

The impact of rock elastic parameters on the hydraulic fracturing process for Enhanced Geothermal Systems (EGS) in Poland

Author:

Rafał Moska, M.Sc.

Supervisor:

Krzysztof Labus, Prof.

Company Supervisor:

Piotr Kasza, Ph.D.

Expanded abstract

Among modern low-emission energy production technologies, Enhanced Geothermal Systems (EGS) demonstrate significant potential (Lu, 2018). These systems are developed within specific rock formations known as Hot Dry Rocks (HDR). Such rocks are typically located at high depths, most commonly below 4000 meters, under high-temperature and high-pressure conditions. They are characterized by extremely low permeability, porosity and minimal amounts of water (Wójcicki et al., 2013). Due to these specific properties, under natural conditions, HDR cannot be exploited for geothermal energy extraction, as their thermal energy cannot be transported to the surface in a technically feasible and economically viable manner. The concept behind EGS is to artificially increase or create hydraulic conductivity within these formations – hence the term "enhanced" in the system's name. The fundamental principle of an EGS-type heat collector involves utilizing the thermal energy stored in HDR formations, accessed through a network of artificially created fractures in the rock mass, which connect injection and production wells. A working fluid is circulated through this system in a closed loop (Tester et al., 2006). It is pumped from the surface under pressure into the injection well, at the target depth, it is heated as it flows through the artificially induced fracture network connecting the injection and production wells. The heated fluid is then transported back to the surface, where its thermal energy is utilized for both electricity and heat generation (Figure 1).

The primary distinguishing feature of EGS compared to conventional geothermal systems is the necessity to artificially enhance formation permeability to hydraulically connect boreholes at the target depth. Industrial practice demonstrates that this is most commonly achieved through hydraulic fracturing (HF), a technique widely employed in the oil and gas industry. The potential for utilizing HDR-type formations for EGS development has been a subject of academic discussion in Poland for over a decade, inspired by analogous projects in Western Europe. Research conducted thus far has focused on assessing the feasibility of employing HDR geological structures in Poland for EGS deployment (Wójcicki et al., 2013), as well as modeling CO₂-based EGS systems (CO₂-EGS) and evaluating their economic and environmental performance (energisers.agh.edu.pl).

