Advances in Geo-Energy Research

Vol. 14, No. 2, p. 90-105, 2024

Original article

Dynamic elastic properties, petrophysical parameters and brittleness of hot dry rocks from prospective areas of Central Europe

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Keywords:
Enhanced geothermal systems
hot dry rock
petrophysical parameters
mineral composition
hydraulic fracturing

Cited as:
Moska, R., Labus, K., Kasza, P. Dynamic elastic properties, petrophysical parameters and brittleness of hot dry rocks from prospective areas of Central Europe. Advances in Geo-Energy Research, 2024, 14(2): 90-105. https://doi.org/10.46690/ager.2024.11.03

Abstract:
Enhanced geothermal systems in hot dry rocks are among the most promising sources of green renewable energy, with increasing interest in Central and Eastern Europe. The effective implementation of enhanced geothermal systems in new areas is based on the use of insights from ongoing projects, particularly in the study of petrophysical properties and reservoir stimulation technologies. This study aimed to characterize hot dry rocks in Central Europe by analyzing permeability, porosity, mineral composition, elastic properties, and brittleness index to assess their susceptibility to hydraulic fracturing. Drill core samples were collected from three formations: granites from the Karkonosze Mountains, volcanic rocks from the Gorzów Block, and tight sandstones from the Mogilno-Łódź Trough. The results indicated that the petrophysical properties and mineral compositions of these rocks are comparable to the corresponding Western European formations. Altered granites and some volcanic rocks showed significant decreases in wave velocities compared to intact samples, while sedimentary formation exhibited lower elastic moduli, indicating less favorable conditions for the development of the fracture network. Dynamic elastic tests suggested that brittleness index interpretation should differ between sedimentary and igneous hot dry rocks. In sedimentary formations, high brittleness index values indicate zones with elevated potential for complex fracture networks, aligning with the classic brittleness index concept. On the contrary, in igneous formations, low brittleness index values indicate zones of alteration and well-developed natural fractures, which are beneficial for hydroshearing stimulation.

1. Introduction

Ambitious EU climate neutrality plans have changed the European approach to energy production. The development of emission-free energy solutions including solar and wind power plants, biomass and geothermal power plants related to these ever tightening commitments was additionally accelerated by the emergence of the conflict in Ukraine, when European states leaders realized that even a temporary return to energy import from the east, in the near future, will be difficult to achieve. This complicated political and energy situation in Europe has resulted in strengthening the diversification of imports and energy production. One of the renewable energy branches that is currently accelerating is the obtaining energy from petrothermal resources, i.e., from deep impermeable or low permeable rocks, more commonly known as hot dry rocks (HDR) in geothermal systems of artificially increased permeability, known as enhanced geothermal systems (EGS). EGS have been known and developed throughout the world

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Yandy Scientific Press

2207-9963 © The Author(s) 2024.
Received July 10, 2024; revised August 5, 2024; accepted August 26, 2024; available online September 1, 2024.

since the 1970s (Tester et al., 2006; Moska et al., 2021). In Western Europe, primarily in France and Germany (Huenges et al., 2007; Blöcher et al., 2016; Vidal and Genter, 2018), petrothermal power plants supplied electricity and heat to the local grid for several years (BESTEC GmbH, 2024a, 2024b). In Central Europe, one of the first research projects on EGS were launched after 2010 in Poland, when the thermal balance potential of prospective geological structures for the needs of EGS was assessed (Wójcicki et al., 2013). In the next years, the state of knowledge was updated, and other prospective areas were considered (Sowiżdżał et al., 2021; Labus et al., 2023), as well as, preparation of the fracturing technology elements for selected areas is currently underway (Moska et al., 2021, 2023).

Extracting petrothermal energy from EGS, unlike conventional hydrothermal systems, requires hydraulic fracturing (HF) in the reservoir to create conductive fractures connecting injection and production wells. HF operations, as the reservoir stimulation methods have been widely known for over 70 years, however, since the 1970s they have also been used to create underground heat exchangers in HDR. The aim of HF in unconventional reservoir, e.g., shales, is to obtain the best possible connection between reservoir and wellbore, i.e., obtaining a high stimulation reservoir volume (King, 2010), to allow the gas to migrate from high volume of reservoir rock into well. In EGS, the purpose is to hydraulically connect two or more wells, to ensure economic and stable production, without causing premature cooling of the formation due to thermal short-circuiting (McClure and Horne, 2014). Unlike shale gas reservoirs, the main conductivity in HDR igneous formations is mainly provided by originally closed natural fractures (Tester et al., 2006; Baujard et al., 2017; Vidal and Genter, 2018). Naturally fractured rocks are characterized by a lower strength compared to the corresponding solid ones, resulting in lower breakdown pressure during stimulation treatment. Natural fractures are activated by shear forces in the hydroshearing mechanism, whereas other fracturing mechanisms are in minority and support the connecting of natural fractures by artificial ones (mixed stimulation mechanism) (McClure and Horne, 2014). The thermal contrast of the cold water pumped into the HDR reservoir causes the rock to contract, opening natural fractures. The vertical principal stress temporally decreases, which facilitates slippage on the fracture surface under the influence of horizontal stress. The fracture surfaces remain displaced and conductive without the use of proppant after pumping has stopped. There is also no risk of embedment phenomena, which can significantly reduce the conductivity of propped fractures in ductile rocks (Masłowski and Labus, 2021).

The design of HF is unique to the specific reservoir and well. The basic data necessary to complete the HF project include (Kasza, 2019):

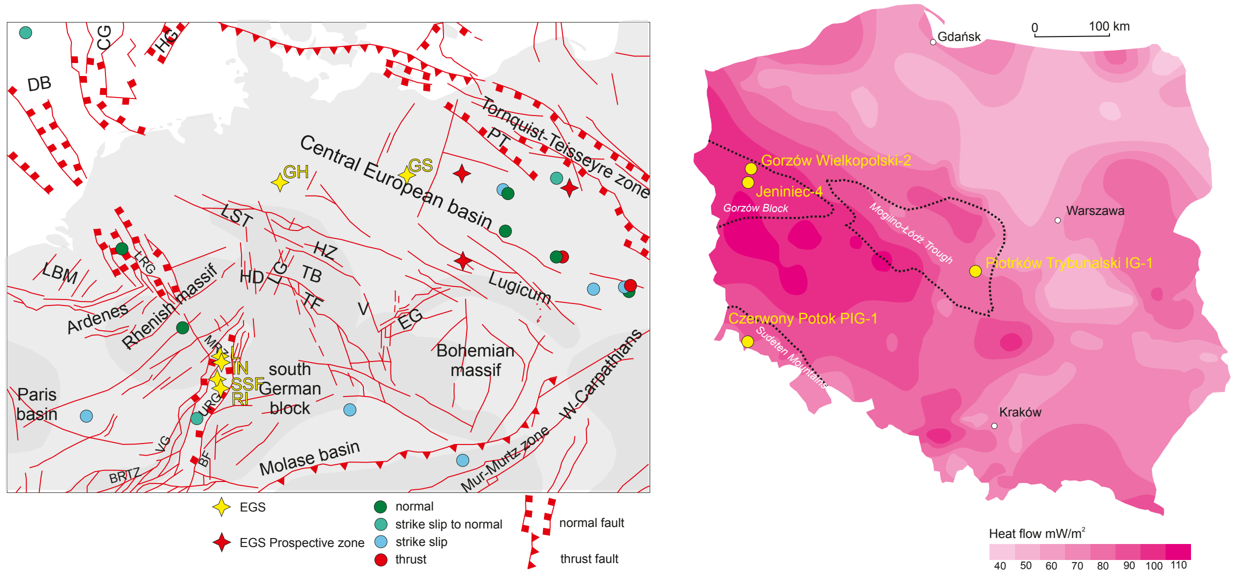
1) Borehole data: Depth, well construction (wellhead parameters, pipe and cementing durability, drilling mud type), types of works, operations and measurements performed in the well.
2) Reservoir data: Rock porosity, permeability, thickness, temperature, pressure, saturation, rock mechanics properties, mineral composition, skin effect, and principal stresses.

Information about the mechanical properties of the reservoir rock, together with the state of stresses, allows to determine the energy needed to create or reopen the fracture, as well as its length and width. The Poisson's ratio (ν) reflects the rocks' ability to fail under stress (Rickman et al., 2008). As the ν increases, the breakdown pressure and fracture closure pressure increase, thus the low ν rocks are easier to fracking. On the other hand, Young's modulus (E) describes the rocks' ability to maintain the fracture. As E increases, the fracturing pressure and fracture length increase, whereas its width decrease. E is used to calculate fracturing pressure and fracture height profile.

Susceptibility for HF in the reservoir can be described by brittleness index (BI) (Zhang et al., 2016). In oil and gas industry, BI is used to select the sweet spots-most promising intervals for perforation, mainly in the unconventional reservoirs (e.g., shales). A rock with a high BI, in general is characterized by properties that allow to create the relatively widespread network of fractures, defined by high stimulated reservoir volume parameter. Reservoir volume parameter is the volume of the hydraulically stimulated rock, calculated based on microseismic events recorded in monitoring wells (King, 2010).

