



## ANALYSING RESERVOIR PROPERTIES OF THE LIASSIC SEDIMENTARY LAYER IN POLAND

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### ABSTRACT

Geothermal water is used in a few places in Poland, mainly for space heating, balneology, bathing, greenhouse cultivation and fish farming. Two operating geothermal plants show good prospects for the future in low-enthalpy geothermal water utilisation, and also new plants being designed. In this paper geothermal resources within the Polish sedimentary basin, covering 80% of Poland's area, are presented. The analysis of temperature and heat flow distribution in Poland, and also of the Early Jurassic (Liassic) water-bearing layer was performed to show the main reservoir features. The Liassic sandstone reservoir includes geothermal water up to 120°C at depths of 3800 m, and together with Early Cretaceous formations has the highest geothermal potential and the best conditions for geothermal water extraction and utilization in Poland.

### 1. INTRODUCTION

The Polish sedimentary basin is situated within the Central European geostructural depression and oil and gas-bearing province covering the North Sea, Holland, Denmark, North Germany and the Baltic Sea (Figure 1). The sedimentary formation, covering 80% of Poland's territory, is of Permian, Mesozoic and Cenozoic age. The maximum thickness of Permian-Mesozoic sediments reaches 8 km in the central part of the basin. This formation is rich in low-enthalpy geothermal resources. Geothermal water has been used since the 19<sup>th</sup> century in Poland in balneology and recreation, mainly in the southern mountain regions, but also in the Polish Lowland (Ciechocinek, Konstancin).

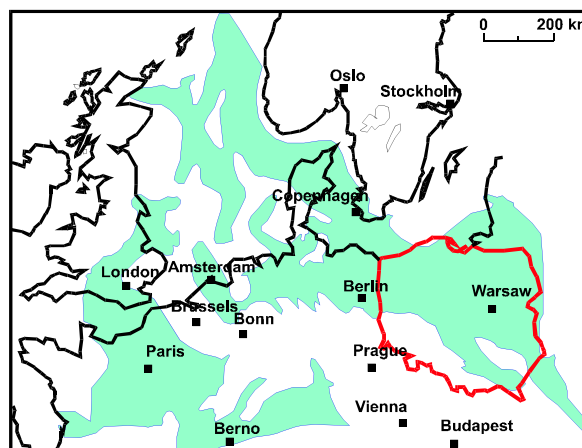


FIGURE 1: Extent of Jurassic sediments (gray)  
in Europe

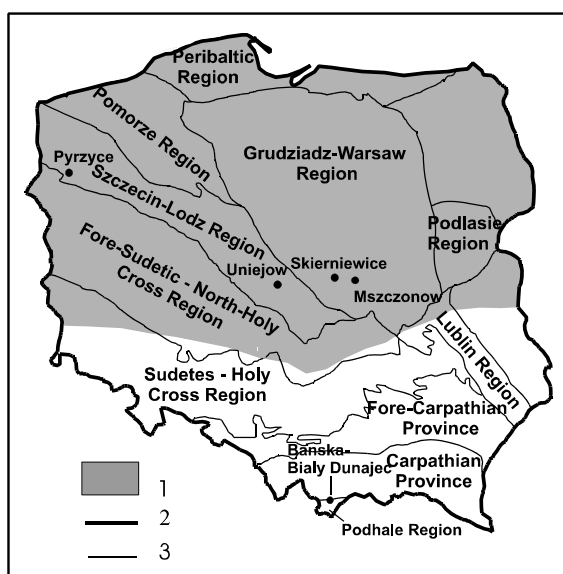


FIGURE 2: The structural and geothermal sub-basins in Poland; 1) Polish lowland, 2) Poland borders, 3) Boundaries of structural and geothermal sub-basins (adopted from Sokolowski, 1992)

Geothermal research in Poland led to the recognition that geothermal water can be used for space heating, bathing, greenhouse cultivation and fish farming. Currently, two geothermal plants are in operation (Banska Nizna and Pyrzyce) and a third one, in Mszczonow, is to be commissioned. In addition there are two others in the design phase (Skierniewice and Uniejow). Pyrzyce, Mszczonow, Skierniewice, and Uniejow are situated in the Polish Lowland, in Szczecin-Lodz Region and Grudziadz-Warsaw Region (Figure 2). In these towns geothermal water from Lower Cretaceous and Lower Jurassic formations is utilized. These two formations are presently the best known in Poland, and seem to be the most promising for future geothermal energy extraction and utilization.

