Conceptual model for geothermal reservoir suitable for Enhanced Geothermal Systems using CO_2 as a working fluid – central part of Poland

Anna Sowiżdżał, Leszek Pająk, Paweł Gładysz

AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow

email address of (main) author: ansow@agh.edu.pl

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ABSTRACT

The article presents the analysis of the geothermal potential of Poland in terms of the construction of the Enhanced Geothermal Systems using CO_2 as a working fluid. On the basis of previous experience and implemented projects in the field of petrogeothermal energy utilization using Enhanced Geothermal System as well as CO_2 sequestration in Polish conditions appropriate geological structure has been selected. Due to the depth of deposition and predicted thermal and petrophysical parameters, the optimal location occurs in central part of Poland. The structure combining the requirements of both systems (EGC and CO_2) is located in sedimentary rocks. For selected structure a conceptual geological model has been developed.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) are unconventional systems, unlike classical systems, where an energy carrier is underground water accumulated in a geothermal reservoir. They make it possible to utilise geothermal energy, when hydrogeothermal conditions of a given location (poor reservoir parameters of rocks or no connection to a supply zone) make it impossible to obtain a suitably high performance of boreholes. The concept of utilising heat of hot dry rocks (HDR) was conceived in 1970, when the method of using energy accumulated in compact rocks not containing any water was put forward in the Los Alamos Laboratory (Brown et al.., 2012). The idea of HDR systems utilising the earth's heat in closed geothermal systems by an artificial increase of hydraulic performance of a geothermal reservoir was developed.

Conventionally, there are two popular working fluids for EGS: water (H_2O) and carbon dioxide (CO_2) (Aminu et al., 2017). Because of the superior thermodynamic properties of CO_2 and the need to reduce atmospheric carbon emissions, an EGS running on CO_2 instead of water as heat transmission fluid would be sufficiently attractive (Zhang et al., 2016; Cui, 2018; Preuss, 2006; Olasolo, 2018). Compared with water-based EGS, the CO_2-based EGS has much higher production flow rate, which results in lower fluid loss ratio especially at low average reservoir permeability and initial reservoir temperature. For CO_2 based EGS, as surrounding formation permeability increases, CO_2 sequestration amount increases, and heat extraction rate decreases slowly, showing that surrounding formation permeability has important influences on CO_2 sequestration and heat extraction (Wang et al., 2018; Guo et al., 2019) .

Enhanced Geothermal System (EGS) with CO_2 instead of water as the working fluid (CO_2 - EGS) has attracted much interest due to the additional benefit of CO_2 geological storage during the power generation process. CO_2 - EGS concept was proposed by Brown (2000) to coincide with the need to reduce carbon dioxide emissions. Besides the potential for CO_2 geological storage because of working fluid losses at great depths, investigations have shown other advantages of CO_2-EGS including large expansivity and compressibility, favorable transport properties (larger ratio of density to viscosity under typical reservoir conditions), low salt solubility and low chemical activity, and self-driven high flow rates due to the strong buoyancy force (Luo, 2014; Pruess, 2006; 2007; 2008; Pritchett , 2009).

Taking into account the above aspects, it seems possible to combine geothermal development and CCS, both in order to reduce carbon dioxide emissions and for cost-efficient heat and/or electricity generation. Processes accompanying CO_2 injection into deep aquifers can be simultaneously used for both sequestration and associated production of clean energy (Wójcicki, 2012).

In this work, the analysis of building of Enhanced Geothermal Systems (EGS) using CO_2 as a working fluid in Poland in terms of geological conditions has been carried out. This method combines the geothermal energy and CO_2 injection instead of water in a closed loop.

The paper is a part of the project aimed at developed an optimal structure of the biomass-fired combined heat and power plant with CO_2 capture integrated with CO_2 enhanced geothermal systems by means of process mathematical modelling and advanced exergo-ecological and technoeconomic analysis. The proposed concept of an integrated energy systems aims to prove the economic and environmental benefits resulting from the synergy of cogeneration of heat and electricity, renewable energy sources usage (biomass and geothermal) and CO_2 capture, utilization and storage technology. The first part of the work, presented in this article, is related to selection an optimal geological reservoir for Enhanced Geothermal System in Polish conditions with the simultaneous construction of the conceptual model of this area. For the selected location (central part of Poland), further work will be continued in the next stages of the project.

