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Evaluating the Efficiency of High Temperature Preformed Particle Gels in Sealing Fractures within Granite-Based Enhanced Geothermal Systems: A Preliminary Study

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ABSTRACT

Mitigating short-circuiting phenomena in Enhanced Geothermal Systems (EGS) holds pivotal significance for optimal heat extraction. The sustainability of EGS is inherently contingent upon the reservoir's ability to yield fluid with the requisite heat for utilization. However, natural and artificial fractures within the reservoir can disrupt the flow of injected water, diverting it from high thermal capacity areas and subsequently impacting production temperatures. Addressing this challenge, polymers have emerged as potential solutions for sealing fractures in EGS reservoirs. This paper delves into the evaluation of a High Temperature Preformed Particle Gels (HT-PPG) in sealing fractures in granite, a predominant rock type in most EGS projects encountered worldwide. The study investigates the potency of HT-PPGs in plugging fractures within a modeled EGS reservoir. Core flooding experiments were conducted on fractured granite models, with variations in HT-PPG swelling ratios and core fracture widths to determine the gel's plugging efficiency. By differing these parameters, crucial metrics – HT-PPG stable injection pressure, water breakthrough pressure, and residual resistance factor are recorded and interpreted. This analysis elucidates the behavior and efficiency of the HT-PPG in sealing fractures, providing valuable insights for practical applications. The findings presented in this study not only contribute to the understanding of fracture sealing mechanisms in granite-based EGS reservoirs, but also offer a pragmatic solution to combat short circulation and channeling issues within EGS reservoirs. This research endeavor holds promise in enhancing the longevity and sustainability of EGS reservoirs by addressing preferential flow pathways, thereby fostering the advancement of geothermal energy technology.

1. INTRODUCTION

As the global community confronts the pressing demands of climate change mitigation and sustainable development, the quest for renewable energy sources has intensified, underscoring the pivotal role of geothermal energy in the evolving energy landscape. Geothermal energy, harnessed from the Earth's internal heat, emerges as a promising avenue for clean, reliable, and sustainable power generation—a compelling alternative to fossil fuel-based sources. At the forefront of geothermal advancements, Enhanced Geothermal Systems (EGS) represent an innovative approach, aiming to unlock geothermal potential in regions traditionally deemed unsuitable for conventional extraction. EGS technology holds the promise of expanding geothermal energy's reach, delving into deeper and hotter subsurface reservoirs, thereby diversifying the global energy mix and reducing dependence on non-renewable resources (MIT et al., 2006). However, the realization of EGS's potential hinges on overcoming intricate challenges inherent to the paradigm, encompassing drilling (Vivas et al., 2020), stimulation (Jia et al., 2022), and methods for assessing heat flow, quantifying geothermal potential, and characterizing reservoirs(Ciriaco et al., 2020; Gyimah et al., 2023a; Gyimah et al., 2023b; Nádor et al., 2020; Sass & Götz, 2012). As technological advancements unfold, the geothermal industry is poised to leverage cutting-edge approaches for a comprehensive exploration of geothermal resources, significantly contributing to the global shift toward cleaner and renewable energy.

A central challenge in EGS operations lies in managing and optimizing subsurface reservoirs, characterized by a complex network of fractures. These fractures, while enhancing reservoir permeability and facilitating fluid flow, introduce complications such as short-circuiting. This phenomenon, where injected water deviates from its intended path, diminishes system performance, jeopardizing long-term productivity and sustainability (Gee et al., 2021; Jelacic et al., 2007; McLean & Espinoza, 2023). In response, research has explored innovative strategies, with polymers emerging as a notable solution (Hamidi et al., 2023; Wang et al., 2023). In this work, we evaluate the effectiveness of high-temperature preformed particle gels (HT-PPG), designed primarily for conformance control in oil reservoirs characterized by elevated temperature conditions (Schuman et al., 2022). HT-PPG is developed from conventional preformed particle gels whose unique rheological properties show potential in sealing fractures and guiding fluid flow, mitigating short-circuiting's adverse effects and enhancing system performance (Bai et al., 2007; Imqam et al., 2016; Seright, 1997; Zhang & Bai, 2011). EGS projects predominantly feature igneous rocks, particularly granite, yet the application of HT-PPGs in granite-based systems remains largely unexplored. This research seeks to bridge this knowledge gap, evaluating HT-PPGs' performance within granite-dominated EGS reservoirs. Through detailed methodology, incorporating core flooding experiments on fractured granite models, the study aims to investigate the dynamics between HT-PPGs and granite fractures, offering insights that could reshape EGS reservoir management and heat harvesting temperatures. The findings hold implications for the future trajectory of geothermal energy technology, catalyzing innovations and contributing to the broader discourse on renewable energy solutions, affirming geothermal energy's potential role in a sustainable and inclusive energy future.