Table 1 presents an overview of the various sedimentary geothermal reservoirs encountered so far in Poland. Also given are depths to the reservoirs and their temperature ranges. The table data are based on many years' standing research by Sokolowski et al. (1995).

TABLE 1: Structural and geothermal sub-basins in Poland

Basin	Rocks	Depth to geothermal aquifer (km)	Temperature (°C)
Upper Tertiary	Conglomerate, sandstone, claystone and clay with gypsum	0.7-4	25-120
Middle Tertiary	Carbonates with anhydrite and siltstone	0.7-5.5	25-135
Lower Tertiary	Sandstone	0.7-5.5	30-150
Cretaceous	Marl and limestone in upper part and sandstone and claystone in deeper part	0.8-2.8	30-85
Malmian	Claystone, siltstone, anhydrite, marl and limestone	1-3.2	25-96
Doggerian	Sandstone and claystone	0.7-3.5	25-105
Liassic	Sandstone, claystone and siltstone	0.7-3.8	25-114
Zechsteinian	Shale, limestone, dolomite, anhydrite and salt	1-4	30-120
Lower Permian	Sandstone, siltstone and claystone with volcanic rocks in some places	0.7-4	30-120
Carboniferous-Devonian	Sandstone, limestone with anhydrite and marl	1-4	30-120
Lower Paleozoic	Sandstone, carbonates and claystone	1-4	30-120

In the following report some large-scale properties of the Lower Jurassic reservoir in Poland are analyzed. Maps of temperature distribution, a map of the heat flow and cross-sections showing properties of reservoir have been drawn. Finally, simple numerical simulation of long term production was done.

The main purposes of the work were collecting complete data about the prospect of geothermal energy utilization within the Liassic reservoir. But also to create a database for further, more detailed analysis of reservoir properties, to present a conceptual model of the reservoir, and to test the possibilities of the GMT public domain plotting routines and the TOUGH2 numerical reservoir simulator, which can be useful in further research into geology and reservoir engineering of the Polish sedimentary basin.

## 2. DATA SOURCES AND DATA PROCESSING

The analysis of the Lower Jurassic reservoir to be presented in this paper has been conducted on the basis of data taken from various sources:

1. Temperature and heat flow data collected by J. Sokolowski et al. (1995);
2. Published maps of Liassic reservoir properties by Gorecki (1990) and Gorecki et al. (1995);
3. Unpublished material by the Robertson Group plc (1991a, b, c), i.e. structural maps and a map of reservoir properties.

Down hole temperatures from 224 wells, heat flow measurements from 83 wells, depths of the Liassic layer in each well, porosity and permeability of core samples, and some additional reservoir properties taken from maps were collected into Excel spreadsheets. This data base was then used for drawing temperature contour maps at 500 m intervals from 0 down to 5000 m below sea level, as well as for mapping heat flow in the Polish territory. There were very few temperature measurements for 4500 m b.s.l. in the data base; therefore, temperatures from that depth level and down were extrapolated according to the geothermal gradient in each well. Also, maps of top and base surfaces of the Liassic formation and reservoir porosity were constructed. All these maps were drawn using the GMT software (Wessel and Smith, 1995a, 1995b, 2000).

Then a cross-section within the basin was selected for more detailed analysis of the Liassic reservoir. On the basis of the previously compiled maps, a simplified geological cross-section of the Liassic layer was drawn manually, perpendicular to the strike of the main geological structures. Also, temperature, heat flow, porosity and water mineralisation cross-sections were drawn along the same line, to show the relationship between thermal, geological and reservoir features in the study area.

## 3. AREA OF RESEARCH

### 3.1 Geological setting

Under the thick sedimentary formations in the Polish territory, several major geological units meet. These are the Precambrian East European craton, the Paleozoic platform with two Paleozoic fold belts (the Caledonides and Variscides) and the Alpine Orogen represented by the Carpathian Mountains. The southwest border zone of the Precambrian platform is named Teisseyre-Tornquist Zone (TTZ), and is a part of the Trans European Suture Zone (TESZ).