The aim of this paper is to characterize HDRs in new prospective areas in Central Europe on the example of Poland, in terms of their petrophysical and mechanical properties in relation to HF operations, that could be performed in promising EGS projects in the future. Such a characterization, including petrophysical, petrographic parameters and HDR brittleness indices of Central Europe, has not been published before. The area of Poland is characterized by a high geothermal gradient compared the other countries of the south east Baltic basin, as well as relatively high heat flow anomaly (Moska et al., 2023). The geology of the country is also relatively well explored in terms of conventional geothermal energy, whereas preliminary research work on EGS has been carried out for several years (Górecki et al., 2013; Wójcicki et al., 2013; Moska et al., 2021; Labus et al., 2023). The work was prepared based on a review of the literature on research on EGS in Poland and Western Europe. HDR characterization based on laboratory measurement included main reservoir data needed for HF design, i.e., rock permeability and porosity, mineral composition, and rock elastic parameters determined using ultrasonic method in simulated reservoir conditions. Such a set of dynamic elastic data, supported by petrophysical and petrographic characteristics of new prospective areas, can constitute the basis for modeling the geometry of hydraulic fractures. Finally, a comparison between Western European and prospective Polish HDR parameters and indications concerning laboratory ultrasonic-based rock mechanics testing of HDR were formulated.

2. Materials and methods



(a) (b)

Fig. 1. (a) Tectonic sketch map of Central Europe with recent tectonic regime in principal structural units and location of current and prospective EGS. Modified after (Grünthal et al., 2018). BF-black forest, BRTZ-Bresse-Rhine transitional zone, BF-Black Forest, BRTZ-Bresse-Rhine transitional zone, CG-Central Graben, DB-Doggerbank, EG-Eger Graben, HD-Hessian depression, HG-Horn Graben, HZ-Harz mountains, LBM-London-Brabant massif, LG-Leine Graben, LRG-Lower Rhine Graben, LST-Lower Saxonian tectogene, LU-Lugicum, MRZ-Middle Rhine zone, PT-Polish trough, TB-Thuringian basin, TF-Thuringian Forest, URG-Upper Rhine Graben, V-Vogtland, VG-Vosges, EGS: GH-GeneSys Hannover, GS- Groß Schönebeck, IN-Insheim, L-Landau, RI-Rittershoffen, SSF-Soultz-sous-Forêts and (b) location of the sampled boreholes in the background of the heat flow map of Poland. Yellow dots/description-boreholes; white dashed lines-boundaries of geological regions considered. Based on (Szewczyk and Gientka, 2009; Karnkowski, 2010).

2.1 Research area

Based on the literature, three prospective HDR were selected for this study: Karkonosze granitoid pluton of Pennsylvanian age, located in the Sudeten Mountains (Czech-Polish border), Permian volcanic rocks of the Gorzow Block German-Polish border, and Lower Triassic sedimentary formation of the Mogilno-Łódź Trough area (Central Poland) (Szewczyk and Gientka, 2009; Karnkowski, 2010; Wójcicki et al., 2013; Moska et al., 2021, 2023 Sowiżdżał et al., 2021; Labus et al., 2023) (Fig. 1). These sites are well documented geologically and are characterized by elevated Earth's heat flux, which results in elevated temperatures in target zones. The structures considered are situated at the depth of more than 4,000.0 m and characterized by typical HDR petrophysical parameters, including low porosity and permeability. Since the potential target zones in these structures were not previously accessible by deep drilling, it was decided to collect samples from shallower depths in existing wells. The Karkonosze granitoid, sampled in the Czerwony Potok PIG-1 (CP-1) borehole is represented by gray-pink, medium to coarse-crystalline granite, moderately fractured, with pegmatite veins. The volcanic rocks from the Gorzów Wielkopolski-2 (GW-2) and Jeniniec-4 (J-4) wells are red-pink and brownish rhyolites with white calcite veins. Sedimentary rocks from Piotrków Trybunalski IG-1 borehole (PT-1) are represented by fine to medium-grained, red and gray sandstones with subhorizontal lamination. The recent tectonic regime in the main structural units in Central Europe and the locations of the boreholes are presented in Fig. 1. Basic data regarding the samples are presented in Table 1, and the appearance of the rocks is shown in Fig. S1 in Supplementary file.

2.2 Sample preparation and characteristics

Cylindrical samples with a diameter of 2.54 cm (1 inch) and a length of 5.08 cm (2 inches) were cut from the drill cores in the vertical direction (along the borehole axis) to reflect the variation of vertical and horizontal stresses in triaxial rock mechanics tests (Fig. 2). Samples were cut out according to ISRM suggested method (Ulusay and Hudson, 2007).

2.3 The research cycle

The research was divided into the following stages (Fig. 3): Core sampling, basic petrophysical and petrological measurements, and ultrasonic core testing. The results can be used in HF projects in the areas considered, and they also provide the possibility of comparison with data from other EGS around the world.

2.3.1 Mineral composition

The mineral composition of the samples was determined based on the X-ray diffraction method using the D2 Phaser apparatus by Bruker (Germany)-(CuKα lamp, voltage 30 kV,

Table 1. Summary of data on the samples analyzed.

No.	Location/Borehole	Depth intervals (m)	Number of samples	Stratigraphy	Litology
1	Karkonosze Mountains/Czerwony Potok PIG-1	137.80-183.86	38	Pensylvanian	Granite
2	Gorzów Block/Gorzów Wielkolpolski-2, Jeniniec-4	3,348.0-3,356.0	8	Rotliegend	Rhyolite
		3,264.0-3,277.0	11	Rotliegend	Rhyolite
3	Mogilno-Łódź Trough/Piotrków Trybunalski IG-1	3,912.5-4,286.0	39	Lower Triassic	Sandstone

(a) (b) (c) (d) (e)

Fig. 2. (a) Dimensions of the sample. Samples were cut perpendicular to the lamination (along the borehole trajectory). S_V is vertical principal stress, S_H is maximum horizontal stress, S_h is minimum horizontal stress. $S_V > S_H = S_h$ is extensional tectonic regime, conventional triaxial stress state. Samples prepared for laboratory tests: (b) granite, (c) sandstone, (d) and (e) rhyolite.

current 10 mA, 2Θ°-62°, step 0.020°. Quantitative analysis conducted using the Rietveld method was supported from HighScore Plus software by Malvern Panalytical (UK).

2.3.2 *Effective porosity and density*

Effective porosity is defined as the ratio of the pore volume of the rock to the total volume of the rock. The method used to measure the porosity coefficient does not take into account the morphology of the pore space and the separated pore space. The values presented in the paper were obtained by the HPG-100 helium porosimeter, from EPS (UK). The measurement consists of registering the pressure drop of a known volume of helium after it is injected into the chamber with the core sample. The grain density and the bulk density were calculated based on the effective porosity results.

2.3.3 *Permeability*

For each sample, the absolute nitrogen permeability was determined as the arithmetic mean of at least seven measurements of permeability at different inlet pressures (from lowest to the highest), with the input nitrogen pressure ranging from 1 to 7 bar. The determination coefficient R^2 for the set of at least 7 measurements was assumed to be at least 0.99. The permeability coefficient was determined using DGP-100, using the EPS (Aberdeen, UK) digital gas permeameter and calculated based on Eq. (1):

$$k = \frac{\mu_g Q_b P_b}{A} \frac{2l}{P_w^2 - P_b^2} \tag{1}$$

where k is absolute permeability, mD; μ_g is nitrogen dynamic viscosity in test temperature, cP; Q_b is nitrogen flow, ml/s; P_w is inlet nitrogen pressure, atm; P_b is outlet pressure, atm; A is face area of the sample, cm^2; l is length of the sample, cm.

2.3.4 *Rock mechanics*

Laboratory ultrasonic methods of the rock elastic parameter measurements has been known and used for several decades. Unlike classical methods of static stress and strain relations, elastic wave propagation is nondestructive and performed in reservoir conditions relatively well reflects the wireline acoustic logging. The differences are mainly in the frequency and in scale effect. Moduli from static tests can be converted into dynamic ones and vice versa. Correlations between these moduli have been developed and updated for years, according to the rock type and range of values (Davarpanah et al., 2020).