2. METHODOLOGY AND MATERIALS

2.1 Materials

High Temperature Preformed Particle Gel (HT-PPG): The HT-PPG, an enhancement of our prior formulation for geothermal applications, underwent modifications (Salunkhe et al., 2021). The gel was dried, crushed, and sieved to obtain different particle size ranges. It was then swelled in 2% KCl. **Figure 1** shows the dried and swollen particle gels used in this study.

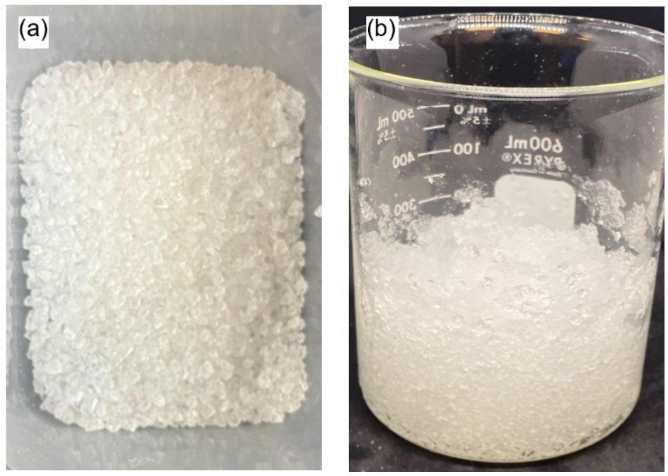

Figure 1: (a) Dry HT-PPG particles (0.500-1.000 mm) (b) 1:10 swollen HT-PPG particles in 2% KCl

Fractured Granite Core Model: Each red granite core, initially 2-inch cylindrical cores, underwent preparation to establish the desired fracture characteristics. Cores were longitudinally divided into two symmetrical halves, facilitating the creation of distinct fracture geometries as shown in **Figure 2**. To simulate varying fracture conductivities, core halves were reassembled using stainless steel strips and an appropriate adhesive with distinct widths: 0.50 mm, 0.77 mm, and 1.00 mm. Subsequently, to prevent leakage and maintain experimental integrity, assembled cores were enveloped with Teflon sheets, serving as an impermeable barrier. Two calculations were used in calculating the cores' permeabilities: **Equation 1** for initial permeability and **Equation 2** for permeability after water breakthrough.

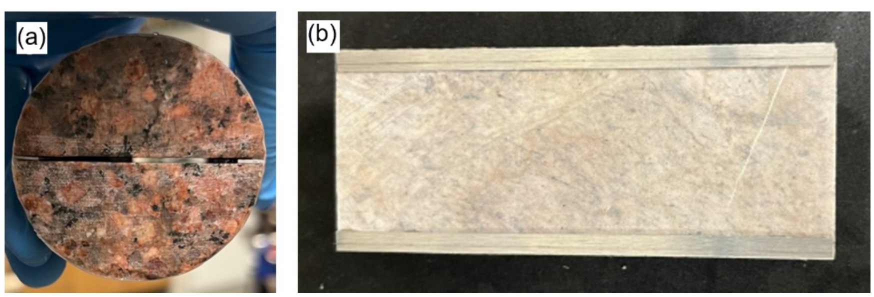

Figure 2: Fractured granite core model (a) cross-sectional area of the core; (b) fracture surface showing the metallic strips