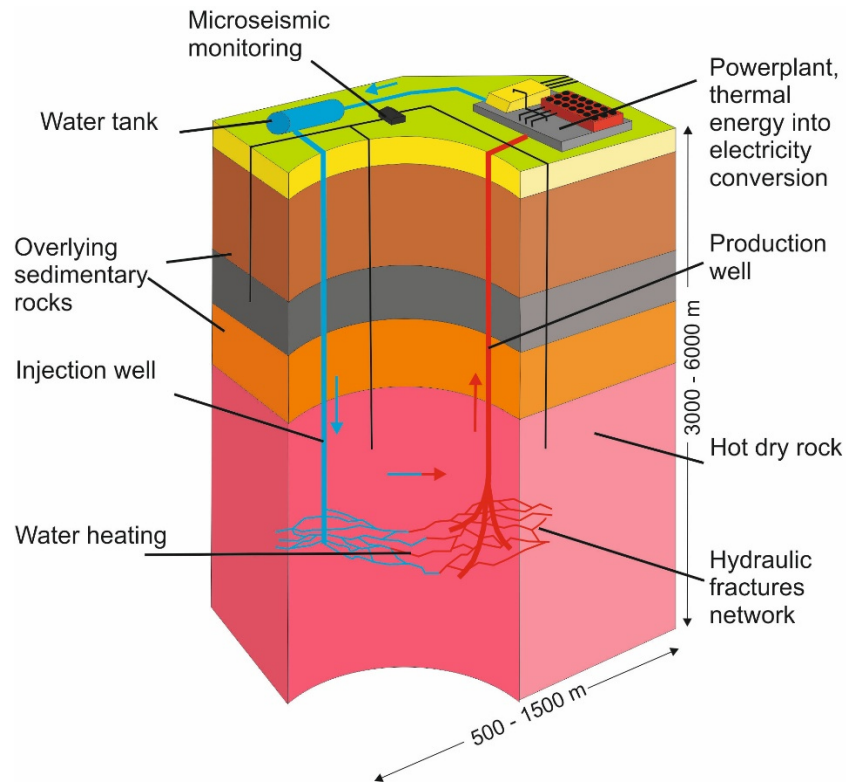


Figure 1. Principle of EGS operation (Moska et al., 2021).

The outcomes of these studies, however, were not directed toward the development of any specific elements of hydraulic fracturing (HF) technology, despite the fact that appropriate selection of these parameters is fundamental to the optimal long-term EGS performance. Moreover, the impact of individual HF technology elements on the geometry of the geothermal reservoir was not analyzed, nor was the influence of the mechanical properties of HDR on the dimensions of the induced fractures. These considerations prompted the author to undertake research on the influence of rock elasticity parameters on the hydraulic fracturing process in EGS, using geologically prospective formations in Poland as case studies. It was assumed, that based on laboratory-determined dynamic elastic properties of rocks, petrophysical data, and *in-situ* stress conditions, the geometry of a fracture induced during a hypothetical hydraulic fracturing treatment can be determined within a geologic structure considered prospective for EGS.

The following research objectives were formulated:

- To determine the influence of elasticity parameters of the rock formation on the fracture geometry during hydraulic fracturing operations, under pressure and temperature conditions typical to prospective EGS development areas in Poland.
- To identify the relations between pressure variability during geomechanical testing and the elastic parameters of the rock;
- To evaluate correlations between parameters obtained via ultrasonic and strength testing methods;

- To refine the methodology for ultrasonic testing of rock samples representative of HDR under high-pressure and high-temperature conditions, preceded by the modification of laboratory equipment to ensure safe operation under such conditions;
- To carry out numerical simulations of fracture geometries in selected Polish regions considered prospective for EGS development;
- To prepare general technological recommendations for HF operations in the analyzed formations.

These objectives were achieved through a comprehensive literature review conducted by the PhD candidate, independently performed laboratory tests on rock samples, and numerical simulations of fracture geometries.

This dissertation was prepared as part of the “Implementation Doctorate” program, 5th edition, in cooperation between the Silesian University of Technology (Politechnika Śląska, PŚ) and the Oil and Gas Institute – National Research Institute (Instytut Nafty i Gazu – Państwowy Instytut Badawczy, INiG-PIB). In accordance with 2020–2025 development strategy, INiG-PIB focuses on expanding services related to renewable-resource-based energy systems, including geothermal energy. The execution of this dissertation addresses the Institute’s need to expand its expertise in unconventional renewable energy technologies, such as Enhanced Geothermal Systems. The outcomes of this work will enhance the Institute’s research capabilities, particularly in the area of mechanical strength testing of deep rock formations and in the design of HF technology components in HDR formations.

The doctoral dissertation is presented in the form of a series of five thematically coherent scientific publications, listed below. The contributions of co-authors to these publications are declared in statements held by the dissertation’s author and the respective co-authors.

- I. **Rafał Moska**, K. Labus, P. Kasza, *Hydraulic Fracturing in Enhanced Geothermal Systems – Field, Tectonic and Rock Mechanics Conditions – A Review*, Energies, Volume 14, 5725, 2021 DOI:10.3390/en14185725 (**IF₂₀₂₁=3.252**)
The PhD candidate contribution amounted to 60% and included: developing the concept of the article, conducting a literature review, preparing the manuscript and creating the visualizations.
- II. **Rafał Moska**, K. Labus, P. Kasza, A. Moska, *Geothermal Potential of Hot Dry Rock in South-East Baltic Basin Counties – A Review*, Energies, Volume 16, 1662, 2023 DOI: 10.3390/en16041662 (**IF₂₀₂₃=3.000**)
The PhD candidate contribution amounted to 60% and included: developing the concept of the article, conducting a literature review, preparing the manuscript, creating the visualizations and overall supervision.
- III. **Rafał Moska**, K. Labus, P. Kasza, *Dynamic Elastic Properties, Petrophysical Parameters and Brittleness of Hot Dry Rocks from Prospective Areas of Central*

