Geologos 22, 2 (2016): 149–163
doi: 10.1515/logos-2016-0015

GEOLOGOS

Analyses of permeability and porosity of sedimentary rocks in terms of unconventional geothermal resource explorations in Poland

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Abstract

Petrophysical investigations are fundamental to natural resource exploration. In order to recognise the geothermal potential of sedimentary rocks in central Poland, 259 samples were collected from prospective deep-lying geothermal reservoirs. Parameters measured include bulk density, skeletal density, effective porosity, permeability, average pore diameter and specific surface. Results indicate that at great depths (mostly > 3,000 m below surface) sedimentary rocks show low values of porosity (mainly less than 5%) and permeability (only sporadically in excess of 1 md). These values call for a petrothermal use of reservoirs, for which an Enhanced Geothermal System (EGS) was developed. Reservoirs suited for the EGS are Carboniferous and Lower Triassic sandstones in the central part of Poland (Mogilno-Łódź Trough region and a small part of the Kujawy Swell and Fore-Sudetic regions). In addition, Carboniferous limestones in this area are potentially prospective.

Keywords: petrophysical parameters, geothermal energy, Enhanced Geothermal Systems, central Europe

1. Introduction

In Poland geothermal interest has grown since the 1960s (Dowgiałło, 1969; Dowgiałło et al., 1969; Dowgiałło, 1972; Čermak, 1979). Initially, projects focused on the study of geothermal fields within geological units. The first research projects devoted to an assessment of the possibility for utilisation of hot groundwaters and geothermal energy were undertaken in the 1980s at the AGH University of Science and Technology in Kraków (Ney & Sokołowski, 1987). Resulting from a number of studies and geothermal projects carried out since that time, hydrogeothermal resources are relatively well recognised (Górecki et al., 1990–2013, Hajto & Górecki, 2005, 2010; Sowiżdżał, 2012, 2015) as are their possible uses (Papiernik et al., 2008; Sowiżdżał, 2010; Tomaszewska & Szczepański, 2014).

It has been shown that Poland is situated in the zone of low-temperature geothermal resources. Today, geothermal waters are used in several geothermal heating plants and a number of extensive recreational centres and balneotherapeutic facilities. However, geothermal resources are not used for the production of electricity, although studies into this are in progress (Bujakowski & Tomaszewska et al., 2014; Miecznik et al., 2015). In many regions, problems arise from the low production rates of wells as a result of the worst petrophysical parameters of reservoir rocks (i.e., low values of permeability and porosity). Improvement of EGS technology has caused that just the low values of porosity and permeability, together with appropriate thermal conditions and rock fracturability, are suitable for development of petrogeothermal resources. Adequate recognition of such resources is dependent

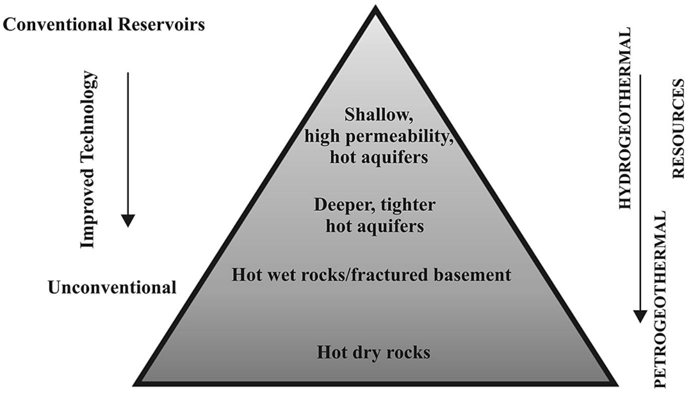


Fig. 1. Geothermal resource pyramids (from Hillis et al., 2004).

of, among other factors, analysis of petrophysical parameters of reservoir rocks.

Originally, petrogeothermal resource was considered a resource distinct from conventional geothermal energy. Types of geothermal resources are shown in Figure 1. The resource pyramid concept suggests that there is a limited amount of prime resources that are easy to extract. There is also a much larger volume of resources that are technologically more difficult to access. Over time, resources near the top of the pyramid are depleted and technological developments lead to resources further down the pyramid being developed cost effectively (Hillis et al., 2004).

The technology of development of conventional geothermal resources (both low- and high-temperature ones) is well known and extensively available. Since the 1970s (the first project led by the Los Alamos National Laboratory, USA) also utilisation of deeper-lying unconventional resources (hot dry or wet rocks) using the Enhanced Geothermal Systems (EGS) has been progressively developed (Tester et al., 2006). The EGS cost cannot yet be assessed accurately because of the limited experience derived from pilot plants, but it appears to become competitive in the near future. The world predictions indicate that petrogeothermal energy is the type of the future and that in the coming years development of this energy sector may be expected (EGEC, 2013).

EGS provide a means of using geothermal energy when hydrothermal conditions are not ideal, that is, when natural conditions in the host rock do not provide sufficient fluid content and/or connected permeability. The idea behind EGS is to emulate what nature provides in high-grade hydrothermal reservoirs at depths where rock temperatures are sufficient for power or heating applications. A fractured reservoir is stimulated hydraulically and connected to injection and production wells separated by sufficient distances to yield a sustainable system for extracting thermal energy stored in the rock (Horne & Tester, 2014). Enhanced Geothermal Systems will greatly increase the geothermal potential as it allows for production of geothermal electricity nearly anywhere in Europe, including Poland, with medium and low temperature (EGEC, 2013).

In 2010–2013 a research project intended to gauge the potential of hot dry rocks for heat and electricity production in Poland was carried out by leading scientific centres (the research consortium consisted of the Polish Geological Institute – National Research Institute, the AGH University of Science and Technology – AGH-UST, the Mineral and Energy Economy Institute of the Polish Academy of Sciences, and the PBG Geophysical Exploration Co Ltd.). The main objective of this project was to assess, by cartographic mapping, the possibility of using geological successions in an EGS development. The goal of the research conducted by the AGH-UST team was to indicate the best location for EGS in sedimentary rocks (Górecki et al., 2013; Sowiżdżał et al., 2013; Sowiżdżał & Kaczmarczyk, 2016).