$$K_b = \frac{b^2}{12} \quad (1)$$

where K_b is the fracture permeability before HT-PPG injection (mD); and b, the fracture aperture (mm)

$$K_a = \frac{Q \cdot \mu \cdot L}{\Delta P \cdot A_f} \quad (2)$$

where Ka is the fracture permeability after water breakthrough (mD); Q is flow rate (mL/sec); μ is the brine viscosity (cp); L is the fracture length in the direction of fluid flow (cm); ΔP is injection pressure (atm); and A_f is the cross-sectional area of the fracture (cm^2)

Table 1: Core flooding experimental design

Experiment №	Particle Size (mm)	Swelling Ratio	Fracture Width (mm)
1	0.250-0.500	1:10	0.50
2	0.250-0.500	1:18	0.50
3	0.250-0.500	1:30	0.50
4	0.500-1.000	1:10	0.50
5	0.500-1.000	1:10	0.77
6	0.500-1.000	1:10	1.00

An overview of the experimental design investigating swelling ratio and fracture width effects on HT-PPGs in granite cores is highlighted in **Table 1**. This structured approach aims to investigate relationships and trade-offs, guiding optimized gel deployment for EGS preferential flow control. Experiments are categorized systematically, enabling a clear framework for result analysis. Experiments 1-3 assess swelling ratio impact on gel rheology and interaction dynamics. By varying swelling ratio, these experiments seek optimal conditions for maximizing gel performance within geothermal reservoirs. Experiments 4-6 address fracture width influence on fluid flow dynamics and geothermal energy extraction efficiency. Varying fracture width clarifies connections between fracture geometry and HT-PPG performance, guiding reservoir engineering for specific fracture characteristics.

2.2 Experimental Setup and Procedure

Coreflooding Test: **Figure 3** depicts the experimental setup which includes an ISCO pump, two accumulators, a hassler-type coreholder, and a pressure transducer interfaced with a computer for accurate data acquisition and analysis.

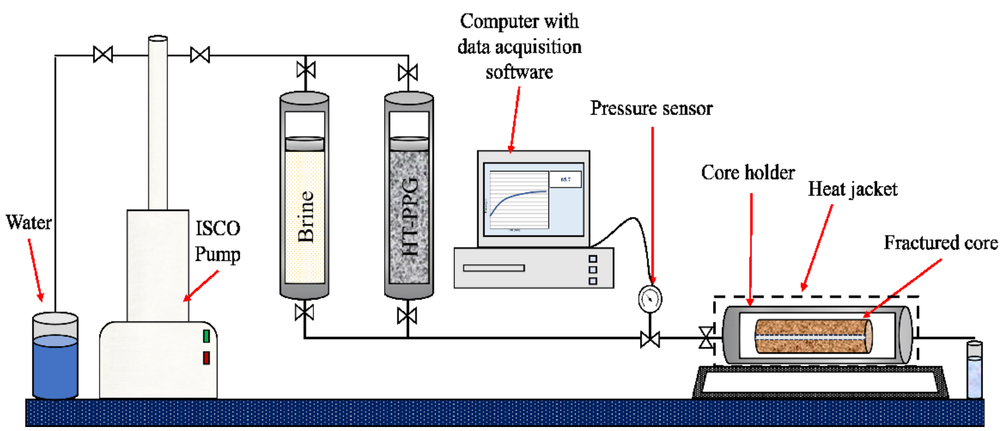

Figure 3: Experimental setup

HT-PPG Injection: In the experimental procedure, the fractured granite model is secured within the core holder, and a confining pressure of 1200 psi simulates subsurface conditions. Subsequently, the core is flooded with 2% KCl after which the swollen HT-PPG, initially within the accumulator, is injected into the fracture to seal it at a flow rate of 1.0 cc/min. Injection continues until stable pressure, monitored by the acquisition software, is achieved. To maintain subsequent test integrity, the core holder's inlet and outlet are purged of any residual gels that might affect water breakthrough test results.