Ultrasonic velocities in the rock are influenced by numerous factors including: stresses, temperature, fluid saturation, anisotropy, wave frequency, and their combinations. In general, the velocity increases with confining pressure and differential pressure, where cracks and fractures play an essential role in this increase. Water saturation makes it difficult to compress the rock, which increases the velocity of the P-wave. Saturation does not affect the S-wave velocity, and the observed effect is due to the density of the rock. The velocity increases

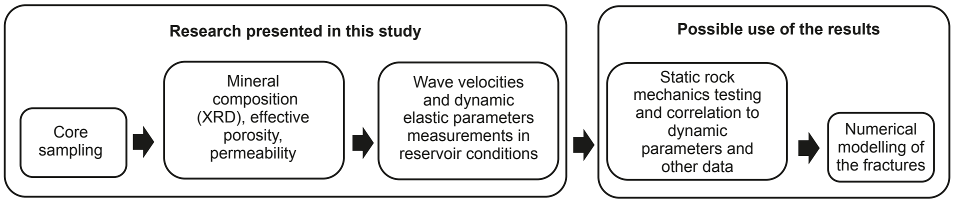


Fig. 3. Scheme of the research cycle.

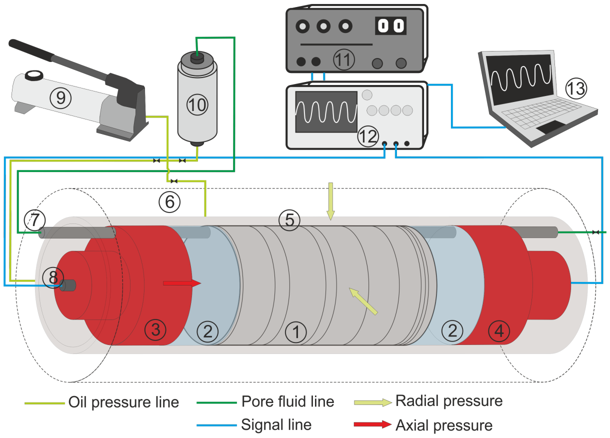


Fig. 4. Acoustic velocity system setup. 1-core sample, 2-titanium spreader, 3-piston/transmitter, 4-receiver, 5-rubber sleeve, 6-core holder, 7-pore pressure inlet, 8-wireline inlet, 9-hand pump, 10-pressure accumulator, 11-pulser, 12-oscilloscope, 13-data acquisition.

with the viscosity of the pore fluid. Anisotropic grain arrangement, lamination or preferred cracks and fractures orientation cause velocities to vary depending on direction. An increase in temperature by 100 °C causes a decrease in velocity by only a few percent. The velocity depends on frequency in an attenuating medium and thus increases slightly with it (Bourbié et al., 1987).

Rock mechanics experiments were carried out on the Acoustic Velocity System AVS-700 by Vinci (France), a device for determining the velocities of elastic waves in reservoir conditions (Fig. 4). The device is equipped with piezoelectric transducers, operating at a frequency of 500 kHz, generating and receiving longitudinal (P) and shear (S) waves. Core samples were tested under conventional triaxial conditions, at temperatures up to 140 °C and pore pressures up to 55 MPa.

Based on waves velocities, the dynamic elastic parameters are calculated using:

$$\nu = \frac{\frac{1}{2} - (\frac{V_S}{V_P})^2}{1 - (\frac{V_S}{V_P})^2} \tag{2}$$

$$E = \rho \frac{{V_P}^2 (1+\nu)(1-\nu)}{(1-\nu)} \tag{3}$$

$$G = \rho {V_S}^2 \tag{4}$$

$$K = \rho \left({V_P}^2 - \frac{4}{3} {V_S}^2 \right) \tag{5}$$

where V_P is P-wave velocity, m/s; V_S is S-wave velocity, m/s; ν is Poisson's rato; E is Young's modulus, GPa; ρ is bulk density, g/cm^3; G is shear modulus, GPa; K is bulk modulus, GPa.

For the purpose of this paper, based on the data presented by Wójcicki et al. (2013), the following depths of HDR target zones were assumed: granite of Karkonosze Mountains-4,000 m, rhyolite from Gorzów Block-4,300 m and sandstone from Mogilno-Łódź Trough area-5,000-6,500 m. The tectonic regime in Poland, according to literature (Jarosiński, 2005; Zuchiewicz et al., 2007; Moska et al., 2021) can be assumed as normal with strike-slip component or strike slip, which means that in the first case the principal vertical stress S_V, exceeds the maximum horizontal stress S_H, where the difference between S_H, and S_H, could be relatively small, and in second case, maximum horizontal stress S_H exceeds vertical stress S_V. Due to the fact, that rocks at these depths have not been drilled so far, and reservoir or tectonic data are not available, it was assumed that the average rock density is 2.4 g/cm^3 (Jarosiński, 2005). Therefore, the vertical principal stress S_V is equal to: 96 MPa, 103 MPa and 120-156 MPa for the Karkonosze Mountains, Gorzów Block and Mogilno-Łódź Trough areas, respectively. Temperatures at the target zone depths, based on heat flux density in Poland (Wójcicki et al., 2013), were assumed to be 165, 160 and 165-195 °C for the respective areas mentioned above. Since the assumed pressure and temperature exceeds the maximum measuring ranges of the laboratory rock mechanics setup used in our experiments, it was decided that the ultrasonic tests would be performed to the maximum capabilities of the device.

The testing methodology was adopted to enable comparison with the static stress-strain tests. Since the deposition depth and tectonic conditions of tested HDR were determined based on the assumptions, ultrasonic tests were performed under a wide range of pressure conditions, from ambient to reservoir conditions. Samples were tested under dry conditions, therefore, confining pressure equaled effective pressure. The methodology was adopted from the proposed methods to determine the strength of rock materials in triaxial compression (Ulusay and Hudson, 2007). At first, axial and radial stresses of 15 and 30 MPa were applied under hydrostatic conditions, then axial stresses, were increased. In hydrostatic conditions, axial and radial pressures were applied simultaneously, from ambient pressure to 55 MPa (Fig. 5). For each radial pressure condition, i.e., 15, 30 and 55 MPa, measurements of at least four samples were performed. Each core sample was used for testing and compressed only once (first load test). A total of 64 samples were tested.

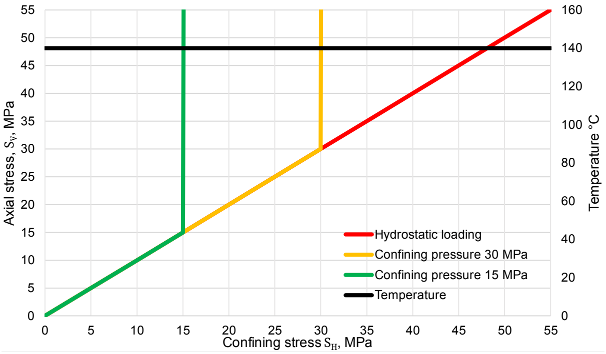


Fig. 5. Scheme of pressure-temperature conditions in ultrasonic measurements.

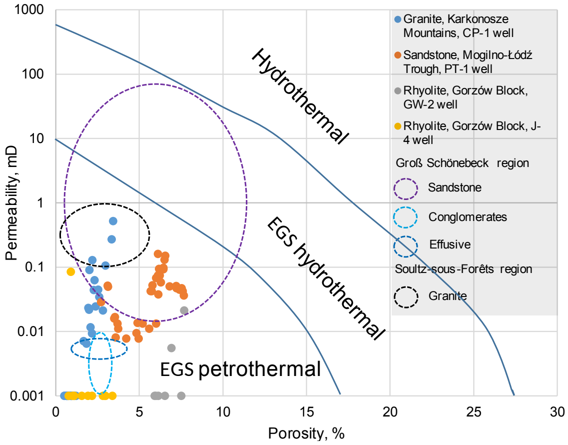


Fig. 6. Permeability-porosity-based classification of the geothermal rocks analyzed, compared to other European formations. Based on Surma and Geraud (2003); Sausse et al. (2005); Moeck (2014); Sowiżdżał et al. (2022).

2.3.5 Brittleness calculation

Rock brittleness is an important rock property related to the behavior of rocks during fragmentation and the energy consumption in this process. The definition of BI, an important parameter for characterizing the fragility of a rock mass has changed over the years. The concepts were based on stress-strain (Andreev, 1995), energy balance analyzes (Tarasov and Potvin, 2013), Lame's parameter λp-μp crossplot studies (Goodway et al., 2010) and the composite method (Mullen and Roundtree, 2007). However, currently the most popular BI definitions are based on: relationship of brittle and ductile minerals in mineral composition (Jarvie et al., 2007; Wang and Gale, 2009; Jin et al., 2014a, 2014b), and relationship of Young's modulus to Poisson's ratio of the rock (Grieser and Bray, 2007; Rickman et al., 2008; Wu et al., 2019; Moska et al., 2021). The mineral composition BI concept is based on distinction between brittle (the most frequent quartz and dolomite) and ductile minerals content (clay minerals, calcite and total organic carbon). Mineral BI may vary significantly for the same rock depending on the adopted BI definition:

$$\mathrm{BI}_{\mathrm{Jarvie}} = \frac{Q}{Q+D+C+C_l} \tag{6}$$

$$\mathrm{BI}_{\mathrm{Wang}} = \frac{Q+D}{Q+D+C+C_l} \tag{7}$$

$$\mathrm{BI}_{\mathrm{Jin}} = \frac{Q+P_l+K_f+M+C+D}{T} \tag{8}$$

where BI is brittleness index; the symbols correspond weight fraction of: Q is quartz, D is dolomite, C is calcite, C_l is clay minerals, P_l is plagioclase, K_f is potassium feldspar, M is brittle mica, T is weight fraction of total minerals.