2. GEOLOGICAL CONDITION OF GEOTHERMAL RESOURCES OCCURENCE IN POLAND

2.1 Geological background

Poland is a country located in Central Europe (fig.1). It is divided into 16 administrative subdivisions, covering an area of ca. 312 km^2 and has a largely temperate seasonal climate. With a population of approximately 38.5 million people, Poland is the sixth most populous member state of the European Union.

Poland is characterized by low-temperature geothermal resources. These kind of geothermal resources are typically used in direct-use applications, such as district heating, greenhouses, balneotheraphy etc. Geothermal resources are strictly geologically determined.

Poland is situated at the interface between three main European geostructural units: the Precambrian East European Platform, the Paleozoic units of Central and Western Europe (Caledonian and Variscan) and the Carpathian range (part of the Alpine system). Each of these structures is characterized by distinct geothermal conditions, both in Europe and Poland. Sedimentary rocks covers almost throughout the territory of Poland, exception is the area located in SW of Poland (Sudets Mts.) where mostly crystalline rocks occurs.

Figure 1: Location of Poland on the background of Europe map.

2.2 Geothermal resources

The results of research work (Górecki (ed.) et al., 2006; Górecki et al., 2015; Sowiżdżał, 2018; Sowiżdżał et al., 2013; 2016; Wójcicki et al., 2013) show that in Poland there are both hydrogeothermal as well as petrogeothermal resources, but currently only hydrogeothermal energy (connected with geothermal water) is utilized. Although petrogeothermal energy that constitutes heat resources of rocks has not yet been utilized, the research work tending to assess the possibility of utilization of this type of energy is carried out (Sowiżdżał et al., 2013; Wójcicki et al., 2013).

Due to the specific geological structure and therefore different hydrogeothermal conditions, Poland can be divided into four major geothermal provinces (Fig.1):

Polish Lowlands, Carpathian Foredeep, Carpathians and Sudetes.

The largest in area (approximately 87% of the country) and the most perspective is a province of the **Polish Lowlands** (Fig.1). Water in these areas are characterized by favourable temperatures (even above 90°C) and relevant value of discharges of wells (to several hundred m^3/h). The principal resources of geothermal waters in the Polish Lowlands are accumulated in the Mesozoic groundwater horizons. Geothermal waters are accumulated first of all in the Lower Jurassic and Lower Cretaceous formations (Sowiżdżał, 2018; Górecki et al, 2015; 2018).

In the southern part of Poland the **Carpathians** region is located (Fig.1). The best reservoir and exploitation properties for geothermal waters utilization occur in the inner Carpathian - Podhale, represented by: favourable reservoir parameters and lithology, usually high yields and regional extent of the aquifer as well as recent recharge and low TDS. Podhale is a region in the Western Carpathians where geothermal waters are utilized recently and will be utilized in the future, preferably for heat generation but also for recreation and balneotherapy purposes. The reservoir rocks for geothermal waters are mainly Triassic carbonates, sometimes Jurassic sandstones and carbonates. The most prospective aquifer (subject of exploitation) occurs within the Middle Triassic limestones and dolomites and in overlying Middle Eocene carbonates at the depths of 1-3.7 km (Hajto, 2011). In the remaining part of the Carpathians reservoir parameters are much worse. Geothermal aquifers in Outer Carpathians are characterised by usually small and non-renewable resources as well as high mineralisations, which excludes their wider use. These waters occur usually in small closed structures, which reduces obtaining higher outflows (Chowaniec, 2009).

In **Carpathian Foredeep** Province the aquifers of the Cenomanian, Upper Jurassic, Devonian-Carboniferous and Miocene are most prospective. However, in these aquifers, the most favourable parameters for location of geothermal intakes occur in small areas and depth intervals. The Cenomanian aquifer is an exception, as high discharges (to 250 m^3/h) can be expected over the whole area of its occurrence (central part of Carpathian Foredeep). The problem in this province could be weak hydrogeological parameters that determine low discharges of geothermal water intakes (Sowiżdżał, 2015).