Post-Water Flooding: The gel's resilience under varying pressures, identifying the threshold where sealing diminishes, leading to channel formation is determined. Brine, introduced at 0.10 cc/min, enables determination of water breakthrough pressure—a critical parameter indicating the gel's sealing capacity. Following breakthrough evaluation, pressure response after brine displaces the gel is monitored. This aids in quantifying the Residual Resistance Factor (F_{rr}), calculated as the ratio of permeability before gel injection to the permeability after gel injection (following breakthrough). The experiment employs alternating flow rates (0.10, 0.25, 0.50, and 1.00 cc/min) over 3 to 6 cycles until pressure readings stabilizes for calculating F_{rr}.

3. RESULTS AND DISCUSSION

3.1 Coreflooding Experiment Results:

Swelling Ratio Effect: The result obtained for gel onset and stable injection pressures as a function of varying swelling ratio is shown in **Figure 4**. Both indicate ascending gradients with reduced swelling ratio. The gel injection pressure recorded were 191.81, 58.11, and 29.01 psi/ft for swelling ratios of 1/10, 1/18, and 1/30 respectively. The HT-PPG with a 1/10 swelling ratio exhibits robust gel strength, requiring high pressure for effective placement within the fracture. Conversely, the HT-PPG with a 1/30 swelling ratio is characterized by a more relaxed gel structure, leading to lower onset and injection pressures. This same trend is notable in the water breakthrough pressure and F_{rr} results as indicated in **Figures 5a** and **5b**. The gel can reduce fracture permeability by up to 10,000 times, significantly affecting fluid flow even after breakthrough. These findings emphasize the gel's potential to alter fracture permeability, influencing fluid flow dynamics within the reservoir.

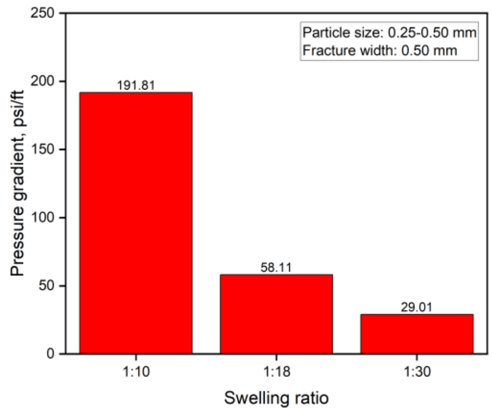

Figure 4: Gel onset and injection pressures for different swelling ratios

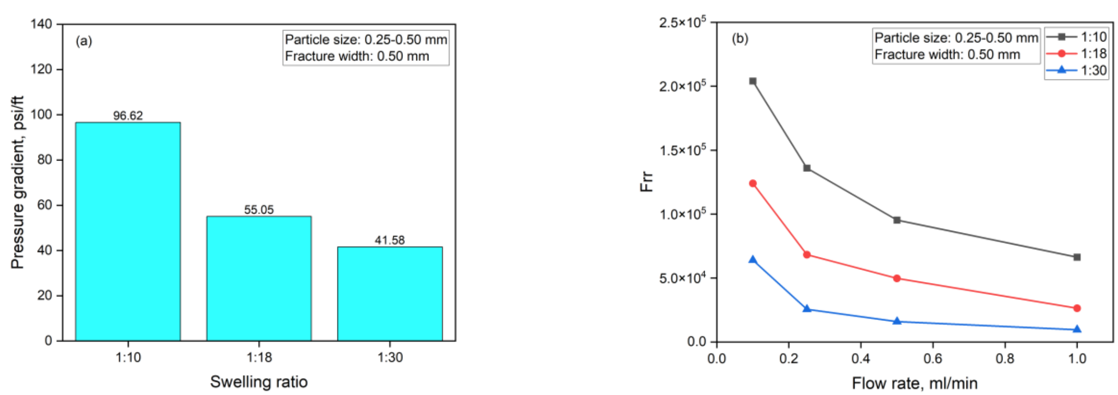

Figure 5: (a) Water breakthrough pressure gradients and (b) F_{rr} for different swelling ratios