The mineral BI is in range between 0 and 100, where values near 0 correspond to purely ductile rock, and near 100 mean purely brittle.

The clearer result is provided by BI based on E and v parameters. In this case, the key to determine reference minimum and maximum E and v values in relation to all rocks found in nature:

$$\mathrm{BI}_{\mathrm{Grieser}} = \frac{\mathrm{YM}_{\mathrm{BI}} + \mathrm{PR}_{\mathrm{BI}}}{2} \tag{9}$$

where

$$\mathrm{YM}_{\mathrm{BI}} = \frac{\mathrm{YM} - \mathrm{YM}_{\min}}{\mathrm{YM}_{\max} - \mathrm{YM}_{\min}} \times 100\% \tag{10}$$

$$\mathrm{PR}_{\mathrm{BI}} = \frac{\mathrm{PR} - \mathrm{PR}_{\max}}{\mathrm{PR}_{\min} - \mathrm{PR}_{\max}} \times 100\% \tag{11}$$

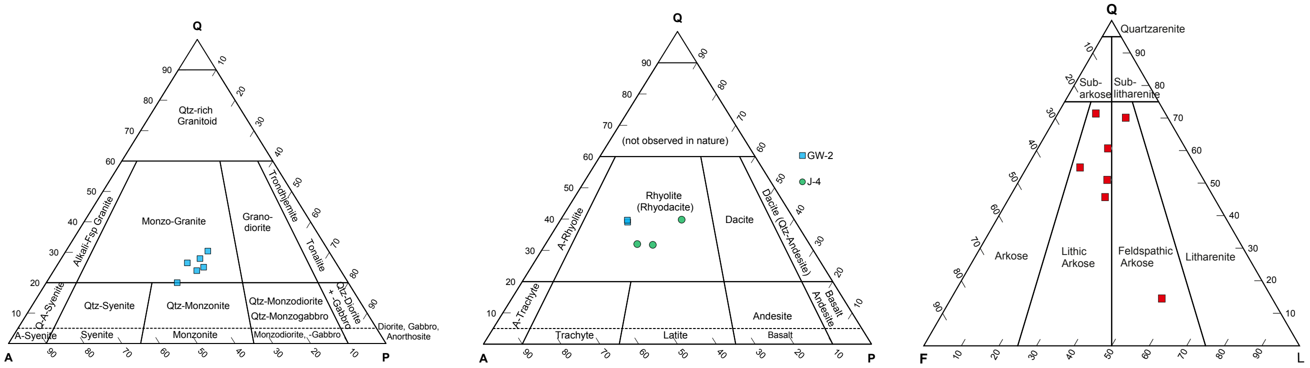
where $\mathrm{YM}_{\mathrm{BI}}$ is BI from E, $\mathrm{PR}_{\mathrm{BI}}$ is BI from v, YM is measured E, PR is measured v. $\mathrm{YM}_{\min}$, $\mathrm{YM}_{\max} \in [0,10]$ and $\mathrm{PR}_{\min}$, $\mathrm{PR}_{\max} \in [0,0.5]$.

$\mathrm{YM}_{\min}$, $\mathrm{YM}_{\max}$, $\mathrm{PR}_{\min}$, and $\mathrm{PR}_{\max}$ are constants, defining minimum and maximum values of obtained results, which corresponds to values from 0 to 10 Mpsi (0-68.95 GPa) for E and from 0 to 0.5 dimensionless for v. $\mathrm{BI}_{\mathrm{Grieser}}$ is in the range between 0 and 70, where values near zero means fully ductile rock, whereas near 70 fully brittle rock. The key factor for a proper estimation of BI is to adopt the minimum and maximum values of E and v to compare the rocks witch each other. Some authors suggest using other reference point values (Rickman et al., 2008): $\mathrm{YM}_{\min}$, $\mathrm{YM}_{\max} \in [1,8]$ (Mpsi) (6.895, 55.16 GPa) and $\mathrm{PR}_{\min}$, $\mathrm{PR}_{\max} \in [0.15, 0.4]$:

$$\mathrm{BI}_{\mathrm{Rickman}} = \frac{50}{7}(E - 28v + 10.2) \tag{12}$$

Wu et al. (2019) proposed narrower values, however they analyzed BI of the steam coal samples, which can be considered as a special case. Regardless of the method of BI definition, brittle rocks typically exhibit a unique set of features including low elongation upon load application, higher ratio of compressive strength to tensile strength, and higher internal friction angles, which favors the formation of extensive fracture networks in such rocks (Zhang et al., 2016). Therefore, BI can be used to compare rocks of the same type from different locations, in terms of their elastic features connected with susceptibility to fracking. This group also includes HDR, both igneous, and sedimentary formations similar to tight gas sandstones.

Despite the confirmed usefulness of BI in shale gas deposits, some authors noted that this parameter may not be appropriate for characterizing the brittleness of other rocks in certain circumstances, and its definition is imprecise (Her-



(a) (b) (c)

Fig. 7. Samples from: (a) The Karkonosze Mountains (CP-well) in the background of the QAP classification diagram, (b) the Gorzów Block (GW-2 and J-4 wells) in the background of the QAPF volcanic classification diagram and (c) the Mogilno-Łódź Trough area (PT-well) in the background of the QFL classification diagram.

wanger et al., 2015; Holt et al., 2015). Bai (2016) points out that brittle formations do not equate to formations that are easier to fracture, since the brittle rocks may have greater strength under higher confinement, i.e., are more difficult to fracture, and vice versa. The brittleness and ductility of the formation also cannot be related to the E and v parameters, since uniaxial compressive strength or fracture toughness gives better relation.

HDR differs significantly from unconventional shale or tight gas deposits. In HDR, especially granite, the major role in conductivity between wells is played by natural fracture zones, which can be stimulated (artificially widened and enlarged) in the hydroshearing mechanism. The strength of these zones, measured as uniaxial compressive strength, can be critically lower than that of the surrounding unfractured rocks. BI based on the E to v ratio can account for natural fracture zones, if the data used are from a sonic log performed in fractured and unfractured interval. If the data come from a laboratory small-scale sample rock mechanics testing, the influence of natural fracture zones can be harder to determine due to difficulties in collecting samples with fractures, as well as in the testing itself.

This article presents selected methods for calculating the BI index based on minerals and the E to v ratio, developed by various authors. In order to compare the obtained results with each other and compare with the presented literature data, methods suggested by Grieser and Bray (2007); Jarvie et al. (2007); Rickman et al. (2008); Wang and Gale (2009); Jin et al. (2014a, 2014b) were used.

3. Results and discussion

3.1 Permeability, porosity and density measurements

Rocks tested at all locations are characterized by low effective porosity and permeability. Granite from Karkonosze Mts., as well as rhyolite from J-4 well in Gorzów Block area have the lowest porosity. The calculated average porosity in this case is mainly natural cracks and fractures, and to a much lesser extent the porosity of the skeleton. The intergranular porosity in the sandstones of the Mogilno-Łódź Trough and rhyolite from GW-2 well in the Gorzów Block translates into relatively small differences between the minimum and maximum values obtained (Table S1, in Supplementary file). The average permeability values of all the rocks tested are significantly below 0.1 mD, and in the case of intrusive and volcanic rocks most of the samples showed permeability below the lower measurement range (0.001 mD). Bulk densities correspond to the literature values for relevant rock formations (Bourbié et al., 1987; Plewa and Plewa, 1992). The petrophysical parameters allow to classify all investigated rocks to petrothermal formations (Fig. 6). Granite from Karkonosze Mts. have slightly lower permeability compared to the average corresponding values of Soultz-sous-Forêts Carboniferous granite basement. Sandstones from Mogilno-Łódź Trough are characterized by relatively narrow distribution of parameters, compared to sandstones from Groß Schönebeck, where the permeability falls in the wide range of 0.01 to 100 mD (Fig. 6).

3.2 Mineral composition measurements

Fig. 7 describes the location of granite, rhyolite and trachyandesite samples on the QAP diagram, as well as sandstone samples on the QFL diagram. Statistical parameters of the mineral composition can be seen in the Table S2 in Supplementary file.