Europe, Advances in Geo-Energy Research, Volume 14, 2, 90-105, 2024. DOI: 10.46690/ager.2024.11.03 (IF₂₀₂₄=**9.000**)

The PhD candidate contribution amounted to 80% and included: developing the concept of the article, conducting a literature review and laboratory measurements, developing of the research results, preparing the manuscript, creating the visualizations and overall supervision.

- IV. K. Labus, **Rafał Moska**, M. Labus, *Potential Enhanced Geothermal System in Western Poland – Petrothermal and Geochemical Issues*, Energies, Volume 18, 876, 2025. DOI: 10.3390/en18040876 (IF₂₀₂₅=**3,200**)

The PhD candidate contribution amounted to 50% and included: conducting a literature review and laboratory measurements, edition and correction of the manuscript.

- V. **Rafał Moska**, K. Labus, P. Kasza, *Impact of Rock Elastic Properties on Fracture Geometry in Potential Enhanced Geothermal Systems in Poland*, Energies, Volume 18, 2869, 2025. DOI: 10.3390/en18112869 (IF₂₀₂₅=**3,200**)

The PhD candidate contribution amounted to 80% and included: developing the concept of the article, conducting a literature review, laboratory ultrasonic measurements, and numerical simulations, developing of the research results, preparing the manuscript, creating the visualizations and overall supervision.

Article I presents the results of a literature review encompassing the most critical geological and reservoir conditions, as well as key elements of hydraulic fracturing technology, in the most significant EGS projects carried out worldwide. The reviewed scientific publications and research project reports clearly indicate that hydraulic fracturing is the most commonly used and most effective method for developing geothermal reservoirs in hot dry formations, both sedimentary and igneous.

One of the most important issues related to hydraulic stimulation of HDR formations is the variation in stimulation mechanisms depending on the lithological type of the rock. Sedimentary formations are typically stimulated through a tensile failure mechanism, wherein new, induced fractures propagate perpendicular to the minimum horizontal stress. In contrast, in igneous formations, the primary conduits for fluid flow are pre-existing natural fractures reactivated via a shear-dominated mechanism (hydroshearing).

In Poland, several regions of elevated geothermal potential, characterized by favorable geothermal gradients have been identified. The most prospective areas include, among others, the Karkonosze region, the Gorzów Block, the Szczecin Basin, the Mogilno-Łódź Basin, and the Upper Silesian Block (Figure 2).

The data compiled in this publication enabled the identification of the most promising study areas for further in-depth analysis as part of the doctoral research. It also allowed for the definition of the scope of laboratory investigations presented in articles III and IV, and for the formulation of assumptions for numerical simulations of hydraulic fracturing operations

tailored to the specific geological and reservoir conditions of the identified prospective areas in Poland, as presented in Article V.