Fracture Width Effect: Fracture width significantly influences fluid flow direction, with larger apertures attracting fluid movement and potentially causing short-circuiting, impacting overall heat production temperature. To investigate the impact on the gel's plugging efficiency, various apertures (0.50, 0.77, and 1.00 mm) were designed, maintaining a constant 1/10 HT-PPG swelling ratio and 0.50-1.00 mm particle size. **Figure 6** illustrates sealing pressure gradients across different fracture widths. The particle size-to-fracture width ratio decreases as the width increases from 0.50 mm to 1.00 mm, correlating with a reduction in sealing pressure gradient. Stable sealing pressure gradients were 205.68, 175.42, and 123.10 psi/ft for 0.50, 0.77, and 1.00 mm fracture widths, respectively. Larger fracture widths correspond to lower injection pressure, given constant particle size and swelling ratio. This highlights the relationship between fracture geometry and gel behavior, aligning with established practices in injecting traditional PPGs into fractures (Zhang & Bai, 2011). The similarity stems from gels deforming and dehydrating in smaller fractures thus increasing their concentration during transport, requiring higher pressure drops to counter these effects.

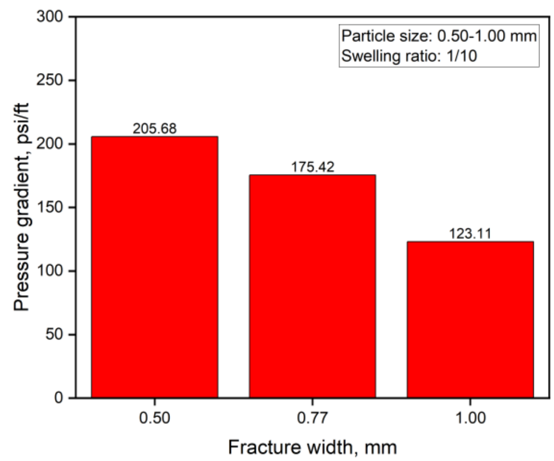

Figure 6: Gel onset and injection pressure gradients in different fracture widths

Figures 7a and **7b** visually illustrate the impact of various fracture widths on brine breakthrough pressure and F_{rr}. The results show that an increase in fracture aperture correlates with a decrease in water breakthrough pressure. The gel demonstrates superior efficiency in sealing smaller width fractures, withstanding higher pressure. Channels formed in the gel at pressure gradients of 187.32, 72.35, and 32.17 psi/ft for the studied widths, as highlighted in **Figure 7a**. Additionally, the plugging efficiency after breakthrough can reach up to 10^6 times, substantially reducing permeability, as shown in **Figure 7b**. The particle size-to-fracture width ratio diminishes with increasing particle size. The selected gel size range (0.500 – 1.000 mm) exhibits optimal packing efficiency in the 0.77 mm fracture width, evident in recorded high F_{rr} values. This underscores the importance of carefully considering the relationship between particle size and fracture width to enhance gel packing efficiency and, consequently, performance in reducing permeability within EGS reservoirs.