The aim of the present paper is to list permeability and porosity of deep-seated hot dry rocks in central Poland. For their unconventional resources they were initially eliminated from potentially prospective regions for utilisation of geothermal energy. However, most recent researches conducted within the framework of the project 'Evaluation of potential, thermal balance and prospective geological structures for needs of closed geothermal systems (Hot Dry Rocks) in Poland' highlight their potential for EGS technology.

2. Geological background

The area selected for detailed analyses in terms of a preliminary assessment of potential EGS development covered the central part of Poland (Szczecin-Mogilno-Łódź Trough region and a small part of the Kujawy Swell and Fore-Sudetic regions) (Fig. 2). The former area is part of a belt of troughs that stretches from the northwest to southeast. This belt, known as

Fig. 2. Location of cored wells for analyses; geothermal installations in Poland also are shown (based on Kępińska, 2015).

the Szczecin-Mogilno-Łódź-Miechów Trough (Synclinorium), extends along the southwestern flank of the Mid-Polish Swell, a part of which is represented by the Kujawy Swell. This synclinorium can be divided into three distinct troughs: the Szczecin, Mogilno-Łódź Trough and Miechów troughs, which are separated by horsts of Jurassic rocks below the sub-Cenozoic surface (Karnkowski, 2008; Doornenbal et al., 2010; Mizerski, 2011).

The Szczecin-Mogilno-Łódź-Miechów Trough is filled with the Upper Cretaceous rocks resting on older rocks which crop out under the sub-Cenozoic surface along the southwestern flank of the Mid-Polish Swell, on the Fore-Sudetic Monocline and on horsts. The Permian-Mesozoic cover, which comprises sediments that fill up the Mogilno-Łódź Trough, and occur in the Fore-Sudetic Monocline and Kujawy Swell zones, rests on Rotliegend, Upper and Lower Carboniferous, Devonian, Silurian, Ordovician and Cambrian sequences that rest on crystalline and effusive rocks of the Precambrian basement. In the study area, units of the Variscan orogeny (Variscan externides) have been poorly recognised due to the great thickness of the Permian-Mesozoic cover (Narkiewicz & Dadlez, 2008; Mizerski, 2011).

Vertical movements of blocks in the sub-Zechstein basement, superimposed by deformations caused by movements of the Zechstein salt masses, were the main factors that shaped the present-day structure of the Permian-Mesozoic complex. In the lower part of this complex, thick beds of Zechstein salt became plastic under the influence of accretion of younger sediment series. Therefore they could move, which impacted subsequent sedimentation (changes in thickness and facies, formation of erosional surfaces and sedimentary gaps) and caused mechanical deformation of the overburden. The area of the strongest impact of salt tectonics in Poland covers the Kujawy region and adjacent regions where there is a zone of salt plugs that penetrate rocks up to the sub-Cenozoic surface or salt plugs and salt horsebacks (elongated salt plugs) that in part do so. This zone is surrounded by a zone of weaker effects of such tectonics, which manifests itself by the occurrence of salt swells and salt pillows (Dadlez et al., 1998).

Based on experience made in other parts of the world (Tenzer, 2001; Tester et al., 2006; Sausse et al., 2007; Antkowiak et al., 2010; Brown et al., 2012) the sedimentary rocks in the regions selected meet the following critical requirements for EGS: thermal parameters of the rocks (i.e., temperatures >150°C); thickness of the reservoir (minimum 300 m); porosity and permeability of reservoir rocks (as the lowest); reservoir depth (up to 6 km). Because of

Table 1. Thermostratigraphy of potential rock reservoirs for EGS systems in central Poland.

Stratigraphic identifier	Stratigraphy	Depth [km b.s.l.]	Maximum temperature at the top of the reservoir [°C]	Total thickness of the reservoir [m]
T2	Middle Triassic	0.5–5	160	300–1000
T1	Lower Triassic	1–6	180	300–2000
P1	Lower Permian	3–6	190	300–500
C1	Carboniferous	3–6	200	300–2500

hydrofracturing importance in the reservoir rocks, compact sandstones or limestones have been considered the most appropriate for mechanical properties.

Thermostratigraphy (Table 1) (Wójcicki et al., 2013) as well as surface heat flow density map (60–100 mW/m^2) (Szewczyk & Gientka, 2009) evidence conditions favourable for EGS systems in the Polish Lowlands. In particular, dense sandstones and dense, slightly fractured limestones and dolomites of Triassic age (mainly Early Triassic but locally also Middle), the Lower Permian and Carboniferous formations are considered potential rock reservoirs for EGS systems.

The Carboniferous strata are developed as follows: in the area of the post-orogenic molasses (to the east and northeast of Poznań, and in the Konin, Sieradz, Łódź and Piotrków Trybunalski areas) – as the flysch lithofacies, so-called exoflysch (debrites, turbidites); in the area of the Kujawy Swell – as sandstones, siltstones and claystones (pseudoflysch), and as sandstones and siltstone-claystone deposits (Narkiewicz & Dadlez, 2008).

The Lower Permian is represented by terrigenous deposits that formed in a desert, i.e., under dry and hot climatic conditions. They typically form thick complexes of vari-grained rocks which are diagonally bedded or lumpy. In the Polish Lowlands, Lower Permian formations rest, with a distinct sedimentary gap, on basement rocks characterised by the Variscan and Caledonian consolidation. Among the Rotliegend formations, Autunian effusive rocks (in the western part of Poland) play an important role. The Saxonian deposits are widely distributed and developed as facies of red clastic rocks. In the Saxonian section, a number of sedimentary cycles can be distinguished, the succession of which is sandstone – siltstone – claystone (Dadlez et al., 1998).