According to seismic investigation, the total thickness of the sedimentary cover in the deepest areas of the Paleozoic part of the basin can reach as much as 20 km (Guterch et al., 1999). The sediments are, however, much thinner within the Precambrian craton. The thickness varies from 200 to 500 m in the region of the Mazury-Suwalki uplift (NE-Poland, where the Cenozoic-Mesozoic sediments directly overlie the crystalline Precambrian basement) up to 8 km in marginal zones of the Craton. There, two structural complexes appear: a lower unit of Cambrian to Silurian age and an upper unit of Permian to Cenozoic age. The basement of the Permian-Mesozoic sedimentary basin within the Paleozoic Platform, consists of Carboniferous, Devonian and older formations, folded during the Variscian Orogenesis. The base of the Permian sediments reaches 5-7 km depths in Central Poland and at the northwest margin of the Paleozoic platform, decreasing to the southwest, south, east and northeast.

The structure of the Mesozoic formation deposited on Permian rocks within the Paleozoic platform and on older rocks within the Precambrian craton is shown in a cross-section in Figure 3.

Within the Polish lowland (Central Polish anticlinorium) Upper Permian salt domes occur. They were formed during the Laramian tectonic phase, when plastic salty sediments were pressed up to the surface, impaling almost 6 km thick overlying Triassic, Jurassic and Cretaceous deposits.

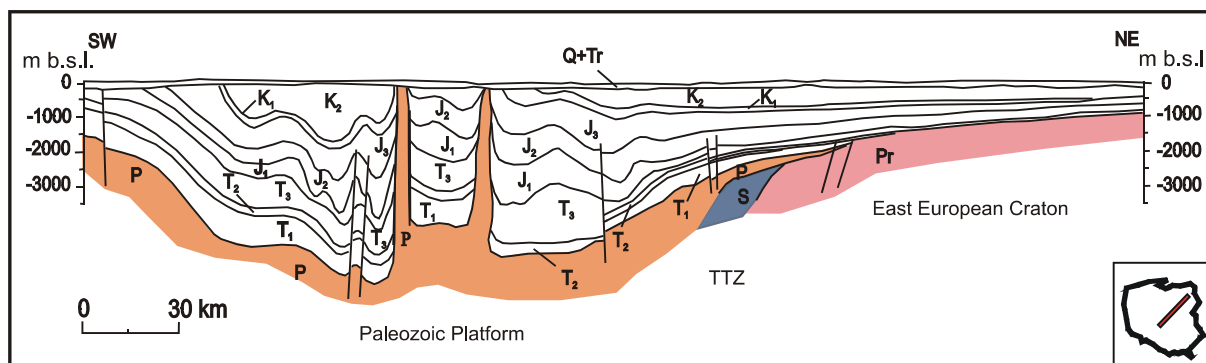


FIGURE 3: A schematic cross-section through the Polish sedimentary basin (adopted from Gorecki et al., 1995). The characters on the graph stand for geological age; these are by age: Pr-Precambrian, S-Silurian, P-Permian, T<sub>1,2,3</sub>-Early, Middle, and Late Triassic, J<sub>1,2,3</sub>- Early, Middle, and Late Jurassic, K<sub>1,2</sub>-Early and Late Cretaceous, Tr+Q-Tertiary and Quaternary

The Liassic formation was deposited on various units of Triassic. It covers an area of approximately 155,000 km<sup>2</sup>. Maximum thickness occurs in the central part of the basin, where sediments were deposited on the Paleozoic platform. In that part of the basin (southwestern part of Grudziadz-Warsaw region and northwestern and southeastern part of Szczecin-Lodz) the thickness varies between 300 and 1500 m. On the East European craton, the Liassic formation is thinner. The thickness in the Grudziadz-Warsaw region varies between 100 and 300 m. In the central part of the basin the depth to the Liassic base is about 3.5 km, whereas at the boundaries it ascends almost up to sea level. The greatest depth to the top of the Liassic is about 3 km and the depth consequently decreases towards the margins of the basin, where in some places it is seen on the surface. The Liassic formation consists mainly of sandstone layers, interbedded with claystone, sandy claystone, mudstone and sandy mudstone.

A large primary Mesozoic sedimentary basin, was deformed during the Laramian tectonic phase between the Cretaceous and Tertiary periods. Increasing tectonic movements split the basin into two sub basins: Szczecin-Lodz sinclinorium and Grudziadz-Warsaw sinclinorium. In between them the Central-Polish anticlinorium was formed where, at present, Jurassic incrops occur below a thin Cenozoic cap. Another Jurassic incrop area extends along the southwest margin of the basin, and an outcrop area occurs on the south margin of the basin (within the Fore-Sudetic - North-Holy Cross region). Mesozoic structures were eroded after this deformation, and later covered by Tertiary and Quaternary horizontally lying sediments (Figure 3).