The **Sudetic** Geothermal Region, located in SW Poland and including the Sudetes Mts and the Fore-Sudetic Block is an exception as compared to the rest of Poland's geological setting. This province is consist mainly of old crystalline rocks covered with younger sediments. Precambrian and Lower Palaeozoic gneisses and schists with not uncommon marble intercalations were intruded by Upper Carboniferous granitoids which form among others the core of the Karkonosze-Izera massif. In synclinal structures the crystalline rocks are covered with Phanerozoic sediments (Silurian-Quaternary). Geothermal waters occur in this region only in the crystalline formations. Most of the fragmentary hydrogeothermal investigations carried out so far in the Polish part of the Sudetes were limited to zones of occurrence of thermal waters utilized for therapeutic purposes, or to a few areas in which prospection has been carried out for such waters (Dowgiałło, 2002: Ciężkowski, 2011). However, the Sudetic region is characterized by favourable thermal conditions. In Cieplice, water with temperature 86.7ºC was obtained from the depth 2002.5 m.

The existing use of geothermal energy in Poland relates mainly to the utilisation of hydrogeothermal resources in the area of the Polish Lowland and Inner Carpathians (Podhale), where geothermal heat plants are presently in operation and new ones are at different stages of construction. Petrogeothermal resources are not currently developed, although the results of studies (Wójcicki, Sowiżdżał, Bujakowski (eds.) et al., 2013) have enabled to indicate 5 interesting zones in terms of building EGS systems located in volcanic, crystalline and sedimentary rocks (Fig.2).

Search for geological structures, prospective for potential application of the EGS technology in Poland, draws our attention mainly to the location of magma rocks, particularly crystalline rocks. In Poland, uncovered magma rocks, which are of interest in the aspect of the application of the EGS technology, with relatively large surfaces and volumes, occur in the south, mainly in the Sudetes (together with the Fore-Sudetic Block), continuing in the Czech Republic. The area with potentially very favourable conditions for utilising the EGS technology, mainly due to the lithological nature of granite formations building it, which are the most susceptible to fracturing processes, i.e. the pluton of Karkonosze. The problem may be deep tectonics, i.e. a possibility of uncontrolled escape and loss of the injected fluids.

In volcanic rocks, the following study areas have been selected: the area of Gorzów Block (basic – Lower Permian vulcanites) and the area of Parczew (Ediacaran and Visenian volcanism).

Due to a higher temperature on a regional scale and large thickness of volcanic formations, a particularly attractive region in the context of using unconventional geothermal resources is north-western and western part of Gorzów Block. The area of Dębno has been selected as an optimum location for an EGS system. This is where the occurrence of trachyandesites containing post-gas bubbles was reported, being rocks with potentially very good properties for fracturing. However, the problem here can be an unfavourable influence of mineral composition of the rock and its susceptibility to fracturing processes and long-term transport of fluids.

The analytical works conducted in sedimentary rocks have enabled to select several potential areas prospective for the construction of closed geothermal systems in sedimentary rocks. In the Polish Lowlands, two areas become apparent. The first area encompasses the region of the Szczecin Trough, whereas the second area is situated in the central part of Poland, mostly in the region of the Mogilno-Łódź Trough and fragmentarily in the Kujawy Swell region. In south part of Poland, the central part of the Upper Silesian Block may be considered to be prospective.

The highest perspectives were indicated in the central part of the Polish Lowland. On the area covering Mogilno-Łódź Trough and a small part of Kujawy Swell and Fore-Sudetic monocline przedsudeckiej, perspectives were indicated to build closed geothermal systems in Middle and Lower Triassic, Lower Permian and Carboniferous. The Krośniewice-Kutno area was found to be the most prospective zone for the location of an EGS system (Fig.2).