The Lower Triassic is represented by lower, middle and upper Buntsandstein rocks which in a major part of the Polish Lowlands are developed as a lithofacies with a predominance of claystone-siltstone deposits. In the lower Buntsandstein of the southern part of the Polish Lowlands basin, sandy fluvial and (less frequently) aeolian deposits occur. In the remaining area of Poland, the Lower Buntsandstein is developed as a monotonous complex of claystone-siltstone rocks with interbeds of oolitic limestones (except for the eastern part of the Mogilno-Łódź Trough) and sandstones. The middle Buntsandstein in the southern part of the basin is represented by sandstones and siltstones. In the Fore-Sudetic Monocline area, sandstones are dominant and towards the Mid-Polish Swell they pass into clayey sediments. The upper Buntsandstein is analysed together with the Muschelkalk (T2+Tp3) in consideration of its predominant carbonate development, whereas sandstones of the lower and middle Buntsandstein (Tp1+Tp2) are treated as prospective formations of the Lower Triassic (Szyperko-Teller, 1997).

The Middle Triassic is represented by the Muschelkalk which can be divided into the lower, middle and upper Muschelkalk. The lower Muschelkalk of the Mogilno-Łódź Trough is developed as grey and beige limestones, often bedded and laminated with claystones and marls. In the northern part of the Kujawy Swell, marly and dolomitic limestones predominate. The middle Muschelkalk, represented by interbedded dolomitic claystones, dolomitic marls and anhydrites, reveals a relatively homogeneous development over vast areas. As a rule, the upper Muschelkalk is composed of limestones in the lower part of the section and claystones with small limestone intercalations in the upper part. This lithological type is characteristic of the upper Muschelkalk in the Mogilno-Łódź Trough. In the area under discussion, the Middle Triassic is represented by the Muschelkalk that is divided into the Lower, Middle and Upper Muschelkalk. In the Mogilno-Łódź Trough, the Lower Muschelkalk is formed of grey and beige limestones, often bedded and laminated with claystones and marls. In the northern part of the Kujawy Swell, marly and dolomitic limestones are dominant. The middle Muschelkalk, represented by intercalated dolomitic claystones, dolomitic marls, dolomites and anhydrites, shows a relatively homogeneous development over large areas. The upper Muschelkalk, as a rule, is composed of limestones in the lower part of its section, and of claystones with thin limestone interlayers in the upper part. Such a lithology is characteristic of the Muschelkalk in the Mogilno-Łódź Trough (Gajewska, 1997).

3. Analyses

In order to recognise petrophysical parameters of rocks that form potential reservoirs for EGS, 259 samples of sedimentary rocks were taken from 12 wells located in the study area (Fig. 2). For these, 259 porosimetric analyses and 57 permeability parameter measurements were carried out. Three types (facies) of sedimentary rocks were analysed: terrigenous (arenites, arkoses, subarkoses), mudstones (siliceous, siliceous-clayey, calcareous, calcareous-clayey, clayey-ferruginous, clayey, clayey-siliceous, calcareous, calcareous-ferruginous, fine- and coarse-grained mudstones) and carbonate (dolomites and micritic, micritic-sparitic, sparitic and microsparitic limestones).

3.1. Porosity

Porosity measurement was performed by mercury porosimetry. In this method, values of effective porosity obtained are a function of bulk density, skeletal density, specific surface of the pore space, and predominant proportion of pores with a determined diameter. Furthermore, the method allows determination and indication of a type of the pore space: simple (porous or fractured pore space) or mixed (porous-fractured pore space) (Tiab & Donaldson, 2004; Giesche, 2006; Semyrka et al., 2008). The essence of the method is based on the assumption that capillary pressures result from interaction between forces acting within a liquid (i.e., cohesion) and forces between liquids saturating the pore space and the rock framework itself (i.e., adhesion). When adhesive forces prevail over cohesive forces, a liquid (e.g., water) is "wetting"; in an inverse relation, a liquid is "non-wetting". Relative wettability of fluids is determined by contact angle between the solid and the wetting/non-wetting liquid interface. In capillary pores, the wetting liquid rises above the interface as a result of adhesion, up to achievement of equilibrium between adhesive forces and gravitational forces (Kuśmierek & Semyrka, 2003).

Quantitative and qualitative investigations of pore space in samples from the cores analysed were conducted using the Auto Pore 20 mercury porosimeter from Micromeritics at the AGH-UST in Kraków. In this apparatus, computer-assisted mercury injection was applied, from a pressure lower than ambient pressure up to $6{\cdot}10^4$ psi (i.e. 413.4 MPa), which allows for penetration of voids from 0.003 μm up to 360 μm.

3.2. Permeability

Determination of the effective permeability coefficient was performed by applying the gas method. The measuring principle consists in bringing steady laminar flow of gas through the test sample (working gas is nitrogen) and calculate the coefficient of permeability using the Darcy equation.

4. Results

Table 2 lists results of laboratory tests on rock samples (average values), within the scope of a quantitative assessment values of the following petrophysical parameters were obtained, i.e. bulk density (ρ_o), skeletal density (ρ_s), effective porosity (φ), pore diameters (Φ), specific surface (S) and permeability (μ), while the qualitative assessment characterised types of pore space in rocks. Selected results of porosimetric investigations of rocks are illustrated in Figures 3–6. Below we outline these results, indicating reservoirs of different lithology and age.

4.1. Middle Triassic deposits

Middle Triassic deposits (T2**)** have been penetrated in the Florentyna IG–2, Grundy Górne IG–1(Fig. 3), Krośniewice IG–1, Piotrków Trybunalski IG–1, Siedlec 1, Strzelce Krajeńskie IG–1 and Zgierz IG–1 wells. These comprise:

- a carbonate facies – rocks with very low porosity (φ = 0.85–1.72%), micropermeable (μ = 0.10 md) and poorly permeable (μ = 3.5 md), with porous-fractured type II reservoir pore space in cores from the Florentyna IG–2, Krośniewice IG–1, Grundy Górne IG–1 and Siedlec 1 wells;
- a mudstone facies – rocks with very low porosity (φ = 1.49–3.30%), micropermeable (μ = 1 md), with porous-fractured and subordinately fractured type II/I reservoir pore space in the Krośniewice IG–1, Siedlec 1 and Strzelce Krejeńskie IG–1 wells, and low porosity in the borehole Piotrków Trybunalski IG–1 (φ = 7.61%), and very low permeability in the order of 0.0001 md;
- a terrigenous facies (very fine-grained subarkoses), recognised in the Krośniewice IG–1 well – rocks with very low porosity (φ = 6.73%), micropermeable (μ = 0.03 md), with porous type I and fractured-porous type II reservoir pore space.