The Karkonosze granitoid pluton in the Sudeten Mountains was formed in the Variscian orogeny 300-350 million years ago. Samples collected from depth from 138.0 to 184.0 m, represent a K-feldspar granite (Fig. 7(a)), where the dominant role in mineral composition is played by albite (average 33.1%) together with orthoclase and microcline (average 15%-19%, respectively). The average quartz content is 23% biotite, illite, kaolinite and chlorite are in the minority. Volcanic rocks from Gorzów Block are mainly built of quartz (average from 22% to 38% for J-4 and GW-2 wells respectively) and K-

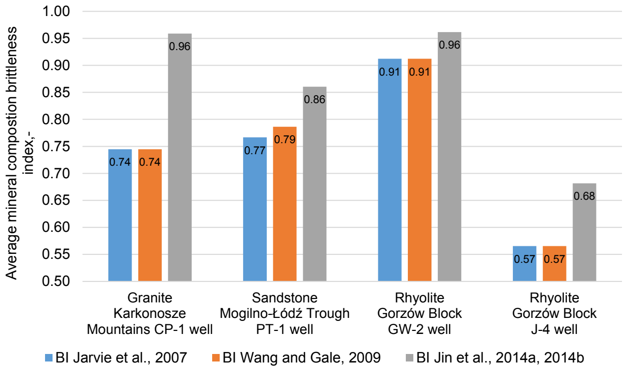


Fig. 8. Average mineral brittleness (BI) of the samples.

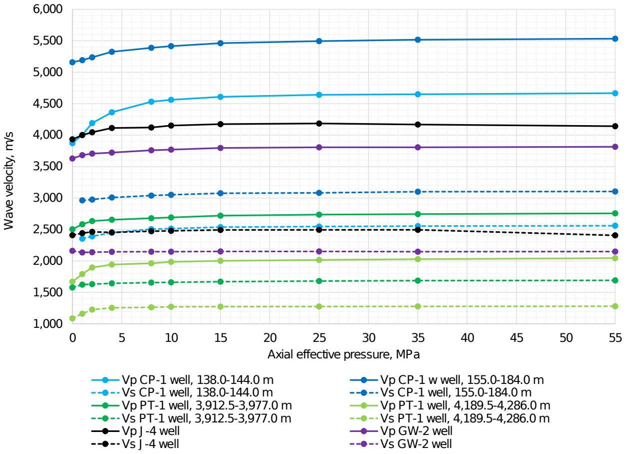


Fig. 9. Average compressional (V_P) and shear (V_S) wave velocities versus axial effective pressure for Karkonosze Mountains granite (CP-1 well), Mogilno-Łódź Trough sandstones (PT-1 well), and Gorzów Block rhyolite (GW-2 and J-4 wells), measured in triaxial conditions. 138.0-144.0 m; 155.0-158.0 m–depth intervals of granite samples collected. 3,912.5-3,977.0 m; 4,189.5-4,286.0 m–depth intervals sandstone samples collected.

feldspar (orthoclase for GW-2 well and microcline for J-4 well, 41% and 24% in average respectively), which allows them to be classified in the QAPF volcanic diagram as rhyolite and rhyodacite (Fig. 7(b)). They also contain plagioclase (albite), clay minerals and others (Table S2, in Supplementary file). Lower Triassic sandstones from Mogilno-Łódź Trough contain mainly quartz (52% in average) and plagioclase (albite, 14% in average). They are characterized by a small amount of carbonates, while clay minerals content (especially illite) reaches a dozen percent (14% in average). These sandstones can be classified as lithic arkose and feldspathic litharenite in QFL diagram (Fig. 7(c)).

Fig. 8 shows a high mineral BI for all types of the considered rocks, except for rhyolite from J-4 well, for which BI can be described as average. Regardless of the calculation method used, the BI for granites and sandstones exceeds 0.7, reflecting the high content of brittle minerals, especially albite, microcline and quartz in granites, quartz, potassium and alkali feldspar in sandstones, and quartz and alkali feldspar in rhyolite from GW-2 well. It can be seen that method presented by Jarvie et al. (2007) and the computational methods showed by Wang and Gale (2009) give very similar results for the rocks considered. Noticeably higher BI values were obtained using the equation of Jin et al. (2014a, 2014b), which results from the highest content of minerals defined as brittle. However, it should be remembered that all applied computational methods were originally developed for sedimentary rocks, and therefore may not fully reflect the variability of the mineral BI of the considered formations. Mineral BI in HDR should rather be used to compare the susceptibility for fracking in the fracture initiation phase, of similar formations types from different depths or wells.

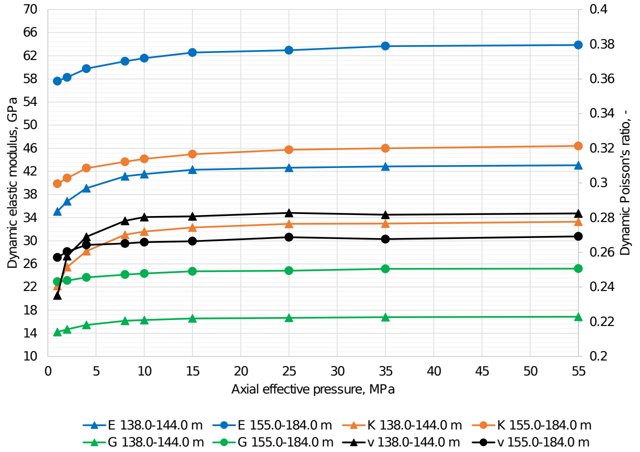


Fig. 10. Average dynamic elastic parameters versus axial effective pressure for the Karkonosze Mountains granite (CP-1 well), measured under triaxial conditions. 138.0-144.0 m; 155.0-158.0 m-depth intervals of the samples collected. E, K, G-dynamic Young's, bulk, shear modulus respectively, v-dynamic Poisson's ratio.

3.3 Ultrasonic measurements

Figs. 9-12 show average propagation velocities of compressional and shear waves and the average dynamic elastic parameters versus axial effective pressure for all samples tested under triaxial conditions. The granite and sandstone samples were taken from a relatively wide depth interval, resulting in significant variability in the ultrasonic properties of these rocks. For this reason, no correlation of the P- and S-wave velocities with the applied radial pressure from 15 to 55 MPa was observed. Such relationships could be observed if individual samples were very similar in terms of structure and mineral composition. Therefore, it can generally be expected that an increase in radial confining pressure causes an increase in the P- and S-wave velocities (Bourbié et al., 1987). Due to the observations described above and the small number of the samples, it was decided to determine average velocity curves and dynamic elastic parameters for all samples of a given rock, tested in triaxial conditions, i.e., for 15, 30 and 55 MPa radial confining pressure. Therefore, each curve of velocity and elastic parameters for granite (Figs. 9 and 10) and sandstone (Figs. 9 and 11) represents the average of the

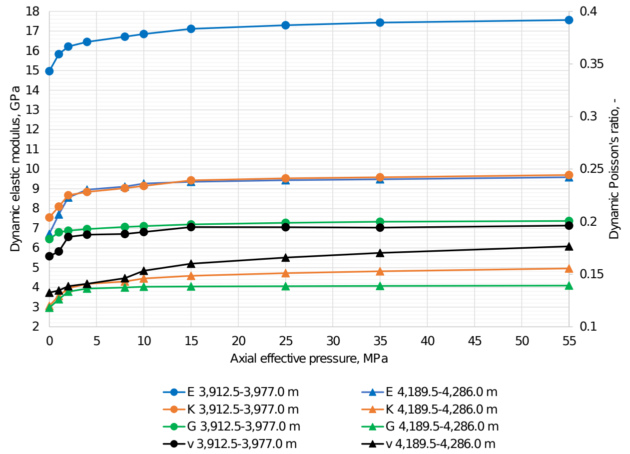


Fig. 11. Average dynamic elastic parameters versus axial effective pressure for Mogilno-Łódź Trough sandstones (PT-1 well), measured under triaxial conditions. 3,912.5-3,977.0 m; 4,189.5-4,286.0 m-depth intervals of samples collected. *E*, *K*, *G*-dynamic Young's, bulk, shear modulus respectively, *v*-dynamic Poisson's ratio.

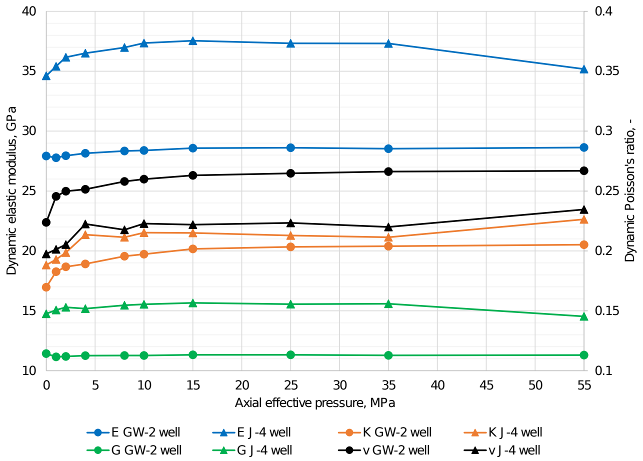


Fig. 12. Average dynamic elastic parameters versus effective axial pressure for Gorzów Block rhyolite (GW-2 and J-4 wells), measured under triaxial conditions. *E*, *K*, *G*-dynamic Young's, bulk, shear modulus respectively, *v*-dynamic Poisson's ratio.

corresponding parameters of at least five samples, measured at the three mentioned three values of radial confining pressure. In the case of rhyolite from the GW-2 and J-4 wells (Figs. 9 and 12), each curve is the average of relevant parameters from at least two samples. Additionally, granite and sandstone samples were divided into two groups in terms of sampling depth and related P-wave velocities.