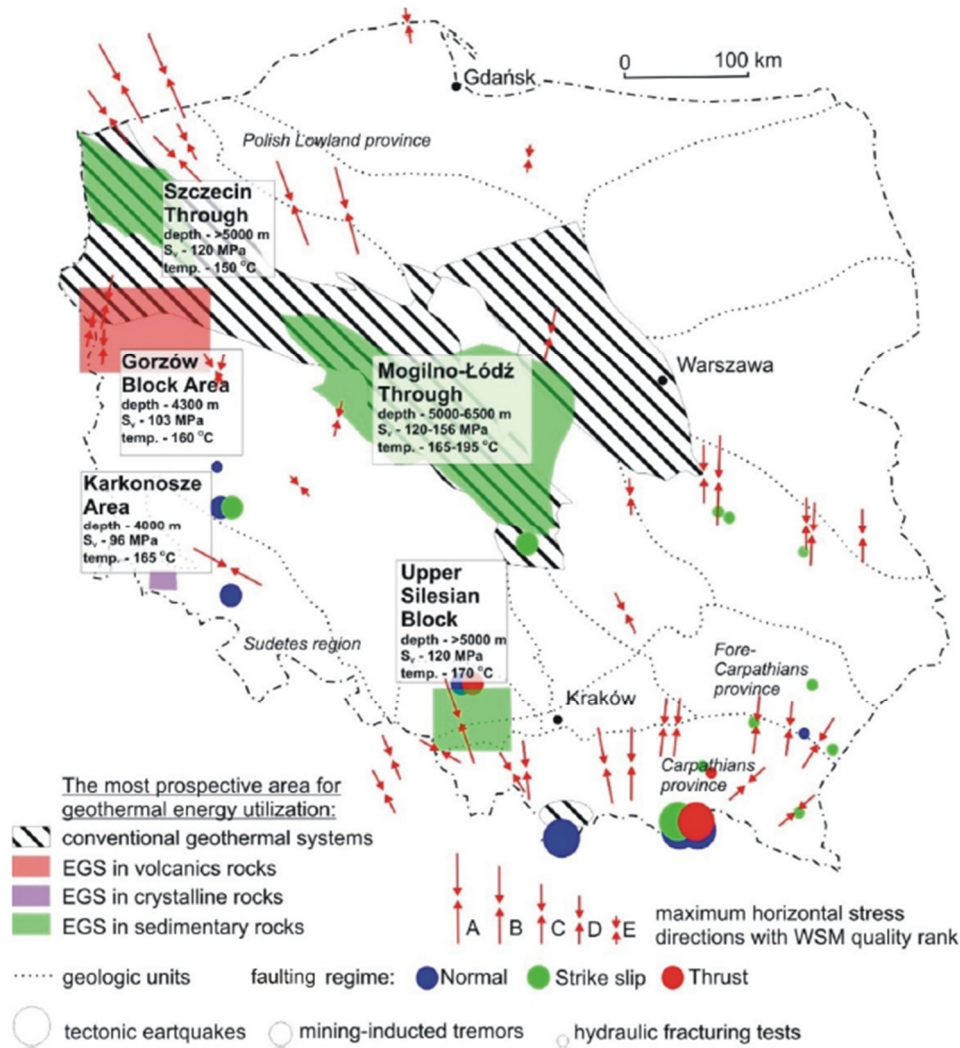


Figure 2: Areas prospective for EGS in Poland (Moska et al., 2021).

Article II complements the literature review by expanding on the topic of prospective areas for EGS technology in Europe, with a focus on the Baltic States, and by comparing the geological conditions in those areas with those in Poland. In the countries characterized in the article: Lithuania, Latvia, and Estonia, located in the southeastern part of the Baltic Basin, the geothermal gradient and heat flow density do not significantly differ from values observed in Western Europe. The HDR potential in these regions is primarily associated with the presence of crystalline basement rocks; however, insufficient understanding of local tectonic settings – particularly the development of natural fracture and fault zones that are crucial for hydraulic stimulation – remains a major barrier to EGS development.

The information and data gathered in Article II enabled the identification of the most promising research areas, which were then analyzed in detail in Articles III, IV, and V.

Article III presents the results of laboratory tests on HDR from selected regions in Poland deemed prospective for EGS. All three analyzed formations – Karkonosze granites,

volcanic rocks from the Gorzów Block, and sandstones from the Mogilno-Łódź Trough – exhibited petrophysical properties consistent with classification as petrothermal rocks suitable for EGS development (Figure 3). Granite samples showed significant variability in elastic properties, depending on hydrothermal alteration. The sandstones demonstrated significantly lower Young's moduli compared to analogous HDR from Western Europe. The mechanical parameters of the volcanic rocks varied depending on their texture and the specific formation from which they were collected.