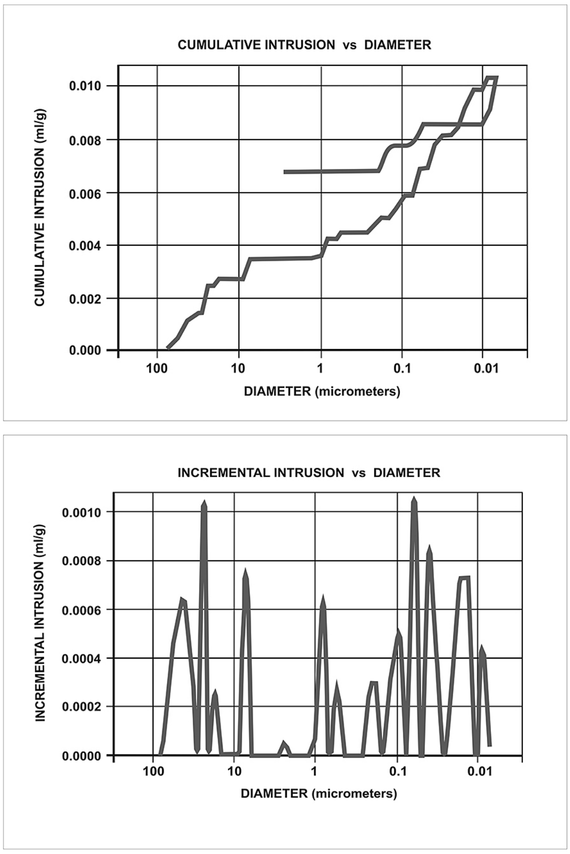
Table 2. Average values of petrophysical parameters of rocks in the well sections analysed.

Well	Stratigraphy	Number of samples (permeability measurment)	Depth of sampling	Facies	Bulk density ρ_o	Standard deviation	Skeletal density ρ_s	Standard deviation	Effective porosity φ	Standard deviation	Permeability μ	Standard deviation	Average pore diameter Φ	Standard deviation	Specific surface S	Standard deviation
	Epoch		[m bgl]		[g/cm^3]		[g/cm^3]		[%]		[mD]		[mm]		[m^2/g]	
Florentyna IG-2	T2	8	2214–2415	carbonate	2.00	0.10	2.67	0.09	1.07	0.55	nd	nd	0.03	0.01	0.63	0.40
	T1	2	2698–2992.5	mudstones	2.58	0.02	2.62	0.015	1.47	0.07	nd	nd	0.08	0.06	0.74	0.59
		4		terrigenous	2.30	0.15	2.45	0.17	7.46	0.90	nd	nd	0.06	0.03	2.64	1.33
Grundy Górne IG-1	T2	7	2200–2346	carbonate	2.40	0.28	2.54	0.26	5.42	8.01	nd	nd	0.15	0.15	0.56	0.27
	T1	4	2584–2739	carbonate	2.70	0.03	2.73	0.03	0.99	0.14	nd	nd	0.22	0.33	0.33	0.31
		1		terrigenous	2.66	0.00	2.70	0.00	0.99	0.00	nd	nd	0.02	0.00	0.40	0.00
	P	3	3946.5–3969.5	mudstones	2.72	0.04	2.74	0.04	1.21	0.48	nd	nd	0.74	0.85	0.62	0.81
		10		terrigenous	2.40	0.18	2.61	0.17	7.01	4.50	nd	nd	0.08	0.03	1.86	0.82
		1		carbonate	2.92	0.00	2.95	0.00	0.98	0.00	nd	nd	0.04	0.00	0.35	0.00
Komorze 1	P	12 (12)	3810–4304.50	terrigenous	2.33	0.22	2.50	0.14	7.76	5.30	2.32	3.22	0.25	0.30	1.62	0.78
	C	5 (5)	4310.5–4338.2	terrigenous	2.66	0.09	2.70	0.10	1.64	0.88	0.04	0.03	0.64	1.17	0.79	0.61
Krośniewice IG-1	T2	5 (1)	4512.7–4598.5	mudstones	2.42	0.23	2.51	0.25	3.40	1.26	0.00	0.00	0.15	0.16	1.28	0.17
		8 (2)		terrigenous	2.48	0.09	2.62	0.09	6.73	2.03	0.03	0.03	0.07	0.04	2.09	0.88
Objezierze IG-1	P	4	4164–4567	mudstones	2.47	0.18	2.52	0.16	1.90	0.76	nd	nd	0.04	0.01	0.90	0.42
		12		terrigenous	2.31	0.26	2.54	0.17	9.84	7.54	nd	nd	0.47	0.44	1.04	0.56
	C	4	4621.2–5090	mudstones	2.67	0.09	2.70	0.09	0.82	0.40	nd	nd	7.90	13.62	0.38	0.24
		23		terrigenous	2.61	0.13	2.65	0.10	1.74	2.36	nd	nd	2.85	8.59	0.47	0.54
Piotrków Trybunalski IG-1	T2	24 (3)	3352.5–3634	carbonate	2.64	0.11	2.68	0.09	1.72	2.42	3.47	4.85	0.23	0.40	0.34	0.24
		3		mudstones	2.39	0.12	2.58	0.08	7.61	1.73	nd	nd	0.23	0.14	0.68	0.24
	T1	13 (5)	3636–4382.5	carbonate	2.59	0.22	2.70	0.13	5.45	5.87	0.14	0.06	0.78	1.97	0.82	1.24
		6		mudstones	2.61	0.11	2.64	0.09	1.95	0.93	nd	nd	0.06	0.06	0.60	0.37
		23 (2)		terrigenous	2.52	0.17	2.60	0.16	3.37	2.44	0.14	0.02	0.09	0.14	0.94	0.57

Table 2. cont.