### 3.2 Hydraulic properties of the Liassic reservoir

The main water-bearing sandstone layers within the Lower Jurassic formation are of Hettangian, Upper Sinemurian, Domerian and Upper Toarcian age. They are interbedded with discontinuous layers of low-permeable or near impermeable fine-grained sandstone, mudstone and siltstone. The total thickness of these permeable layers varies between 10 and 650 m. The greatest thickness is found within the Pomeranian anticlinorium in the northeastern part of the reservoir and within the Kujawy-Holy Cross anticlinorium in the central and southeastern part of the reservoir.

The transmissivity of the Liassic aquifer varies between 10 and  $1650 \times 10^{-5}$  m<sup>2</sup>/s. The greatest transmissivities ( $600-1650 \times 10^{-5}$  m<sup>2</sup>/s) are observed in the central and northwest parts of the reservoir, thus coinciding with the thickest water-bearing sandstones.

The Liassic reservoir is predominantly of the confined type. Unconfined conditions are only found close to the outcrops. Most wells drilled into the Liassic reservoir are non-artesian. Artesian wells are, however, found in the southeastern part of the Grudziadz-Warsaw region, and in the northern part of the Pomeranian region. Outcrop areas directly recharged by meteoric waters are insignificant in comparison with the total area of the aquifer. More intensive is believed to be the indirect recharge through the incrops under Quaternary sediments, in some areas through permeable Tertiary and Upper Jurassic and

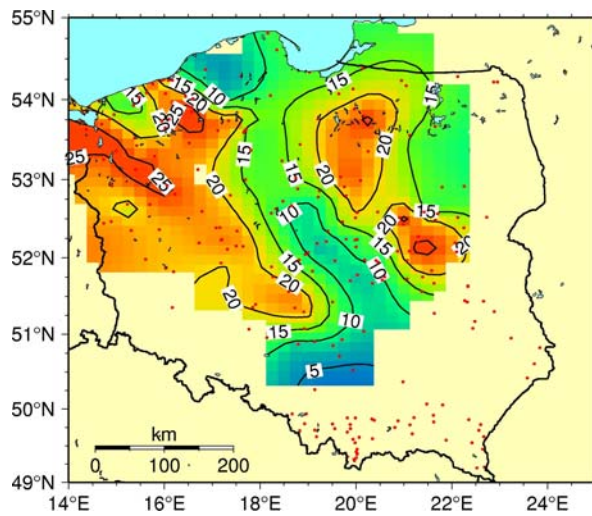


FIGURE 4: Liassic reservoir porosity

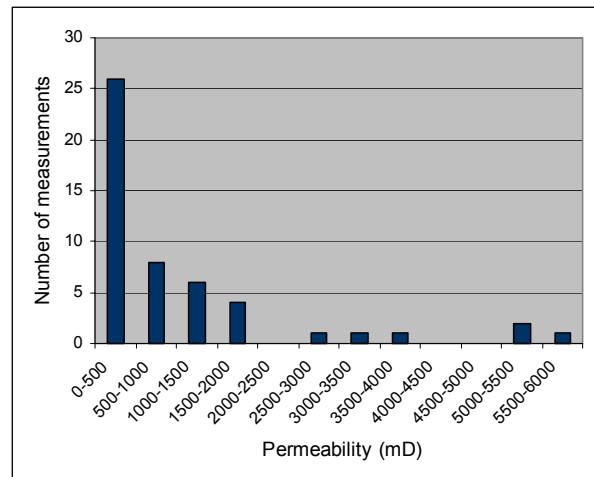


FIGURE 5: Liassic reservoir permeability

even Cretaceous deposits above, and tectonic or erosional windows as well as fault or crack zones (Gorecki, 1990).

Data on the Liassic reservoir porosity and permeability are available from core studies. Total porosity ranges from 5 to 20%. Figure 4 presents a contour map of this reservoir property, showing a smooth pattern. The permeabilities are, on the other hand, very diverse and range between a few mD up to 6000 mD. Figure 5 shows this data presented as a histogram. This diversity is difficult to interpret. Generally, it is assumed that average permeability of water-bearing Liassic rocks is around 1100 mD (Gorecki et al., 1995).

Geological structure and depth to the Liassic formation cause directional changes in the subsurface water flow. This is shown in Figure 6, together with some pressure contours. Generally, one can say that the regional flow is from southeast to northwest.

