensuring the sustainable production of geothermal energy in the region.

II. Applied Methods

A combination of advanced imaging techniques, laboratory experiments, and digital simulations was utilized to explore these processes of physical clogging in detail.

The primary technique employed was Micro-Computer Tomography (μ-CT) imaging, which provided high-resolution images of the internal pore structures of sandstone samples. These samples were meticulously prepared and scanned at varying resolutions, ranging from 5 μm to 1 μm, to capture both broader pore networks and the finer details of the microstructures. The μ-CT images were first analyzed to determine the optimal scanning resolution for subsequent scans in the study. These scans produced detailed three-dimensional images that were analyzed to assess the distribution and connectivity of the pore spaces within the sandstone. This analysis was crucial for understanding how these microstructures influence fluid flow and contribute to clogging during the reinjection of geothermal fluids. By processing these images with Avizo, (2019) software, it was possible to quantify key parameters such as porosity, permeability, pore sizes, and pore throat size, providing essential insights into the microstructural characteristics of the formation.

In addition, techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) were utilized to analyze the mineralogical composition of the natural sandstone samples, offering a deeper understanding of the materials being studied.

Laboratory simulations were then conducted using core flooding experiments to replicate the in-situ geothermal environment. These experiments, performed on both artificial and natural core samples, allowed for the observation of clogging locations. By monitoring pressure changes as fluids—mimicking geothermal brines—were injected at controlled flow rates, these experiments provided direct evidence of clogging mechanisms within the pore spaces. The clogged cores were subsequently examined using μ-CT imaging, revealing specific locations where clogging occurred.

Following the laboratory simulations, DRP simulations were employed to further investigate and validate the laboratory findings. These digital simulations utilized the μ-CT images of both artificial and natural sandstone samples to create highly accurate digital models. By incorporating parameters such as fluid viscosity, particle size distribution, particle concentration, and injection pressure, the DRP simulations successfully replicated the clogging phenomena observed in the laboratory tests. The use of DRP simulations, especially when validated against experimental data, was instrumental in exploring the fluid flow and particle transport within the complex pore networks (Linden et al., 2018). The simulations highlighted how specific pore-scale features, such as pore throat size and connectivity, directly influence the likelihood and severity of clogging (Washburn, 1921).

The methodologies employed in this research provided a wider framework for understanding the complex interactions that lead to clogging during geothermal fluid reinjection. By combining cutting-edge imaging techniques, controlled laboratory experiments, detailed characterization methods, and advanced digital simulations, this study represents a significant initial step toward addressing one of the key challenges in geothermal energy production. The insights gained from this research are expected to inform the next level of research development, leading to more effective and sustainable geothermal operations not only in the Pannonian Basin but also in other geothermal reservoirs worldwide.

III. New Scientific Results

Through the integration of digital rock and traditional petrophysical methods, the following findings have been arrived at.

T1: µ-CT imaging showed that a 2 µm resolution effectively characterizes medium to coarse-grained sandstones, favorable for reinjection, while fine-grained sandstones require higher than 1 µm resolution to resolve their microstructures.

The use of µ-CT imaging at various resolutions (5 µm, 2 µm, and 1 µm) provided a comprehensive understanding of the DG sandstone's pore networks. The study found that a 2 µm resolution was particularly effective in characterizing medium to coarse-grained sandstones, which are more favorable for GTWR due to their higher permeability and porosity. However, the research also revealed that fine-grained sandstones, with lower permeability and pore connectivity, are less suitable for reinjection and require resolutions higher than 1 µm to adequately resolve their microstructures. The findings highlight the critical role of resolution in accurately assessing pore structures, with medium to coarse-grained sandstones showing better fluid pathways, whereas fine-grained sandstones demonstrate significant limitations, highlighting the need for tailored imaging strategies in reservoir characterization.

T2: The integration of traditional petrophysical methods with µ-CT imaging revealed that micro-scale structural differences, particularly in pore throat size and connectivity, significantly affect clogging and highlight the need for detailed microstructural analysis in reservoir assessments.