The variability of wave velocities depending on the sampling depth is shown in Fig. 9. Granite samples collected from the 155.0-184.0 m interval are characterized by higher P- and S-wave velocity and dynamic elastic moduli. This can be explained by a lower alteration and a lower number of natural cracks and fractures in the deeper interval. The highest increases in velocities and moduli are observed at low values of effective pressure as a result of the gradual closing of the pore space in rock samples. Above an effective pressure of 15 MPa, the velocity increase slows down and eventually flattens out, due to the higher bulk modulus of the grain skeleton with a closed pore space. Also, the sandstones show strong variability with depth. In this case, the higher waves velocities and elastic moduli for the shallower samples are probably due to variability in mineral composition. Samples from the 3,912.5 to 3,997.0 m interval are characterized by an elevated amount of quartz and a lower content of illite. The relatively low value of *v* (below 0.2) is probably related to minimal saturation of the samples (measured under dry conditions). The rhyolite of the GW-2 well, consisting of 95% quartz and feldspar, exhibits lower velocities compared to the rhyolite of the J-4 well, probably due to its higher porosity (6%-8%). In the rhyolite of the J-4 well, a decrease in velocity is clearly visible, after exceeding the axial pressure of 25 MPa for the P wave and 35 MPa for the S-wave. This behavior can be associated with microcracking of the matrix (groundmass), which is the beginning of sample disintegration. The decrease in velocities reflects lowered *E* and *G* moduli, which for the maximum axial pressure reach values similar to those for ambient pressure. At the same time, an increase in *v* is recorded, which reflects an increase in radial deformation compared to the axial deformation. A summary of data from ultrasonic tests, including minimum, maximum, and average wave velocities and elastic parameters of measured samples is presented in Table S3 in Supplementary file.

Fig. 13 presents a cross plot of *E* and *v* of measured samples. A relatively low *v* of sandstones from both intervals of the PT-1 well is visible, corresponding to their low *E*. This is reflected in the lowest BI value compared to the other rock types studied-Fig. 14. Granites are characterized by high BI due to the relatively high level of *E*, while in the rhyolite group the variability depends on the drill hole considered. The relatively low ductility, low matrix permeability and presence of natural fractures in granite, and rhyolite from J-4 well allow to consider slickwater or fresh water with shale inhibitor as a fracturing fluid, which would be consistent with the common trend of fracking in plutonic and volcanic rocks (Tester et al., 2006; Blöcher et al., 2016; Moska et al., 2021). Open fractures in these types of rocks exhibit self-propping capacity due to the hydroshearing mechanism. Fracking such rocks may not require the use of any type of proppant material or any fluids to transport it. The selection of fracturing fluid for the tested sandstones requires taking into account the proppant material, which involves considering the main fracturing fluid as a polymer-based, linear, or cross-linked gel, similar to the fluids used in the sedimentary intervals of the Groß Schönebeck project (Blöcher et al., 2016).

The correlation plots for the parameters of the tested rocks are shown in the Fig. 15. As the effective porosity decreases, the wave velocities increase, which corresponds to the increase of elastic moduli. Granites and rhyolites from the GW-2 well show the highest coefficient of determination (0.90 and 0.78, respectively, for the P-wave linear regression model; 0.68 and 0.81, respectively, for the S-wave). An increase in the effective

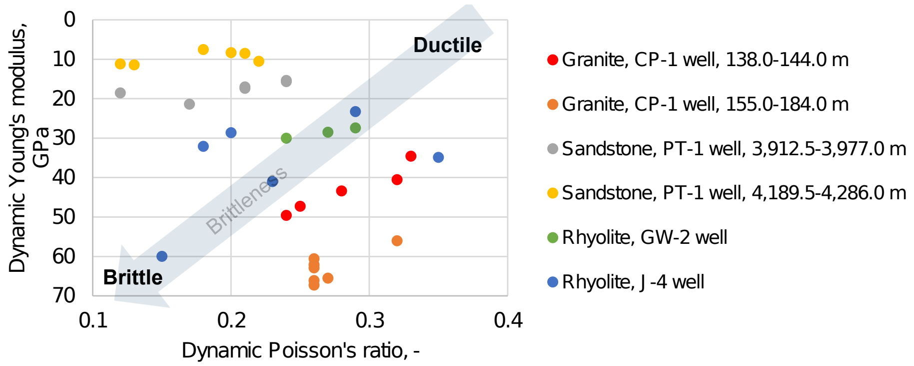


Fig. 13. Cross plot of dynamic Young's modulus and dynamic Poisson's ratio of measured samples, showing brittleness increasing towards the southeast corner of the plot.

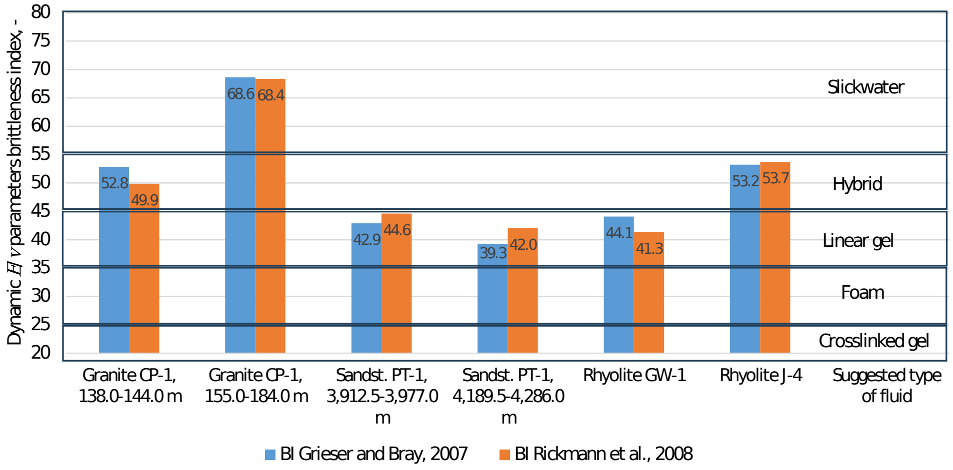


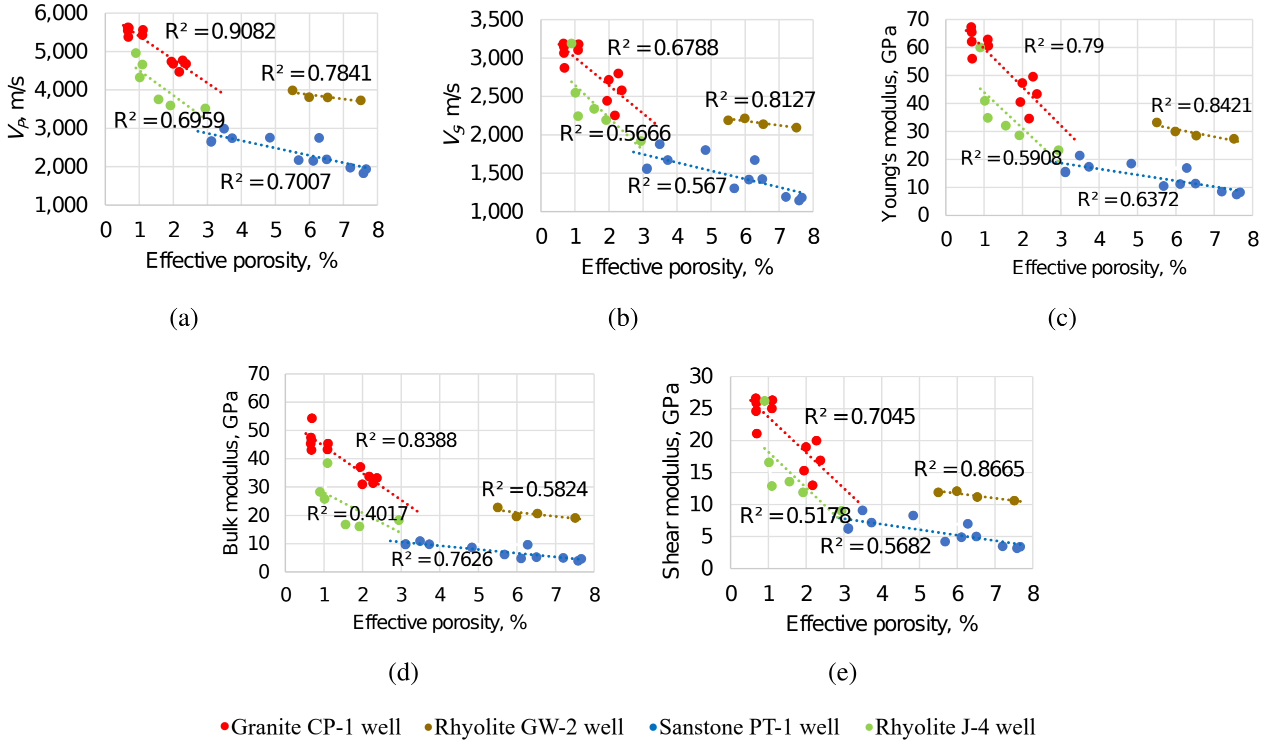
Fig. 14. Dynamic E to dynamic v-based BI of measured samples, based on methods by Rickman et al. (2008) and Grieser and Bray (2007). In the method by (Rickman et al., 2008) the following values $\mathrm{YM}_{\max} = 10$ Mpsi (68.95 GPa) and $PR_{\min} = 0.12$ were used to fit to parameters of measured samples. Suggested types of fracturing fluid correspond only to the results calculated according to Rickman et al. (2008).