The brittleness index (BI), regardless of the calculation method used, was found to be high for all analyzed formations (except for the volcanic rocks from the Jeniniec-4 borehole, for which BI values were in the medium range). The article proposes a novel interpretation of the BI for igneous HDR rocks. Lower BI values, particularly when associated with a reduced Young's modulus, may indicate zones of weakened rock mass – typical of tectonically disturbed and/or hydrothermally altered areas – which may serve as primary conduits for fluid flow in EGS following hydraulic stimulation. Therefore, in contrast to sedimentary rocks, reduced BI values in igneous rocks are considered favorable.

The petrophysical, petrographic, and geomechanical parameters obtained in these studies served as input data for FracPro software used in the numerical modeling of fracture geometry, as described in Article V.

Article IV presents the laboratory analyses results of thermal properties of rocks from selected prospective EGS regions in western Poland, as well as estimates of formation temperature changes, cooling extents, and geochemical modeling results of reactions during geothermal energy extraction. The measurements indicate that the Karkonosze granite exhibits high thermal diffusivity and conductivity, making it a strong candidate for EGS development (Table 1). Although the rhyolites from the Gorzów Block showed slightly lower values of these parameters, their high initial temperatures are promising in terms of the long-term viability of potential EGS projects. The geochemical simulations suggest that secondary mineral precipitation – which could impair permeability – is unlikely to occur in the analyzed formations. On the contrary, a simulated increase in porosity could lead to a reduction in hydraulic resistance, which may result in excessive flow rates and, consequently, have a negative impact on overall EGS performance.

Article V presents the results of mechanical strength tests and complementary ultrasonic testing of HDR samples from selected prospective regions in Poland. Based on these data – as well as literature reviews and the findings from Articles I, II, and III – numerical simulations of fracture geometry in HDR formations were conducted. Additionally, the influence of rock elastic parameters on fracture geometry was determined, which constitutes the main scientific objective of the dissertation. A comparison between the static and dynamic Young's moduli of the analyzed rocks revealed significant discrepancies in the granite formation, likely due to hydrothermal heterogeneity. In contrast, the tested sandstones exhibited very similar values for both static and dynamic moduli (Figure 4).

In the case of both formations, the correlation between dynamic and static elastic moduli is well described by a linear model – the coefficients of determination (R^2) are 0.84 for

sandstones and 0.89 for granites. It has also been demonstrated that full saturation of the pore space with water leads to a significant increase in the average dynamic Young's modulus, from 43 to 51 GPa for granites and from 9 to 31 GPa for sandstones. A significant increase in the average Poisson's ratio was observed only in the sandstone formation, rising from 0.17 to 0.31. Hydraulic fracturing simulation in the sandstone formation resulted in an induced fracture with the following average dimensions: fracture half-length – 61 m, fracture height – 81 m, and fracture width – 1.4 cm (Figure 5). In contrast, for the granite formation, the fracture geometry was as follows: half-length – 337 m, height – 160 m, and width – 0.58 cm (Figures 6 and 7).