Well	Stratigraphy Epoch	Number of samples (permeability measurment)	Depth of sampling [m bgl]	Facies	Bulk density ρ_o [g/cm^3]	Standard deviation	Skeletal density ρ_s [g/cm^3]	Standard deviation	Effective porosity φ [%]	Standard deviation	Permeability μ [mD]	Standard deviation	Average pore diameter Φ [mm]	Standard deviation	Specific surface S [m^2/g]	Standard deviation
Polwica 1	P	4 (4)	3323.1–3723.7	terrigenous	2.48	0.11	2.68	0.24	7.55	3.36	0.30	0.53	0.98	1.03	0.39	0.58
	C	2 (2)	3879.7–3916.3	terrigenous	2.69	0.04	2.70	0.04	0.48	0.15	0.03	0.02	0.04	0.03	0.14	0.01
Siedlec 1	T2	9 (2)	4240.3–4389.1	carbonate	2.66	0.11	2.69	0.11	1.29	0.45	0.19	0.27	1.83	2.99	0.36	0.40
		1		mudstones	2.72	0.00	2.76	0.00	1.49	0.00	nd	nd	0.05	0.00	0.47	0.00
	T1	4	4402.3–4433.8	mudstones	2.58	0.17	2.66	0.19	3.11	2.17	nd	nd	0.03	0.02	2.88	1.90
		4		terrigenous	2.72	0.10	2.78	0.12	2.41	1.96	nd	nd	0.02	0.01	0.66	0.71
Siekierki Wielkie 3	P	4 (2)	3669.3–4061.9	terrigenous	2.55	0.06	2.64	0.04	5.51	1.21	0.26	0.27	0.21	0.12	0.52	0.12
	C	4 (4)	4091.10–4125.3	mudstones	2.67	0.09	2.70	0.09	1.24	0.37	0.03	0.05	3.36	3.45	0.04	0.05
		7 (6)		terrigenous	2.55	0.20	2.60	0.19	1.69	0.84	0.30	0.57	2.02	3.08	0.32	0.40
Solec 6	P	2 (2)	3335.3–3341.3	terrigenous	2.17	0.22	2.60	0.03	17.26	8.37	1.27	1.78	6.20	8.58	0.51	0.72
	C	2 (2)	3087.3–3144.3	mudstones	2.64	0.02	2.16	0.01	1.21	0.50	0.01	0.00	9.72	0.88	0.00	7.00
		4 (3)		terrigenous	2.66	0.07	2.69	0.04	1.51	1.31	0.01	0.00	0.08	0.10	0.82	0.78
Strzelce Krajeńskie IG-1	T2	4	2331–2334.5	carbonate	2.46	0.19	2.48	0.19	0.85	0.54	nd	nd	0.57	0.46	17.11	17.79
		1		mudstones	2.52	0.00	2.58	0.00	2.19	0.00	nd	nd	1.58	0.00	0.02	0.00
	T1	2	2441–2553.2	carbonate	2.74	0.07	2.76	0.05	0.80	1.30	nd	nd	0.66	1.32	9.57	26.99
		2		mudstones	2.56	0.03	2.63	0.04	2.42	0.17	nd	nd	1.74	0.23	0.02	0.00
	P	4	4030.5–4042	terrigenous	2.51	0.06	2.55	0.08	1.65	0.94	nd	nd	1.20	0.81	7.13	14.21
Zgierz IG-1	T2	10	3746–3924	carbonate	2.61	0.19	2.67	0.18	2.12	2.40	nd	nd	0.46	0.99	0.59	0.37
	T1	3	3970–4196.5	mudstones	2.57	0.05	2.65	0.04	3.47	0.62	nd	nd	0.03	0.00	2.30	0.75
		4		terrigenous	2.31	0.29	2.36	0.23	3.62	2.55	nd	nd	0.10	0.07	1.27	0.62

nd – no data.



Effective porosity
$\varphi = 2.69\%$
Apparent (skeletal) density
$\rho_s = 2.61\ \mathrm{g/cm^3}$
Bulk density
$\rho_o = 2.68\ \mathrm{g/cm^3}$
Average capillary diameter
$\Phi = 0.0521\ \mu\mathrm{m}$
Total pore area
$S = 0.789\ \mathrm{m^2/g}$

Type of the pore space:
fractured (III)

Fig. 3. Results of porosimetric investigations of Middle Triassic (Muschelkalk) rocks in the Grundy Górne IG–1 well (sample of microsparitic limestones from a depth of 2,346.0 m).

4.2. Lower Triassic deposits

Lower Triassic deposits (T1) have been identified in the Florentyna IG–2, Grundy Górne IG–1, Piotrków Trybunalski IG–1(Fig. 4), Siedlec 1 and Strzelce Krajeńskie IG–1 wells. They are developed in:

- a mudstone facies – rocks with very low porosity (φ = 1.47–3.11), mostly with fractured type III and subordinately porous-fractured type II reservoir pore space;
- a terrigenous facies – generally low-porosity rocks, with fractured and porous-fractured reservoir pore space, except for the Florentyna IG–2 well which reveals low porosity, mostly with fractured reservoir pore space;
- a carbonate facies – rocks with very low porosity, mostly with fractured reservoir pore space. Only the Piotrków Trybunalski IG–1 well section departs from this picture, having revealed low porosity of deposits;