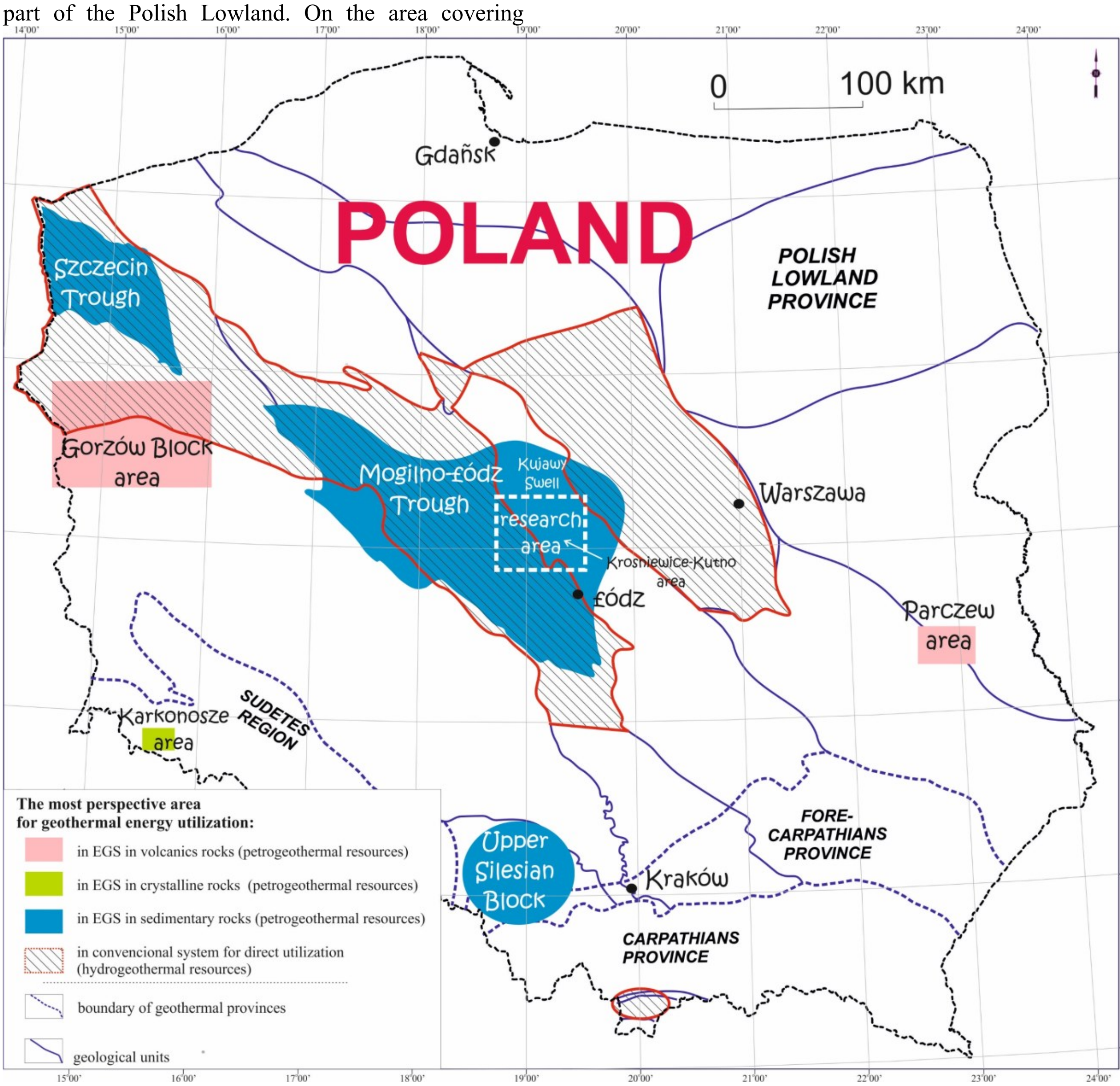

Figure 2: Localization of research area on the background of the most prospective area for geothermal energy utilization in Poland (based on Górecki (ed.) et al., 2006; Wójcicki et al., 2013).

3. SELECTION OF AN OPTIMUM STRUCTURE FOR THE LOCATION OF EGS SYSTEMS UTILISING CO_2 AS A MEDIUM

The selection of the an optimum structure for the location of EGS systems utilising CO_2 as a medium has covered the analysis of geological and hydrogeothermal conditions suitable for building EGS systems while taking into account possibilities of concurrent underground storage of CO_2.