The integration of traditional petrophysical methods, such as helium pycnometry and gas permeability tests, with high-resolution µ-CT imaging provided a detailed understanding of how mineral composition and pore structure influence GTWR. This combined approach revealed that even with similar mineralogical and bulk properties, certain sections may not perform well due to micro-scale structural challenges. For example, despite similar porosity values, some samples showed significant differences in pore throat size and connectivity, leading to varying susceptibility to clogging. The study was performed with clogging particles in the 10–17 µm range, which tended to accumulate in the smaller pore throats, further emphasizing the necessity of incorporating microstructural analysis into reservoir assessments to accurately predict reinjection success.

T3: The study highlights that pore throat and pore sizes, particularly 50 µm and 150–250 µm, are crucial in assessing reservoir suitability, with smaller sizes more prone to clogging, suggesting a shift to detailed microstructural analysis.

The conventional reliance on porosity and permeability as the primary indicators of a reservoir rock's suitability for reinjection has been challenged. Using high-resolution µ-CT imaging, the research revealed that the size and distribution of pores and pore throats are more significant in determining the rock's susceptibility to clogging. Specifically, pore throats around 50 µm and pore sizes ranging from 150–250 µm are associated with better fluid flow and lower clogging risk, while smaller pore throats, approximately 25 µm, and pore sizes around 100 µm are more prone to particle entrapment, leading to a rapid decline in permeability and overall efficiency. These pores and pore throats can be clogged by clays and loose/brittle grains already present in the reservoir, in addition to particles carried by the reinjection fluid and various chemical reactions taking place. This reevaluation calls for a shift in how reservoir suitability is assessed, emphasizing the need for detailed analysis of micro characteristics.

T4: Experimental core flooding and digital simulations revealed that particles cause clogging in pore throats, with artificial samples showing unexpected permeability increases, stressing the need for improvements to better replicate natural sandstone behavior.

Experimental core flooding and digital simulations provided insights into the mechanisms of physical clogging during GTWR. Core flooding experiments demonstrated that fine particles, either within the reinjected fluid or dislodged from the rock, migrate through pore spaces and accumulate in pore throats, leading to blockages. In addition to the lab experiments, digital rock simulations showed that, clogging predominantly occurs as a filter cake near the fluid entry point, severely restricting flow. While artificial samples were invaluable in early-stage testing due to their availability, affordability, and consistency, they exhibited significant limitations. The unexpected permeability increase of approximately 15% in artificial samples during initial testing, compared to the 5% decrease typically observed in natural samples under similar conditions, highlights the need to improve artificial samples to better mimic natural sandstone behavior, ensuring that they can accurately replicate the persistent and irreversible clogging seen in natural sandstone.

T5: The study demonstrated that digital samples can effectively replicate physical core behavior, enabling more extensive geothermal research, while recognizing that the variability in pore structures across the DG makes a one-size-fits-all approach to fluid reinjection unviable.

The study demonstrated that digital samples could effectively replicate the behavior of physical core samples, addressing the challenge of limited core availability in the Pannonian Basin. This capability is crucial for future research and operational planning, enabling more extensive studies, using digital methodologies and reducing dependency on physical core samples. In this case, drilling chips can be scanned to produce digital replicas. Digital simulations combined with experimental data provided a robust framework for understanding the spatial distribution of clogging within geothermal reservoirs. Notably, the study employed systematic DRP simulations for the first time to analyze clogging. However, it is important to note that a one-size-fits-all approach to GTWR is unlikely to be effective due to the variability in pore structures across the DG.

IV. Challenges and Recommendations

A significant challenge in my research was the limited availability of core samples, essential for studying reservoir properties and optimizing geothermal energy production. This scarcity restricted the number of lab experiments conducted.

To address this, digital samples created through μ-CT imaging were used as a complementary approach. These digital samples provided valuable insights into pore structures and fluid flow, but they also highlighted limitations, particularly in simulating chemical reactions and complex physical processes. Despite these challenges, digital samples remain a useful tool, especially for preliminary studies when physical samples are unavailable. Ongoing research is focused on improving these models.

I recommend that Hungarian authorities and stakeholders enhance support for geothermal research by increasing access to core samples and funding coring stages in exploration projects. Establishing a national repository for core samples, alongside the existing drill chips repository, would ensure systematic access for ongoing and future research.