4.3. Permian deposits

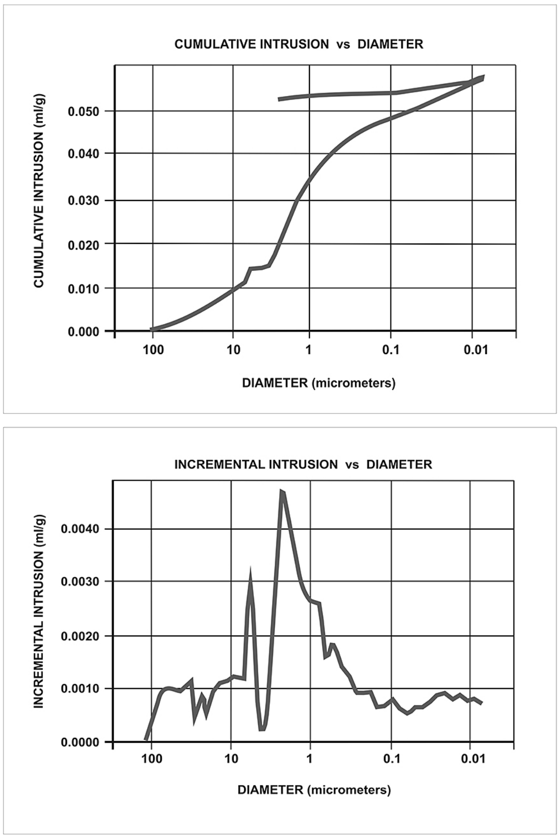
Permian strata (P) have been encountered in the Grundy Górne IG–1, Komorze 1 (Fig. 5), Objezierze IG–1, Polwica 1, Siekierki Wlk. 3, Solec 1 and Strzelce Krajeńskie wells, as:

- a terrigenous facies – mainly arenites and subarkoses with low porosity, with porous and sporadically fractured or porous-fractured reservoir pore space. Only in the distant Strzelce Krajeńskie IG–1 well are there rocks with very low porosity and fractured reservoir pore space;
- a mudstone facies, occurring only in the neighbouring Grundy Górne IG–1 and Objezierze IG–1 wells. These are rocks with very low porosity and composite fractured-porous reservoir pore space;
- a carbonate facies with very low porosity and fractured reservoir pore space, identified only in the Grundy Górne IG–1 well.

4.4. Carboniferous deposits

Carboniferous rocks (C) have been encountered in the Komorze–1, Objezierze IG–1 (Fig. 6), Polwica–1, Siekierki Wielkie–3 and Solec–6 wells. They are developed in:

- a terrigenous facies – arenites and subarkoses with low porosity ($0.48 < \varphi < 1.7\%$), micropermeable (below 0.3 md; mostly 0.1 mD), with



Effective porosity
φ = 13.02%

Apparent (skeletal) density
$\rho_s = 2.27\ \mathrm{g/cm^3}$

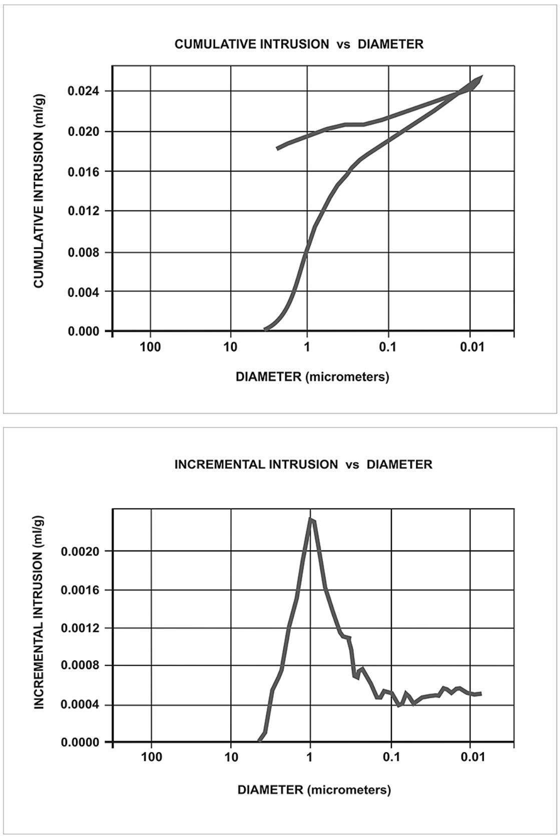
Bulk density
$\rho_o = 2.68\ \mathrm{g/cm^3}$

Average capillary diameter
$\Phi = 0.1118\ \mu\mathrm{m}$

Total pore area
$S = 2.054\ \mathrm{m^2/g}$

Type of the pore space:
porous - fractured (III)

Fig. 4. Results of porosimetric investigations of Buntsandstein rocks in the Piotrków Trybunalski IG–1 well (sample of micritic limestones from a depth of 3,746 m).



Effective porosity
φ = 5.81%

Apparent (skeletal) density
$\rho_s = 2.31\ \mathrm{g/cm^3}$

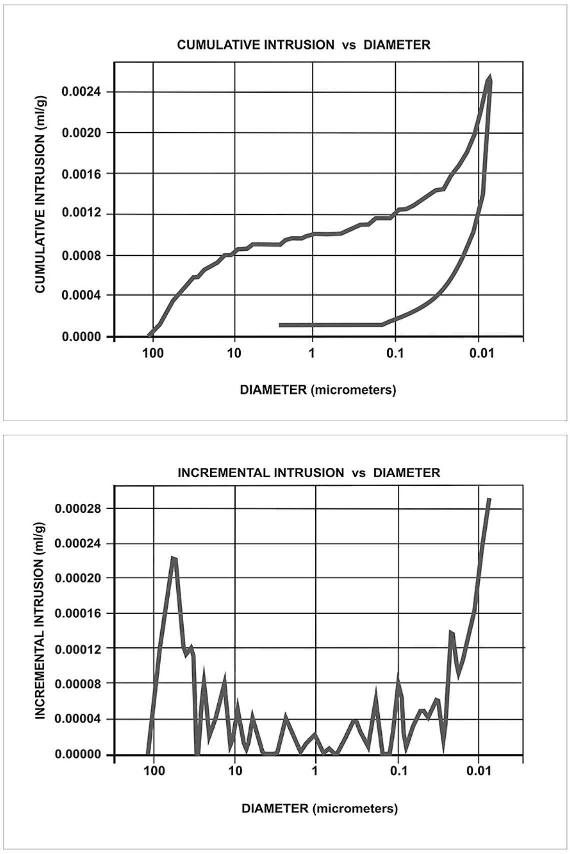
Bulk density
$\rho_o = 2.40\ \mathrm{g/cm^3}$

Average capillary diameter
$\Phi = 0.0740\ \mu\mathrm{m}$

Total pore area
$S = 1.362\ \mathrm{m^2/g}$

Type of the pore space:
porous (I)

Fig. 5. Results of porosimetric investigations of Permian rocks in the Komorze–1 well (sample of fine-grained arenite from a depth of 4,304.5 m).