Underground storage of CO_2 can be considered when there are suitable geologic conditions. Sedimentary basins located in tectonically stable areas, with no contemporary volcanism or earthquakes, are best for this purpose (Bachu, 2000). The basic geological condition decisive about a possibility of underground storage large CO_2 quantities is the occurrence of sedimentary rocks with large thickness, considerable spread, good collection properties, having an isolating rock overburden (Tarkowski, 2005).

In a long-term perspective, underground CO_2 storage is determined by an impact of four basic mechanisms (Holloway, 2002):

- immobilisation in reservoir traps – replacement of reservoir fluids with CO_2,
- solution in surrounding reservoir fluids,
- geochemical reactions with reservoir fluids or rock building minerals,
- if sealing is not perfect, migration outside the reservoir, where geological storage is performed.

Geological structure designated for underground CO_2 storage should meet the following criteria:

- form a structural or stratigraphic trap, most favourably in the form of an anticline, characterised by considerable capacity,
- reservoir rocks should have appropriate porosity and permeability to ensure suitable storage capacity,
- it should be tight, covered with impermeable rocks with suitable thickness,
- it should be located at a suitable depth so as to ensure required pressure and capacity of CO_2 being injected.

Rock formations designated for CO_2 storage should be located much below any utilised aquifers. They should be separated from them by one or several layers of impermeable insulation rocks, preventing gas from getting through to potable water levels located higher. The absorbent zone of the level selected for storage should be characterised with sufficient rock porosity in order to receive as much injected gas as possible. The CO_2 injection area should be geologically stable. CO_2 storage should take place with no gas migration to other layers. A degree of isolation of the formations to be used for storage should be considered in relation to the system of hydrodynamic conditions in a given geological structure, trying to control CO_2 distribution. A big role is played by strength of insulating layers, including layer plasticity. It should be high enough to prevent the phenomenon of fracturing and, in consequence, layer puncture as a result of excessive injection pressure. It is necessary to analyse in detail overlaying sealing beds, which requires detailed studies, tests and trials. Geological tightness is particularly important, since storage in such structures usually requires higher pressures than hydrostatic pressure. Lack of geological tightness can occur, for instance, in tectonically involved aquifers, which eliminates a given structure for the purposes of carbon dioxide storage (Tarkowski, 2005).

The results of the performed works (Tarkowski and Uliasz-Misiak 2005, Wójcicki, 2010, Dubiński et al., 2010) have enabled to indicate in Poland formations and geological structures suitable for underground CO_2 storage. From the geological point of view, basic factors to be analysed include, similarly as in case of structures for unconventional geothermal systems, geological, geothermal and hydrogeological conditions. Yet, the geological structure itself has to meet a number of conditions, such as depth, volume, thickness of isolating overburden, reservoir tightness, permeability and porosity of rocks determining storage capacity for CO_2, hydrogeological contacts and the like.

Geological structures with a view to making an underground CO_2 storage in Poland were recognised in a number of projects, studies and analyses (Tarkowski and Uliasz-Misiak 2005, Wójcicki, 2010, Dubiński et al., 2010), however, it concerned CO_2 sequestration in depleted gas and oil reservoirs, deep coalbeds and deep aquifers. None of the above-mentioned works accounted for concurrent use of the potential of hot dry rocks and CO_2 sequestration in Poland.

Due to the analysis of the above-listed factors, potential structures for CO_2 sequestration were indicated within Lower Cretaceous, Lower Jurassic and Lower Triassic formations in the area of the Polish Lowland. Due to thermal conditions occurring in those reservoirs, interesting formations for EGS systems are Lower Triassic formations, where in the central part of the Polish Lowland temperatures exceed the assumed limit by at least 100°C. What is more, Lower Cretaceous and Lower Jurassic reservoirs constitute basic hydrogeothermal reservoirs in the area of the Polish Lowland characterised by considerable geothermal potential (Fig.2). Geothermal installations operating currently in the area of the Polish Lowland utilise successfully waters from those reservoirs. It is thus a key premise to treat the Lower Cretaceous reservoir and the Lower Jurassic reservoir only as geothermal reservoirs.