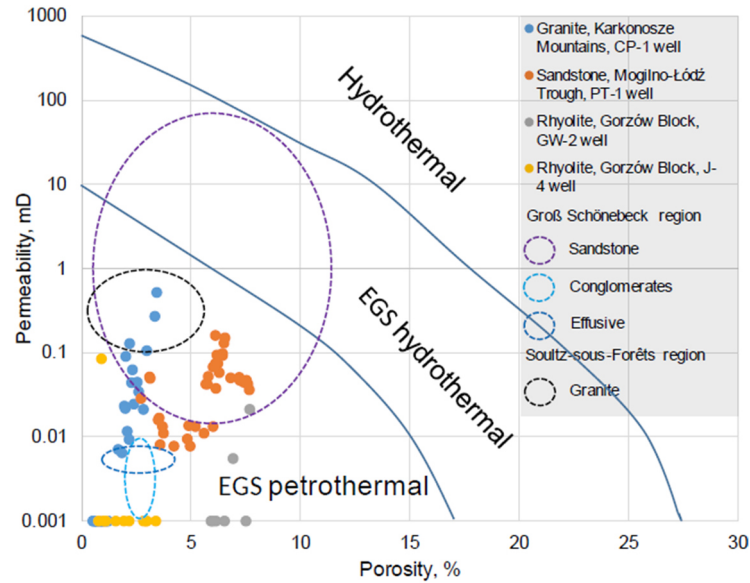


Figure 3: Permeability-porosity-based classification of the analyzed HDR, compared to other European formations (Moska et al., 2024).

Table 1: Selected average thermal parameters of tested HDR (Labus et al., 2025).

Type of the rock, location	Effusivity e , $W \cdot s^{1/2}/m^2/K$	Diffusivity α , m^2/s	Thermal conductivity k , $W/m \cdot K$	Bulk heat capacity c_{ps} , $J/kg \cdot K$
Granite, Karkonosze, CP-1 well	2781,25	$1,78 \times 10^{-6}$	3,70	809,82
Rhyolite, Gorzów Block, GW-2 well	2510,90	$1,53 \times 10^{-6}$	3,10	831,00
Rhyolite, Gorzów Block, J-4 well	2338,39	$1,37 \times 10^{-6}$	2,74	794,39

In both analyzed formations, sensitivity analysis revealed that the impact of Young's modulus on fracture geometry does not exceed a few percent. The influence of this parameter on fracture aperture in sandstones also remains at a few percent, while in granites it reaches several tens of percent. Conversely, the effect of Poisson's ratio on fracture geometry and conductivity in both formations is marginal. However, it is noteworthy that an increase in Young's modulus in the sandstone formation leads to a significant reduction in the embedment phenomenon and to an increase in fracture conductivity by several percent. This may have a considerable impact on the performance of EGS located within such a formation.

Due to the lack of data on the development and characteristics of natural fractures in the granite formation – as well as on their interaction with hydraulically induced fractures – the obtained results should be treated as an approximation. Based on all the research conducted during the doctoral project, technological recommendations have been formulated for hydraulic fracturing operations in selected geologically prospective formations for EGS development in Poland.

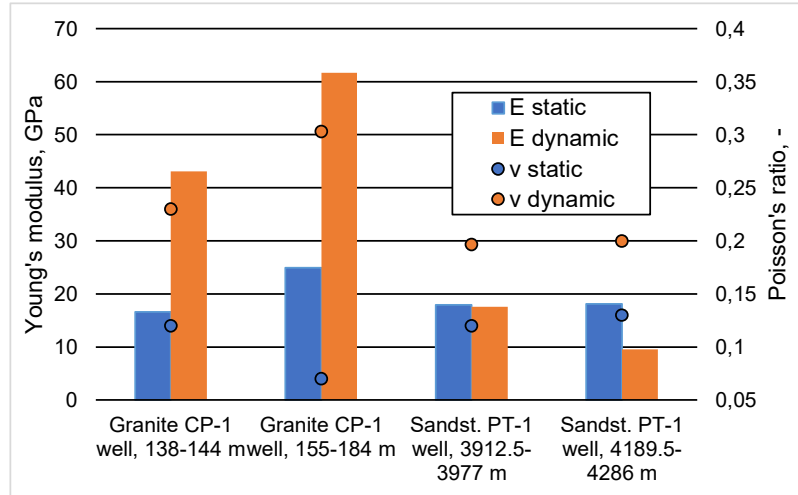


Figure 4: Comparison of the average static and dynamic Young's moduli and Poisson's ratios of dry rock samples from selected prospective HDR areas in Poland (Moska et al., 2025).