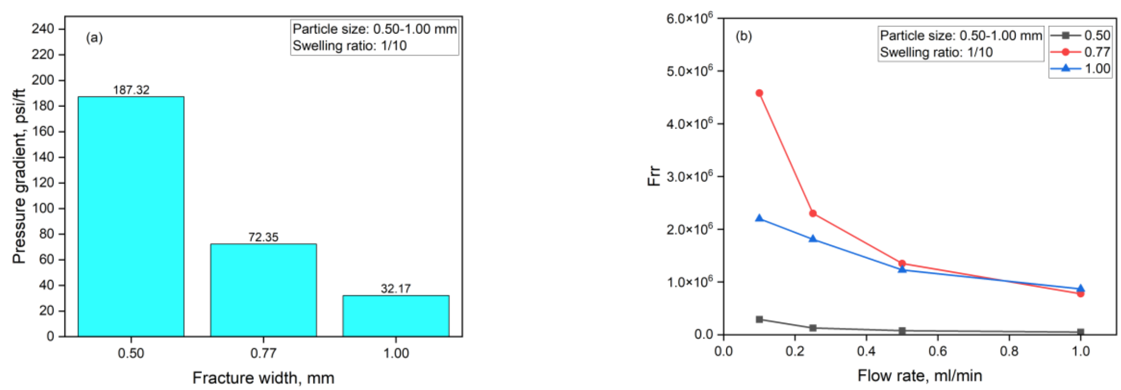

Figure 7: (a) Water breakthrough pressure gradients and (b) F_{rr} for different fracture widths

4. CONCLUSION

In evaluating High-Temperature Preformed Particle Gels (HT-PPG) for mitigating preferential fluid flow in geothermal systems, this study analyzed gel injection and plugging performance, with emphasis on particle size, swelling ratio, and core fracture width. Our findings indicate that the gel can be easily injected into fractures characterized by high plugging efficiencies. The recorded water breakthrough pressure gradients highlight the effectiveness of the gels to resist fluid flow with fracture permeability reduction reaching more than 99%. Additionally, the gel offers opposition to fluid flow even after channels are created which is an exceptional characteristic. The study underscores the gel's potential for addressing flow challenges in geothermal reservoirs effectively.

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REFERENCES

Bai, B., Liu, Y., Liu, H., Wang, Z., & You, C. (2007). Preformed Particle Gel for Conformance Control: Factors Affecting Its Properties and Applications. *Proceedings - SPE/DOE Symposium on Improved Oil Recovery*.

Ciriaco, A. E., Zarrouk, S. J., & Zakeri, G. (2020). Geothermal resource and reserve assessment methodology: Overview, analysis and future directions. In *Renewable and Sustainable Energy Reviews* (Vol. 119). Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109515

Gee, B., Gracie, R., & Dusseault, M. B. (2021). Multiscale short-circuiting mechanisms in multiple fracture enhanced geothermal systems. *Geothermics*, *94*. https://doi.org/10.1016/j.geothermics.2021.102094

Gyimah, E., Metwally, M., Tomomewo, O., Hurtado, J., Alamooti, M., & Gosnold, W. (2023). Geothermal Energy Storage: A Conceptual Assessment of Geologic Thermal Storage Systems in North Dakota. *ARMA*.

Gyimah, E., Tomomewo, O., Vashaghian, S., Uzuegbu, J., Meenakshisundaram, A., Ouadi, H., & Laalam, A. (2023). Heat Flow Study and Reservoir Characterization Approach of the Red River Formation to Quantify Geothermal Potential. *GRC Transactions*.

Hamidi, F., Heras Murcia, D., Carroll, N., Stormont, J., & Taha, M. R. (2023). A New Polymer Nanocomposite for Improving Geothermal Sweep Efficiency. In *GRC Transactions* (Vol. 47).

Imqam, A., Aldalfag, A., Wang, Y., & Bai, B. (2016). Evaluation of Preformed Particle Gels Penetration into Matrix for a Conformance Control Treatment in Partially Open Conduits. *SPE Annual Technical Conference and Exhibition*. http://onepetro.org/SPEATCE/proceedings-pdf/16ATCE/1-16ATCE/D011S018R008/1366670/spe-181545-ms.pdf

Jelacic, A., Kennedy, M., Renner, J., Bruton, C., Blankenship, D., & Nichols, C. (2007). *Enhanced Geothermal Systems Reservoir Management and Operations Workshop Summary Report*.