porosity of dry rock leads to a decrease in the dynamic elastic moduli and strength of the rock. A reduction in E in the igneous HDR is usually the indicator of altered or naturally fractured zone, which may be desirable for hydroshearing stimulation. Reduced E in sedimentary HDR is rather undesirable as it leads to a reduction the fracture lengths and overall tendency to produce less-developed fracture networks.

For over 30 years, several EGS projects have been developed in Western Europe (Batchelor, 1987; Wallroth et al., 1999; Blöcher et al., 2016; Kukkonen and Pentti, 2021). Most of them started as research projects, but only a few have reached the stage of application in the energy sector. Due to their research purpose, these projects are usually well described in the literature. The published data generally concern the results of stimulation and well tests, seismic monitoring, and to a lesser extent, information from laboratory core measurements, including petrophysical and geomechanical studies. In most projects, laboratory geomechanical ultrasonic tests were not performed at all or their results were not published. Therefore, in this paper, we compared our new results with published data, being aware, that differences in methodology may generate difficulties in the comparisons.

All lithological types examined in this study can be classified as petrothermal formations (Fig. 6). The Karkonosze Mts. granites are characterized by lower permeability than the Soultz granite, for which the average permeability obtained from modeling, based on well logging, ranges from 0.1 to 1.0 mD. In both cases, depth variability is visible, depending on the mineral composition and the development of natural fractures. The sandstones of the Mogilno-Łódź Trough are characterized by permeability in the range of approx. 0.01-0.1 mD and an average porosity of 0.055, which corresponds to the lower limit of the permeability range and average porosity of sandstones of the German Basin, presented in literature (Moeck, 2014; Sowiżdżał et al., 2022). Rhyolite samples, regardless of their porosity show permeability below 0.001 mD which is slightly lower than effusive the rocks from the Groß Schönebeck area (Sowiżdżał et al., 2022).

Comparing the Karkonosze granites in terms of mineral composition with their Western European counterparts is difficult due to the large variation in mineral composition within a single formation. Although the main granite body



(a) (b) (c)

(d) (e)

Fig. 15. Linear regression models for P-(a), S-(b) wave velocity, (c), (d), (e) dynamic elastic moduli and effective porosity of measured samples.

in Soultz is characterized by a low clay content (Table S4, in Suppementary file), some of its zones are highly modified. For example, in the GPK1 well in Soultz, several zones of anomalous mineral composition were identified, i.e., clay-rich fractured and altered zones of increased potassium, or leucogranitic dikes with elevated uranium and potassium content (Sausse, 2002; Sausse et al., 2006). Zones of increased clay mineral content corresponding to fractured zones can be prospective for conductivity in EGS. In the conditions of the Karkonosze Mountains, it can be assumed that zones of a similar nature may be promising. Samples taken from a depth of 138.0-144.0 m, in which a greater number of fractures and greater alteration were found, contained an increased amount of clay minerals, especially kaolinite, illite, and chlorite. These samples are characterized also by significantly lower wave velocities-reflecting lower mechanical strength. Such zones, which can occur at greater depths with higher temperatures, may form conducting arteries after hydraulic stimulation.

Similarly to granites from Karkonosze Mts., examined sandstones from Mogilno-Łódź Trough and rhyolite from Gorzów Block are difficult to compare directly. EGS's in sedimentary and volcanic rocks are a minority, and the only projects in Europe in this type of formations are Genesys in Hannover and Groß Schönebeck near Berlin (Tischner et al., 2013; Blöcher et al., 2016). While in Genesys the target formation was Middle Buntsandstein (Volpriehausen sequence), in the Groß Schönebeck project, the target is Upper/Lower Rotliegend (Dethlingen formation). The formation in Groß Schönebeck can be treated analogously to the Rotliegend in the Gorzów Block. Data on the mineral composition of volcanites from the GT GrSK well in the Groß Schönebeck area are limited, but they are generally referred to as andesites in which permeability is mainly related to natural fractures (Zimmermann et al., 2010). They consist mainly of quartz and plagioclase, with small amounts of mica, carbonates, and chlorite (Table S4, in Suppementary file).

The sedimentary cover in Dethlingen is represented by well-sorted, medium- to fine-grained, poorly cemented sandstones (Zimmermann et al., 2010). Regional data for this formation characterize it as having a medium-high quartz content and significant carbonate content, while K-feldspar and plagioclase are in the minority (McCann, 1998) (Table S4, in Supplementary file). No information was found on the average content of clay minerals. Compared to these rocks, the examined sandstones from Mogilno-Łódź Trough contain lower amounts of quartz and carbonates, but an increased content of feldspar. The content of clay minerals does not exceed several percent.

The mineral content of considered formations allows the determination of BI values of 0.96, 0.86 and 0.68-0.96 for granites, sandstones and rhyolites respectively. BI of comparable Western European formations, calculated on the basis on data available in literature (Table S4, in Supplementary file) and using the method proposed by Jin et al. (2014a, 2014b) are 0.99, 0.94 and 0.94 for Soultz granites, Groß Schönebeck sandstones and volcanites, respectively. This means that all examined rocks are characterized by slightly lower susceptibility for HF operations (less development of the inducted fractures network and greater tendency to create double wing fractures) especially in the fracture initiation stage.

The mechanical parameters of target zones in EGS, as one of the most important information required for designing hydraulic stimulation, are reported in many works including (Zimmermann et al., 2010; Meller and Ledésert, 2017; Villeneuve et al., 2018). Typically, these data come from dipole sonic logging (Mullen and Roundtree, 2007) or less often from laboratory stress-strain core testing. On the other hand, wave velocity data, especially from laboratory core measurements under reservoir conditions, are often unavailable. Although this type of information is not necessary if logging data are available, such tests provide precise data at smaller scales, but when combined with petrophysics, petrography, and other data from large data set, can provide reliable and useful information.

Ultrasonic testing of granite from the Karkonosze Mts. revealed a significant difference in velocities between samples from the shallower and deeper intervals. While samples taken from the 138.0-144.0 m interval, significantly altered, fractured and with an elevated clay minerals content, show velocities on average of 4,700 and 2,600 m/s for the P- and S-wave respectively, the samples taken from the deeper, less altered and fractured interval, i.e., 155.0-184.0 m, show velocities of 5,500 and 3,100 m/s, respectively. The velocities of the deeper samples correspond to their higher dynamic moduli (E up to 67 GPa) (Table S3, in Suppementary file). This interval is probably characterized by higher strength, and therefore the fracturing pressure could be higher there. The E values for Soultz granite are in the range of 40-80 GPa for fresh intact rock, but in the fractured zones they can be much lower (Meller and Ledésert, 2017; Villeneuve et al., 2018). Hot dry granites from other EGS are characterized by very diverse E and v e.g., from 15-33 GPa and 0.12-0.22 in Fenton Hill; by 65 GPa and 0.25 in Habanero, 40-56 GPa and 0.23-0.33 in Qiabuqia, to 73.7 GPa and 0.22 in FORGE Utah (Moska et al., 2021).

Data presented for granite not related to HDR areas are variable. Domede et al. (2019) in comparison of mechanical properties for several dozen types of granites showed, that the range of P-wave velocity is from 2,260 to 6,690 m/s, while the range of E and v is 12.9-85.0 GPa and 0.14-0.36, with a mean value of 47 GPa and 0.25, respectively. Bourbié et al. (1987) suggested, that P- and S-wave velocities for granite are in the range of 4,500-6,000 and 2,500-3,300 m/s, respectively, with a density of 2.5-2.7 g/cm^3, and v between 0.18 and 0.33. Plewa and Plewa (1992) reported dynamic E and v parameters of 54.5 GPa and 0.20, respectively, for dry biotite granite. Domonik (2011) showed a relatively low variability of the static E for granite from the Strzegom massif (Poland), depending on the depth and the associated pressure. While in surface conditions, the average static E modulus was calculated to be approximately 65 GPa, at a depth of about 3,500.0 m, this average modulus was close to 75 GPa. In these studies, static v was found to range from 0.15 to 0.35, regardless of depth and pressure.