Additionally, investment in digital laboratories is crucial. This includes acquiring high-resolution μ-CT scanners, advanced software, and workstations to enhance the accuracy of digital samples. These efforts would help mitigate physical core shortages, expand research capabilities, and significantly advance geothermal development, supporting Hungary's sustainable energy goals.

This research sheds light on the micro processes of physical clogging during geothermal fluid reinjection in the Pannonian Basin, emphasizing the critical role of pore throat size and connectivity. By integrating advanced imaging and simulations, I challenge traditional assumptions and open a new chapter in investigating clogging mechanisms within the basin. My research is not a closed story; we have just opened "the book on reinjection." The evolution of digital simulations offers a promising avenue for advancing our understanding of reinjection!

V. DATA AVAILABILITY

The μ-CT data utilized in this study are publicly accessible on the Digital Rocks Portal, with direct links provided via the respective article DOIs for convenient access.

VI. References

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VII. List of Publications

Rita Njeru MTMT ID: 10069623

VII.1. Articles Published and Used in the PhD Dissertation

Njeru, R. M., Sofyan, A., Halisch, M., Kóbor, B., & Szanyi, J. (2024). Optimizing Micro-CT Resolution for Geothermal Reservoir Characterization in the Pannonian Basin. *Energies*, 17(13), 3081. https://doi.org/10.3390/en17133081

Scimago Journal Rank in 2024: Q2 - Impact Factor in 2024: 3.0

Njeru, R. M., Halisch, M., & Szanyi, J. (2024). Micro-scale investigation of the pore network of sandstone in the Pannonian Basin to improve geothermal energy development. *Geothermics*, *122*. https://doi.org/10.1016/j.geothermics.2024.103071

Scimago Journal Rank in 2024: Q2 - Impact Factor in 2024: 3.

Njeru, R. M., Halisch, M., Jacob, A., Weber, A., Koroncz, P., Fedor, F., & Szanyi, J. (2024). A joint methodical case study for understanding severe formation clogging processes within a highly utilized geothermal reservoir in the Pannonian Basin of Hungary. *International Symposium of the Society of Core Analysts*. (In Press) *E3S Web of Conferences, 2024*

Scimago Journal Rank in 2024: Q1 – H-Index in 2024: 39

VII.2. Other Publications

Sofyan, A., Syafira, W., Szanyi, J., Suranta, B. Y., & **Njeru, R.M** (2023). Determination of scaling zone and scaling type in slotted liner based on the fluid flow pattern in the geothermal well "X." *International Journal of Renewable Energy Research*, 13(1), 276-286.

VII.3. Conference Abstracts/Proceedings

Njeru R. M.., Halisch, M., Jacob, A., Weber, A., Koroncz, P., Fedor, F., & Szanyi, J. (2024). A joint methodical case study for understanding severe formation clogging processes within a highly utilized geothermal reservoir in the Pannonian Basin of Hungary. *37th International Symposium of the Society of Core Analysts* Fredericton-Canada.

Njeru R.M., Sofyan A., Geretovszky Z., Vajda B., Kóbor B., Medgyes T., Halisch M., Szanyi J. (2024). 3D Printing of Late Miocene Sandstone for Laboratory-Based Physical Simulation of Reinjection Clogging *Kenya Geothermal Congress (KGC 2024*) Nairobi-Kenya

Njeru, R.M., Koroncz, P., Halisch, M., Jacob, A., Kóbor, B., & Szanyi, J. (2024). Impact of injection-induced physical clogging on porosity in porous geothermal reservoir. *15th European Geothermal PhD Days (EGPD 2024)*, TU Delft-Neatherlands.

Njeru, R.M., Koroncz, P., Halisch, M., & Szanyi, J. (2023). Pore dynamics and clogging in geothermal reinjection: Insights from natural and lab-manufactured Miocene sandstone *German Geothermal Congress (Der Geothermie Kongress – DGK)*. Essen-Germany

Njeru, R.M., Koroncz, P., & Szanyi, J. (2023). Experimental setup for investigating particle behavior and flow dynamics during core flooding. *13th Kőzettani és Geokémiai Vándorgyűlés* Szekszárd-Hungary

Njeru, R.M., (2023). Successes and challenges for 3-D printing of complex pore microstructures intended for laboratory scale flooding experiments. *14th European Geothermal PhD Days* (EGPD 2023), Glasgow-United Kingdom.