Effective porosity
φ = 0.67%
Apparent (skeletal) density
ρ_s = 2.69 g/cm^3
Bulk density
ρ_o = 2.71 g/cm^3
Average capillary diameter
Φ = 0.0256 μm
Total pore area
S = 0.390 m^2/g

Type of the pore space:
porous - fractured (III)

Fig. 6. Results of porosimetric investigations of Carboniferous rocks in the Objezierze IG–1 well (sample of mudstone from a depth of 4,676.5 m).

fractured-porous type II and subordinately fractured type III reservoir pore spaces;

- a mudstone facies with low porosity and fractured reservoir pore space (0.82 < φ < 1.24%) and low permeability (below 0.03 mD), fractured-porous type II, subordinately fractured type III or porous type III reservoir pore spaces.

5. Discussion

The rocks examined are essentially sedimentary. For this purpose, both types of sedimentary rock and places of their occurrence were considered. Samples of rocks analysed were taken from various depths between 2,200 and 5,090 m below surface. (interval 4,621.2–5,090 m). Carboniferous deposits (mudstones and terrigenous rocks) in the Objezierze IG–1 well were the deepest-lying strata, while Middle Triassic carbonate deposits identified in the Strzelce Krajeńskie IG–1, Florentyna IG–2 and Grundy Górne IG–1 wells occurred in the shallowest zone.

Among 259 samples of sedimentary rocks taken from 12 wells in the study area 82 samples represented carbonate deposits, 44 mudstones and 133 terrigenous deposits. Carbonate rocks occur mainly within Triassic reservoirs, while terrigenous and mudstone rocks occur in all reservoirs analysed.

The rocks studied are low to very low porous, have low permeability and sporadically have fractures. These rocks are characterized by absence or low content of water (Tiab & Donaldson, 2004). These features differ widely from conventional conditions useful for operable geothermal systems (Górecki et al., 2006a). However, the rocks studied are mostly appropriate for unconventional geothermal systems (Tester et al., 2006; Brown et al., 2012). In particular, high values of reservoir parameters of rocks (both effective porosity and permeability) are characteristic of Permian sandstones (favourable for conventional geothermal systems), whereas relatively low values of the parameters analysed (favourable for EGS systems) are related to Carboniferous and Lower Triassic sandstones. The average porosity of terrigenous rocks is in the range of 0.5% to 10%, with one exception (>17%; Permian deposits in the Solec–6 well; see Table 2). The maximum porosity value (29%) has been measured for a Permian sandstone sample in the Objezierze IG–1 well at a depth of 4,165 m below surface (Fig. 7A). The average porosity of carbonate rocks is variable, from less than one to over 5% for all stratigraphic horizons analysed (Table

2), with Carboniferous limestones characterised by the lowest values. Most samples analysed are characterised by porosity below 5% but in few cases porosity greater than 10% was measured (maximum value 25.06% inGrundy Górne IG–1 well, the Middle Triassic at a depth of 2,201 m below surface) (Fig. 7A). The average porosity of mudstone rocks is in the range of less than 1% to almost 8% (Table 2). Most of the samples analysed are characterised by a porosity of a few percent; only in the Piotrków Trybunalski IG–1 well (the Middle Triassic) are values slightly higher. Permeability measurement was performed for a much smaller number of samples. The samples were taken from depths of 3,000 to 4,500 m below surface (Fig. 7B). The highest value of permeability (10.33 mD) was recorded for the Lower Triassic carbonate deposits in the Piotrków Trybunalski IG–1 well. All results for mudstones are slightly above than 0 (Table 2; Fig. 7B). Permeability of terrigenous deposits mostly is less than 2 mD, with few exceptions (Permian sandstones in the Komorze–1 well) (Fig. 7B).

Following the petroleum-industry classification, rocks can be qualified based on effective porosity (k_e) as:

- very low porosity ($\varphi < 3.5\%$);
- low porosity ($3.5 < \varphi < 10\%$);
- moderate porosity ($10 < \varphi < 15\%$);
- high porosity ($15 < \varphi < 20\%$);
- very high porosity ($\varphi > 20\%$).

However, this classification cannot be applied to fractured rocks, in view of different characters of potential filtration (Plewa & Plewa, 1992,Bachleda-Curuś & Semyrka, 1997; Burzewski et al., 2001; Such, 2002; Tiab & Donaldson, 2004; Semyrka et al., 2008; Semyrka, 2013).

In consideration of permeability, rocks can be classified as:

- rocks with very high permeability ($\mu > 1000$ md);
- rocks with high permeability ($100 < \mu < 1000$ md);
- rocks with good permeability ($10 < \mu < 100$ md);
- rocks with low permeability ($1 < \mu < 10$ md);
- impermeable (micropermeable) rocks ($\mu < 1$ md).