The wave velocities for the sandstones from the Mogilno-Łódź Trough showed strong variability with depth, probably due to the mineral composition, while the relatively low v is related to the measurement under unsaturated conditions. Despite significant discrepancies in moduli between sampling intervals, the average E (11-18 GPa) of these sandstones is much lower compared to the data presented for the Groß Schönebeck site (55 GPa), while v reaches similar values (0.18-0.20) (Tables S3 and S5, in Supplementary file). The sandstones of the Genesys Hannower project also had significantly higher E (45-65 GPa) and similar v (0.18-0.22) (Tischner et al., 2013). This results in lower fracturing pressure, increased fracture width and reduced length, in the case of rocks of the Mogilno-Łódź Trough, compared to sandstones from the above-mentioned sites under similar stress conditions.

The examined rhyolites from the Gorzów Block are characterized by variable velocities depending on the sampling well. Samples from the GW-2 well showed lower velocities (on average 3,800 and 2,200 m/s for the P- and S-waves respectively), while samples from the J-4 well had velocities on average 4,100 and 2,400 m/s for respected waves, with high variability between individual samples. The average values obtained for E (29-35 GPa for GW-2 and J-1, respectively), are lower than those presented for the Groß Schönebeck site (55 GPa), while the v (0.23-0.27) is elevated (Tables S3 and S5, in Supplementary file). The dynamic elastic data presented for the rhyolite from the FORGE site (Utah, USA) show high variability of the E and v parameters (21-67 GPa and 0.19-0.39, respectively) (Bauer et al., 2017).

The BI range based on the E to v ratio is 49.9-68.4 for granites, 42.0-44.6 for sandstones and 41.3-53.7 for rhyolites, depending on the wellbore and sampling depth. However, the average values for comparable sedimentary and volcanic formations, based on the data presented in the literature (Table S5, in Supplementary file), concerning Groß Schönebeck formations and calculated using the method proposed by Rickman et al. (2008) are 78.0 and 74.5, respectively. It should be noted that the mentioned literature probably reports E to v values obtained from static testing or well logging, The BI values obtained for all formations considered in this study, using both mineral-based and E-v ratio methods, are in the middle or upper limits of the ranges which means that these rocks may generally be susceptible to fracture propagation. The mineral-based BI calculation method proposed by Jin et al. (2014a, 2014b) gives the highest BI results due to inclusion of a large number of brittle minerals versus ductile minerals. However, the remaining tested methods (Jarvie et al., 2007; Wang and Gale, 2009) give very similar results. In the case of methods based on the E to v ratio, the differences in results depending on the method used are insignificant. It should be noted, however, that the reference values in the method proposed by (Rickman et al., 2008) were modified due to match the parameters of measured samples. It is important to note that the calculated BI should rather be treated as the BI for the intact rock body, despite the presence of natural fractures and alteration in some samples.

In light of the above, in the case of HDR formations, the method of BI interpretation may be useful but also controversial. Since BI's were originally intended for evaluation of sedimentary rocks, especially shale gas deposits, in the case of

HDR, its application without interpretive modifications seems inappropriate. In shale rocks, the increase of permeability during hydraulic stimulation occurs through the process of hydraulic fracturing (pure opening mode-creating new fractures in the tensile mode) or hydraulic jacking (reopening preexisting fractures in tensile mode). Generally, in these models, a high content of brittle minerals (e.g., quartz) and low content of plastic minerals (clays), favor the formation of an extensive fracture network, increasing the stimulated reservoir volume and, consequently, the volume of the reservoir hydraulically connected to the well.

Therefore, in simple terms, the greater the BI (calculated based on mineral content or elastic parameters) the greater the likelihood of obtaining an extensive fracture network and greater gas flowback. In EGS the goal is to create a connection between two or more wells, however, too extensive fracture network, or more precisely too high conductivity, may lead to undesirable thermal short circuiting, which leads to a decrease of temperature in the production well. In typical HDR formations (granites, volcanites), the main role in stimulation is played by the hydroshearing mechanism (inducing slip and dilatation of natural fractures in shear mode). Naturally fractured intervals are stimulated first, and new fractures are even created, which act as connectors between other natural fractures. Naturally fractured, altered intervals are generally characterized by a lower uniaxial compressive strength and a significantly lower E (Table S5, in Supplementary file). These properties can significantly reduce mineral and geomechanical BI as a result of the elevated clay content and reduced E, respectively.

Therefore, it should be considered whether BI should be interpreted differently in HDR formations stimulated by the hydroshearing mechanism than in the rocks to which it was originally adapted and applied. In granites, rhyolites, or andesites, the lowest values of the E and the increased content of plastic minerals (and thus the lowest BI compared to rest of considered interval) may indicate prospective zones for hydroshearing stimulation. On the other hand, in less naturally fractured sedimentary HDR, much more similar to the formation for which BI was originally intended and applied, the highest values may be considered more favorable.

Laboratory ultrasonic measurements can provide useful, complementary data for well logging or, in the absence of logging data and a large number of tested samples over wide depth interval, can be used as input to HF operation design software. The tests showed that elastic parameters of granites and sandstones were quasi-stabilized above the effective axial pressure of 25 MPa in triaxial tests. Although the tests were performed up to a confining pressure of 55 MPa it can be assumed, based on the literature (Bourbié et al., 1987), that a further increase in confining pressure should result in moduli changes, which could be insignificant in HF design. In the case of the tested rhyolites from J-4 well, a decrease in the P-wave velocity above 35 MPa axial pressure was observed, which can be associated with the previously mentioned microcracking of the matrix, which may be equivalent to the beginning of sample disintegration.

Testing under dry conditions seems appropriate for low-porous and permeable HDR, however, it can be mentioned that even in the case of low porosity and stress-resistant rock skeleton of the sample, saturation may lead to some increase in the moduli, due to the increase in P-wave velocity. In turn, a change in temperature by 100 °C causes a change in the P-wave velocity by less than 5% (Bourbié et al., 1987), which makes it possible to consider performing tests at lower temperatures, without a significant impact on the moduli.

So far no EGS project has been initiated in this part of Europe. Therefore, the results obtained of the dynamic elastic moduli in relation to the petrophysical and petrographic parameters, especially for the granite from the Karkonosze Mts. and the sandstone from the Mogilno-Łódź Trough, due to large the number of samples examined, could be used to a preliminary design an HF operation under expected conditions in these areas. Such a study, combined with the simulation of flow between wells, depending on the assumed rock features, stresses, and parameters of fracking operation, as well as evaluation of the potential for thermal energy extraction from these areas, would be an important step towards the development of enhanced geothermal systems, following the example of Western European countries.

4. Conclusions

1) Newly obtained data indicate that petrophysical parameters determining the HF operations in three prospective HDR formations in Central Europe: granites from the Karkonosze Mts., sandstones of the Mogilno-Łódź Trough and rhyolites from the Gorzów Block, have similar values to those in rocks in active HDR sites: Soultz granites, sandstones of the German Basin and effusive rocks from the Groß Schönebeck area, respectively.
2) The intact granites Karkonosze Mts. are similar in terms of mineral composition and susceptibility to fracturing to the corresponding Soultz formation. The elevated average clay content of the Mogilno-Łódź Trough compared to the Groß Schönebeck area leads to a decrease in mineral-BI, which facilitates the formation of double wing fractures. The BI of the Gorzów Block rhyolites is strongly dependent on the sampling location due variability of the mineral composition and development of natural fractures.
3) The altered granites, with well-developed natural fractures, and increased clay content, show a significantly lower mean E compared to less altered ones. The dynamic elastic moduli of the sandstones show strong variability with depth, due to the differential cementation and development of natural fractures. Nevertheless, the BI values based on the E to v ratio are much lower compared to the sedimentary rocks of the Groß Schönebeck, which means less favorable conditions for the development of a multi-fracture network. On the other hand, lower BI of the tested rhyolites compared to the corresponding formation in German Basin suggests a higher susceptibility to fracking due to a better developed natural fracture network.
4) Mineral, and elastic moduli-based BI are useful in interpreting susceptibility to HF. In sedimentary rocks with

intergranular porosity, higher BI indicates greater susceptibility to HF, but in igneous rocks with fracture porosity, low BI indicates zones of alteration and fractures that are desirable for hydroshearing stimulation.

Acknowledgements

The authors would like to thank Jacek Nowak PhD and Zdzisław Adamczyk DSc from the Silesian University of Technology for their help in work related to XRD research. This paper is based on research carried out at Silesian University of Technology and Oil and Gas Institute - National Research Institute (Poland), as a part of the implementation doctorate program RJO/SDW/005-33, founded by Ministry of Science and Higher Education of Poland.

Supplementary file

http://doi.org/1046690/ager.2024.11.03

Conflict of interest

The authors declare no competing interest.

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