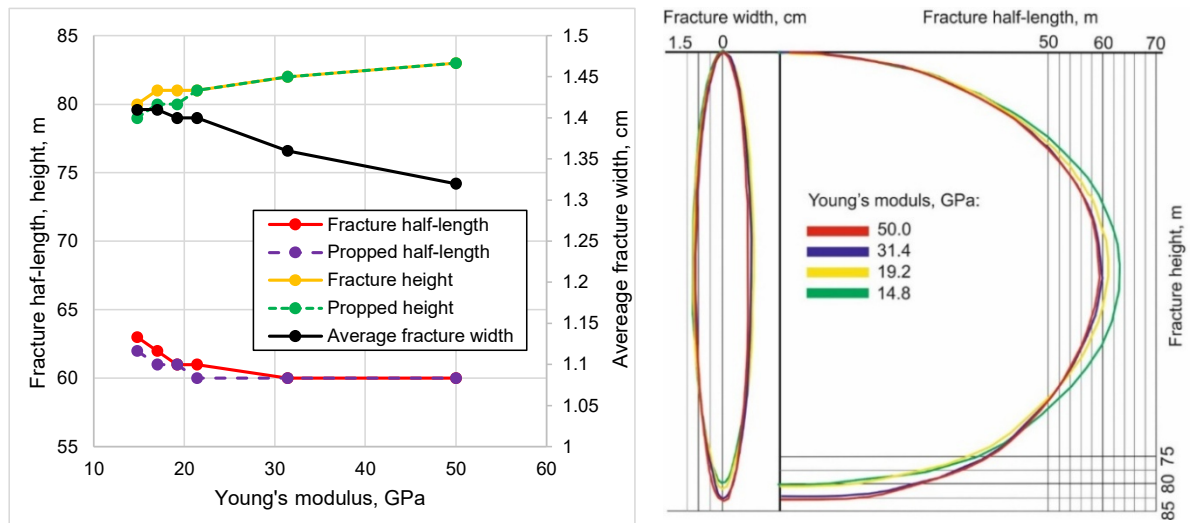


Figure 5: **A** – Variability in the selected fracture geometry parameters as a function of Young's modulus in the Mogilno-Łódź sandstone formation. **B** – Variability in fracture geometry with increasing Young's modulus in the pay zone of the Mogilno-Łódź HDR area (Moska et al., 2025).

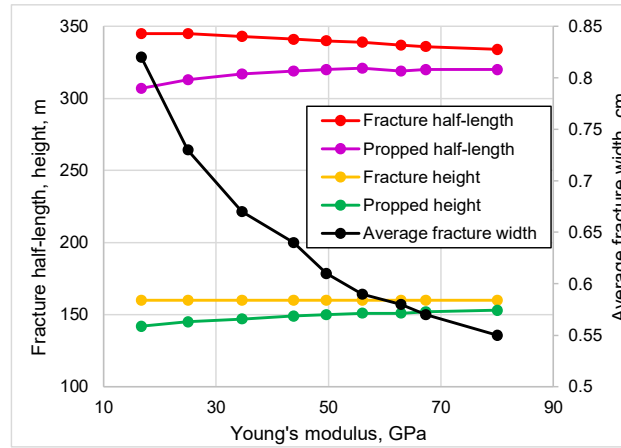


Figure 6: Variability in the selected fracture geometry parameters as a function of Young's modulus in the Karkonosze Mountains granite formation (Moska et al., 2025).