The situation is different in case of a Lower Triassic reservoir. All studies conducted so far (Sowiżdżał et al., 2013; Wójcicki et al., 2013) point out rather poor water content in this reservoir and low perspectives for building conventional geothermal installations.

Although a EGS geothermal system with the location in the zone of sedimentary rocks occurrence shows slightly poorer thermal parameters than in case of locating such geothermal systems in crystalline or magma rocks, from the point of view of CO_2 sequestration the best solution is to select sedimentation basins located in tectonically stable areas, which is proven by the above-shown criteria. Therefore, the optimum structure combining the requirements of both systems (EGS - CCS) is a structure located in sedimentary rocks. Due to the depth and expected thermal and petrophysical parameters of Lower Triassic formations, an optimum location occurs in central Poland in the area of Krośniewice–Kutno (Fig.2).

4. CONCEPTUAL MODEL FOR GEOTHERMAL RESERVOIR SUITABLE FOR ENHANCED GEOTHERMAL SYSTEMS USING CO_2 AS A MEDIUM

For the selected area, a conceptual geological model was developed, which will be used in further works relating to system operation modelling. A petrogeothermal reservoir is made up of Lower Triassic sandstones (Lower and Middle Buntsandstein). The top Lower Triassic formations on the area being analysed is located on the study area at depths ranging from ca. 4000 to 6000 m under sea level, whereas in the location of a potential EGS installation the Lower Triassic top occurs at depths ranging from 5000–5500 m under sea level. Lower Triassic formations are characterised by considerable thickness, exceeding 1000 m. Reservoir rocks are characterised by average porosity of ca. 2.5-3% and low permeability (0.02- 0.1 mD) and average bulk density of ca. 2.7 g/cm^3. Petrophysical studies run in Poland (Sowiżdżał, Semyrka, 2016) confirm that sedimentary rocks in the central part of Poland on large depths are characterised by low porosity and permeability values, which – taking into account thermal conditions of a given region – enables to regard them as prospective for potential petrogeothermal energy management. Temperatures in the top of the Lower Triassic reservoir range from 165-170°C, whereas within the reservoir boundaries one can expect higher temperatures even up to 190°C. Reservoir overburden is built up from compact impermeable carbonate Muschelkalk formations (T2). Below there are Permian formations: Zechstein and Rotliegend (P1 and P2) as well as Carboniferous (C) (Fig.3).