Jia, Y., Tsang, C. F., Hammar, A., & Niemi, A. (2022). Hydraulic stimulation strategies in enhanced geothermal systems (EGS): a review. In *Geomechanics and Geophysics for Geo-Energy and Geo-Resources* (Vol. 8, Issue 6). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s40948-022-00516-w

Klee, J., Trullenque, G., Ledesert, B. A., Potel, S., Ledésert, B., Hébert, R., Chabani, A., & Genter, A. (2021). Petrographic Analyzes of Fractured Granites used as An Analogue of the Soultz-sous-Forêts Geothermal Reservoir: Noble Hills, CA, USA. *Proceedings World Geothermal Congress*. https://www.researchgate.net/publication/358581050

Lu, Y., Lu, G., Fei, F., Cusini, M., & Bunger, A. P. (2023). Understanding In Situ Stress Complexities in EGS Reservoirs through True-Triaxial Block Fracturing Experiments on High Temperature Analogue Utah FORGE Granites. *GRC Transactions*.

McLean, M. L., & Espinoza, D. N. (2023). Thermal destressing: Implications for short-circuiting in enhanced geothermal systems. *Renewable Energy*, *202*, 736–755. https://doi.org/10.1016/j.renene.2022.11.102

MIT, Tester, J. W., Anderson, B. J., Batchelor, A. S., DiPippo, R., Drake Elisabeth M, Garnish, J., Livesay, B., Moore, M. C., Nichols, K., Petty, S., Toksoz, M. N., & Veatch, R. W. Jnr. (2006). The future of geothermal energy-Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. *US Department of Energy*.

Nádor, A., Sebess-Zilahi, L., Rotár-Szalkai, Á., Gulyás, Á., & Markovic, T. (2020). New methods of geothermal potential assessment in the Pannonian basin. *Geologie En Mijnbouw/Netherlands Journal of Geosciences*. https://doi.org/10.1017/njg.2019.7

Salunkhe, B., Schuman, T., Al Brahim, A., & Bai, B. (2021). Ultra-high temperature resistant preformed particle gels for enhanced oil recovery. *Chemical Engineering Journal*, *426*. https://doi.org/10.1016/j.cej.2021.130712

Sass, I., & Götz, A. E. (2012). Geothermal reservoir characterization: A thermofacies concept. *Terra Nova*, *24*(2), 142–147. https://doi.org/10.1111/j.1365-3121.2011.01048.x

Schuman, T., Salunkhe, B., Al Brahim, A., & Bai, B. (2022). Evaluation of Ultrahigh-Temperature-Resistant Preformed Particle Gels for Conformance Control in North Sea Reservoirs. *Proceedings - SPE Annual Technical Conference and Exhibition*, *3660*. http://onepetro.org/SJ/article-pdf/27/06/3660/3058199/spe-206007-pa.pdf

Seright, R. S. (1997). Use of Preformed Gels for Conformance Control in Fractured Systems. In *SPE Production & Facilities*. http://onepetro.org/PO/article-pdf/12/01/59/2596490/spe-35351-pa.pdf

Vivas, C., Salehi, S., Tuttle, J. D., & Rickard, B. (2020). Challenges and Opportunities of Geothermal Drilling for Renewable Energy Generation. In *GRC Transactions* (Vol. 44).

Wang, D., Ji, Y., Gosnold, W., Alamooti, M., Namie, S., & Oni, O. (2023). Enhanced Sweep Efficiency in EGS Using a Bio-polymer Supplement from Over Fractured Oil/Gas Operations. In *GRC Transactions* (Vol. 47).

Winn, C., Dobson, P., Ulrich, C., Kneafsey, T., Lowry, T. S., Akerley, J., Delwiche, B., Samuel, A., & Bauer, S. (2023). Context and mitigation of lost circulation during geothermal drilling in diverse geologic settings. *Geothermics*, *108*. https://doi.org/10.1016/j.geothermics.2022.102630

Zhang, H., & Bai, B. (2011). Preformed-Particle-Gel Transport Through Open Fractures and Its Effect on Water Flow. In *Journal*. http://onepetro.org/SJ/article-pdf/16/02/388/2106777/spe-129908-pa.pdf/1