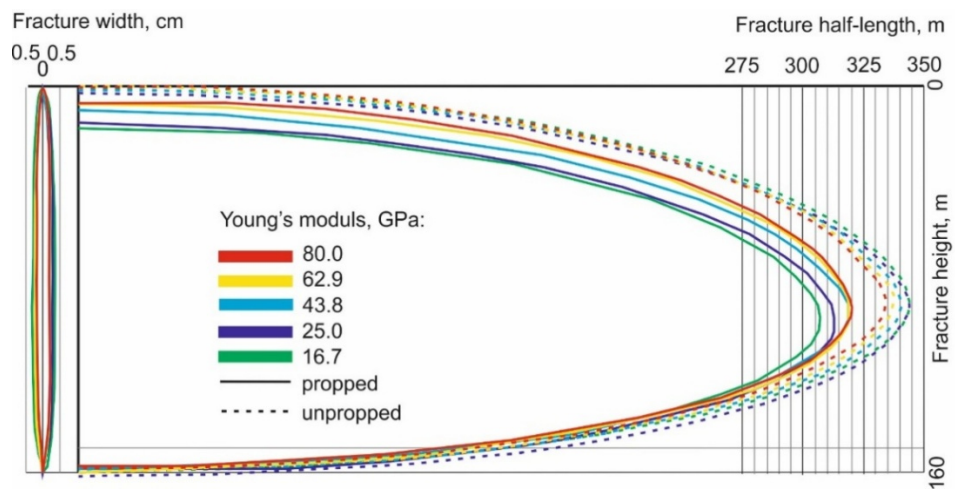


Figure 7: Variability in fracture geometry with increasing Young's modulus in the pay zone of the Karkonosze Mountains granite formation (Moska et al., 2025).

The completion of this work allowed for the formulation of the following conclusions:

1. EGS systems have been implemented worldwide in both igneous and sedimentary rocks. These formations differ significantly in terms of hydraulic stimulation mechanisms, resulting from distinct processes of conductive fracture generation.
2. Several regions with elevated geothermal potential, characterized by favorable geothermal gradients, have been identified in Poland. The most prospective areas include, among others, the Karkonosze region, the Gorzów Block, the Szczecin Trough, the Mogilno-Łódź Trough, and the Upper Silesian Block.
3. In the countries of the southeastern Baltic Basin (Lithuania, Latvia, Estonia), the HDR potential is mainly related to the presence of crystalline basement. Heat flow density values in these regions do not significantly differ from those recorded in Western Europe. The main barrier to EGS technology development in these countries is the

insufficient understanding of local tectonic conditions, particularly the development of natural fracture and fault zones, which play a critical role during hydraulic stimulation.

4. The rocks subjected to laboratory testing, originating from selected prospective EGS areas in Poland – namely the Gorzów Block, the Karkonosze region, and the Mogilno-Łódź Trough – exhibit petrophysical parameters qualifying them as petrothermal formations suitable for EGS systems.
5. The brittleness index (BI), determined based on the relationship between Young's modulus and Poisson's ratio, can be a useful parameter for assessing the prospectivity of the interval within HDR formations. However, it should be emphasized that its interpretation in igneous rocks significantly differs from that applied to sedimentary rocks.
6. Karkonosze granites exhibit higher values of effusivity, diffusivity, and thermal conductivity compared to the rhyolites from the Gorzów Block, making them more prospective for effective heat extraction in EGS systems.
7. In the sandstones of the Mogilno-Łódź Basin and the granites of the Karkonosze region, sensitivity analysis showed that the influence of Young's modulus on fracture geometry, understood as fracture length and height, does not exceed a few percent. The influence of this parameter on fracture width in sandstones also remains at a few percent level, whereas in granites it reaches values on the order of several tens of percent. The effect of Poisson's ratio on fracture geometry and permeability in both formations is marginal.
8. An increase in Young's modulus in the sandstone formation leads to a significant reduction of the embedment phenomenon and an increase in fracture permeability by several tens of percent. This may have a notable impact on the efficiency of an EGS system located in this type of formation.
9. Due to the lack of data concerning the development and characteristics of natural fractures in the granite formation as well as the interaction between these and induced fractures, the obtained results should be treated as an approximation.

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