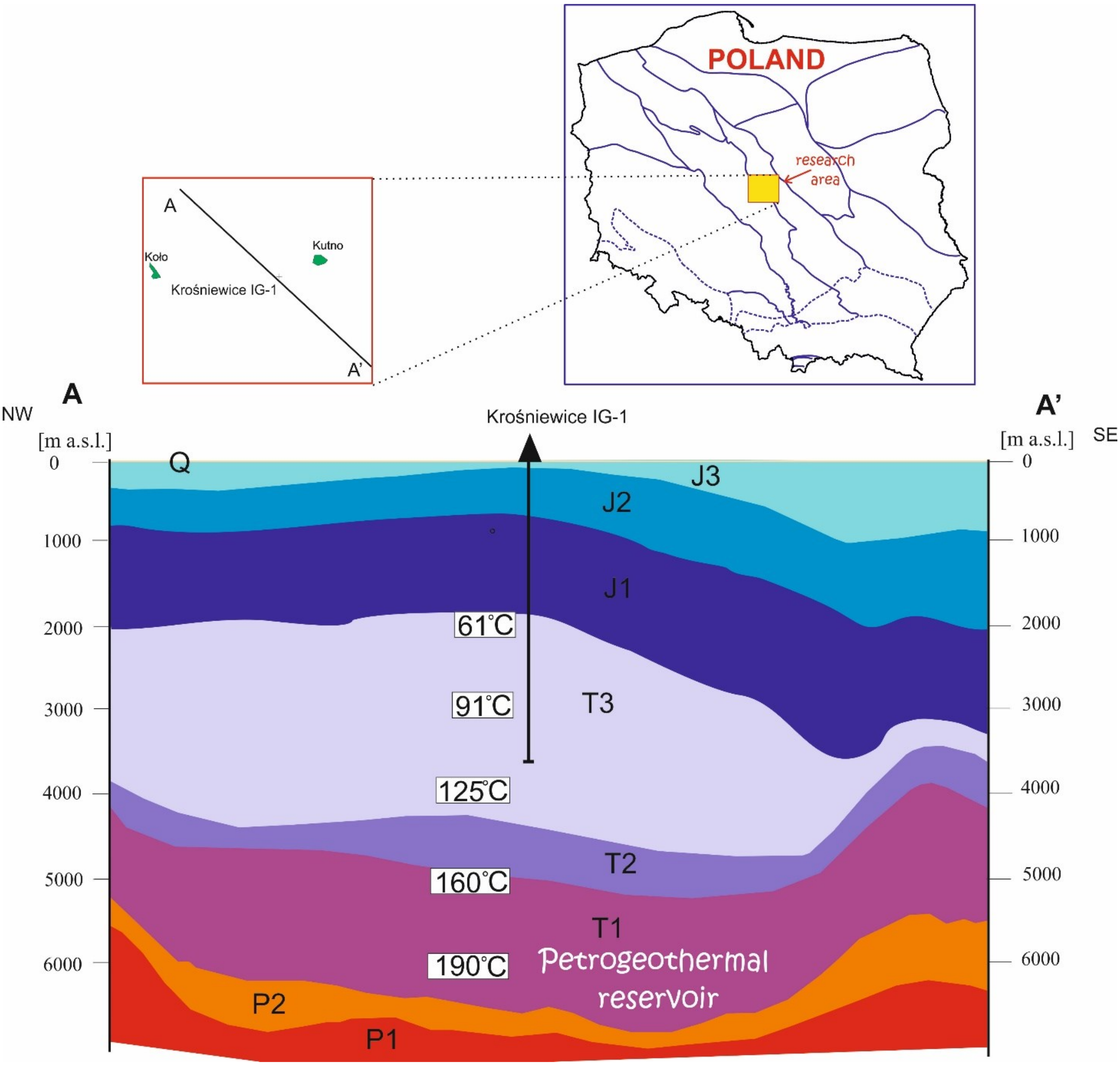

Figure 3: Geological cross-section through the Krośniewice-Kutno region together with the forecast distribution of the temperatures.

3. CONCLUSIONS

The considerations presented in this article contains the first part of research aimed at examining the legitimacy of building EGS installations in Poland, utilising CO_2 as a medium. In Poland, current hydrogeothermal resources are utilised, which are related to underground waters from various reservoirs. In the area of the largest geothermal province, i.e. the Polish Lowland, the most prospective for the use of geothermal waters are Lower Cretaceous and Lower Jurassic reservoirs, from which currently exploited waters are used for heating, recreational and balneotherapeutic purposes. The other reservoirs occurring in the area of the Polish Lowland are not currently very significant, and their development perspectives are limited. This is proven by research conducted so far, aiming at recognising a geothermal potential of different geological formations. Those works also concerned recognition of the potential for building unconventional geothermal installations (EGS) utilising energy of hot dry rocks. Geological structures, prospective for a potential application of the EGS technology in Poland were looked for in three different geological conditions: in places where magma rocks, particularly crystalline, as well as volcanic and sedimentary rocks occurred. The selection of an optimum structure for the location of EGS systems utilising CO_2 as a medium covered the analysis of geological and hydrogeothermal conditions, suitable for the construction of both EGS systems, and possibilities of underground CO_2 storage. For this reason, since the basic geological condition decisive about a possibility of storing large CO_2 amounts underground is the occurrence of sedimentary rocks with large thickness, considerable spread, with good collection properties, having an insulation rock overburden, the area of Krośniewice-Kutno, located in the central part of the Polish Lowland, has been considered to be the most prospective zone for the location of an EGS system using CO_2 as a medium. In this area the most prospective horizon for EGS location is clastic deposits of the Lower Triassic.The top of the reservoir of more than 1000 m thick, is behind at depths 5000-5500 m below sea level and the temperature within the reservoir is in the range 165-195°C. The porosity of reservoir rocks is approximately 2.5%, while the permeability is about 0, 1 mD.

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