Njeru, R.M., Halisch, M., & Szanyi, J. (2023). Using digital rock technology for pore scale investigation for the success of geothermal fluid reinjection. *International Conference on Emerging Science and Engineering Technologies (ICESET-23), Muscat-Oman.*

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Njeru, R. M., Halisch, M., & Szanyi, J. (2022) Pore Network Modelling. *13th European Geothermal PhD Days* (EGPD 2022), Aachen-Germany.

VIII.1. Co-authors' Declaration

We, the co-author of the publication "**Njeru, R. M**., Sofyan, A., Halisch, M., Kóbor, B., & Szanyi, J. (2024). Optimizing Micro-CT Resolution for Geothermal Reservoir Characterization in the Pannonian Basin. *Energies*, 17(13), 3081. https://doi.org/10.3390/en17133081" officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and was not or will not be used in the past or in the future, respectively, for the purpose of acquiring an academic degree or title.

Date: Szeged (Hungary), 6th September, 2024

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VIII.2. Co-authors' Declaration

We, the co-author of the publication "**Njeru, R. M.**, Halisch, M., & Szanyi, J. (2024). Micro-scale investigation of the pore network of sandstone in the Pannonian Basin to improve geothermal energy development. *Geothermics*, *122*. https://doi.org/10.1016/j.geothermics.2024.103071" officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and was not or will not be used in the past or in the future, respectively, for the purpose of acquiring an academic degree or title.

Date: Szeged (Hungary), 6th September, 2024

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VIII.3. Co-authors' Declaration

We, the co-author of the publication "**Njeru, R. M**., Halisch, M., Jacob, A., Weber, A., Koroncz, P., Fedor, F., & Szanyi, J. (2024). A joint methodical case study for understanding severe formation clogging processes within a highly utilized geothermal reservoir in the Pannonian Basin of Hungary. *International Symposium of the Society of Core Analysts. E3S Web of Conferences, 2024*." (in Press) officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and was not or will not be used in the past or in the future, respectively, for the purpose of acquiring an academic degree or title.

Date: Szeged (Hungary), 6th September, 2024

Name and Signature of the co-authors

Matthias Halisch *(Hannover – Germany)*

Arne Jacob *(Kaiserslautern - Germany)*

Andreas Weber *(Kaiserslautern - Germany)*

Péter Koroncz *(Pécs - Hungary)*

Ferenc Fedor *(Pécs -Hungary)*

János Szanyi *(Szeged - Hungary)*

IX. DECLARATION OF THE SUPERVISOR

I, **János Szanyi**, hereby confirm that the content of the dissertation titled "*A Micro- to Laboratory-Scale Investigation of Physical Clogging Processes during Geothermal Tail Water Reinjection in the Pannonian Basin*" is based on the independent work of **Rita Mwendia Njeru**, the doctoral candidate. Rita has made a decisive contribution to the results presented in this dissertation through her independent and creative research efforts. I consider the entire dissertation to be of high academic and professional quality, and I fully support its submission for review and acceptance.

Szeged (Hungary), 6th September, 2024

Dr. János Szanyi,
PhD Supervisor

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Date: August 8, 2024

To whom it may concern

I hereby confirm that the conference paper (SCA2024-1014, "A joint methodical case study for understanding severe formation clogging processes within a highly utilized geothermal reservoir in the Pannonian Basin of Hungary") submitted by Ms. Rita Mwendia Njeru for the SCA Annual Meeting 2024 has undergone a rigorous peer-review process. The paper was evaluated by two experts in the field, ensuring the highest standards of academic and scientific integrity.

The reviewers provided thorough evaluations, and their feedback was instrumental in refining and improving the quality of the paper. The acceptance of this paper reflects the valuable contribution of Ms. Njeru's research to the field of core analysis.

Should you require any further information or documentation regarding the review process, please do not hesitate to contact me.

Thank you for your attention to this matter.

Sincerely,

M Young

Melanie Young
SCA Executive Director
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