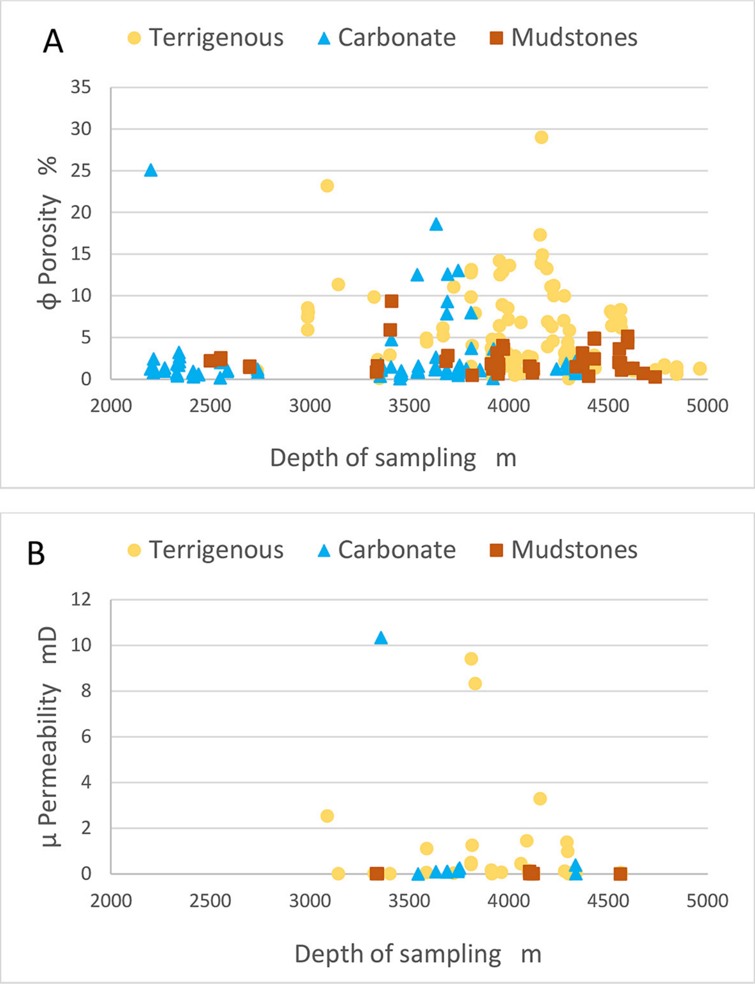


Fig. 7. Distribution of porosity (**A**) and permeability (**B**) as a function of sampling depth and facies.

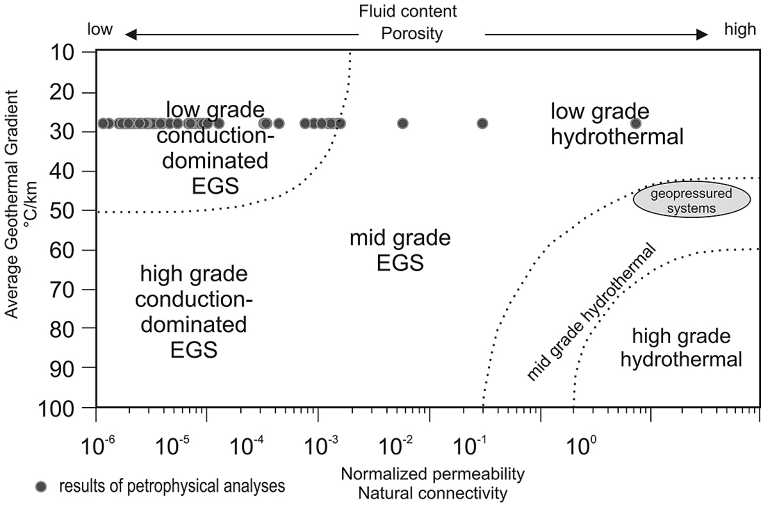


Fig. 8. Continuum of geothermal resources as a function of average temperature gradient, natural connectivity and fluid content. Relative values of permeability (μ) and porosity (φ) indicate effective ranges in natural geological settings. The arbitrary scale for permeability is the ratio between the effective permeability of the entire geothermal system relative to a very permeable unconsolidated sand (adapted from Thorsteinsson et al., 2008).

Three genetic types of reservoir can be distinguished: porous (I), porous-fractured (II) and fractured (III) (Semyrka et al., 2008).

As can be observed in the above analysis, the lithological varieties occurring in the well sections are characterised, for the most part, by very low and low porosity, with predominant porous-fractured and fractured reservoir pore space (Table 2). Relatively increased porosity values, with porous type I reservoir pore space, are seen in Permian deposits.

With the purpose of analysis of results of petrophysical investigation for samples collected from wells in central Poland, functions of average temperature gradient, natural convectivity and fluid content were used (Horne &Tester, 2014), on which results obtained were superimposed. The geothermal gradient in this region ranges from approximately 21 to 35°C/km (Wójcicki et al., 2013).

For the study area, an average value of 28°C/km was accepted. According to the classification presented above, it was assumed that low porosity values are those under 3.5% whereas high porosity values are over 20%.

As can be seen from Figure 8, the majority of samples in central Poland have indicated the occurrence of low-grade, conduction-dominated EGS. Samples located outside the area plotted are related to Permian sandstones, the porosity of which attests to the occurrence of low-grade hydrogeothermal resources.

7. Summary

Our petrophysical investigations have confirmed that sedimentary rocks in the central part of Poland, at depths between 2,200 and 5,000 m below surface, are characterised by low values of porosity and permeability. Their thermal conditions on site allow us to describe the rocks as prospective for potential development of petrogeothermal energy.

EGS is recognised as a technology of the future, but it is far from being applied. At this stage it is important to recognise a geological reservoir with such a type of geothermal potential. Petrophysical analyses represent one of many ways to assess this in Poland. These studies will provide data on some other relevant parameters, including susceptibility of rocks to fracturing (Horne & Tester, 2014) which could affect the effectiveness of EGS, i.e., the presence of heterogeneity, clay material and mineralised waters.

Acknowledgements

The research has been undertaken at the request of the Ministry of the Environment and financed by the National Fund for Environmental Protection and Water Management. The paper prepared under AGH-UST statutory research grant No. 11.11.140.321.

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Manuscript received: 3 November 2015
Revision accepted: 5 April 2016