According to estimates by Sokolowski et al. (1995), the volume of geothermal fluids in the Liassic Grudziadz-Warsaw sub-basin is about 1850 km<sup>3</sup>, and in the Szczecin-Lodz sub-basin around 1900 km<sup>3</sup>. Water temperatures range between 25 and 114°C and the average outlet temperature is between 48 and 68°C. The potential geothermal energy possible to extract is accordingly  $20 \times 10^{16}$  J and  $40 \times 10^{16}$  J. The geothermal reserves in the Liassic appear to be in the northwest part of the Szczecin-Lodz region (30-130 GJ/km<sup>2</sup>) and in the central and western part of the Grudziadz-Warsaw region (20-60 GJ/km<sup>2</sup>) (Gorecki et al., 1995).

Geothermal fluids in the Grudziadz-Warsaw sub-basin and in the Szczecin-Lodz sub-basin are rich in dissolved solids (50-180 g/l), particularly in their deepest parts, along axes of main synclines. Most of the water in these sub-basins is of Na-Cl type. In some parts of the basin, particularly in the Grudziadz-Warsaw sub-basin, J, Br, K and Mg occur in the water. These minerals are presumed favourable for balneology (Gorecki et al., 1995).



FIGURE 6: Subsurface water flow in the Liassic reservoir; 1) Outcrops and incrops, 2) Subsurface water pressure (atm. above reduced level), 3) Extent of Liassic sediments, 4) Main directions of subsurface flow (Modified from Gorecki et al., 1995)



### 3.3 Geothermal features of the area

The distribution of the terrestrial heat flow in Poland changes according to the geological structures. The heat flow in the Precambrian East European craton is lower than in other geological units (Figure 7).

An average value for the heat flow is  $48.3 \text{ mW/m}^2$ . Within the Teisseyre-Tornquist zone the heat flow is more diverse, but on average  $51.6 \text{ mW/m}^2$ . The value of heat flow is higher in the Paleozoic platform, on average  $62.1 \text{ mW/m}^2$  (Plewa, 1994). The average geothermal gradient in the Precambrian craton is  $1.96^\circ\text{C}/100 \text{ m}$ . Within the Teisseyre-Tornquist zone the average geothermal gradient is  $2.6^\circ\text{C}/100 \text{ m}$ , but abnormally high gradients of  $3.55^\circ\text{C}/100 \text{ m}$  and

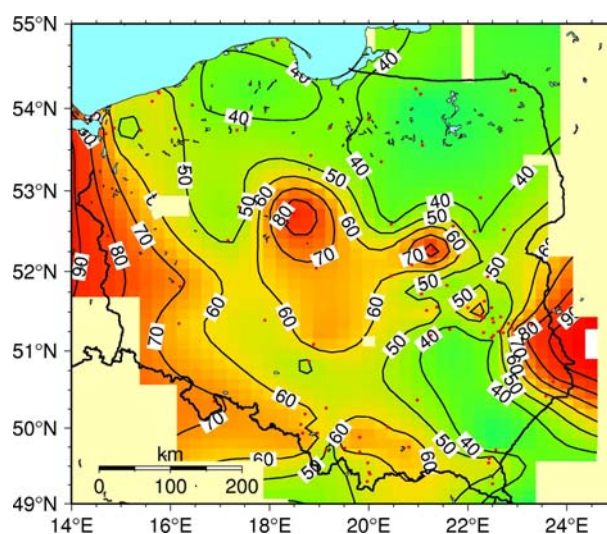


FIGURE 7: Heat flow in Poland ( $\text{mW/m}^2$ )

$3.04^\circ\text{C}/100 \text{ m}$  do occur near salt domes within the border zone between the Grudziadz-Warsaw and Szczecin-Lodz sub-basins. On the Paleozoic platform, within the Polish lowland, the average gradient is  $2.89^\circ\text{C}/100 \text{ m}$ , in the Upper Silesian coal basin it is  $3.15^\circ\text{C}/100 \text{ m}$  and in the Carpathians  $2.35^\circ\text{C}/100 \text{ m}$  (Plewa, 1994).

The distribution of the temperature field in Poland at several depths is contoured in Figure 8. The maps presented, clearly show different temperatures between the Precambrian craton and the Paleozoic platform at every depth. The reasons are the structure and depth to the crystalline basement and the thickness of the sedimentary cover. Usually, the thermal conductivity of the Earth's crust near the surface is lower in areas of thick sedimentary caps compared

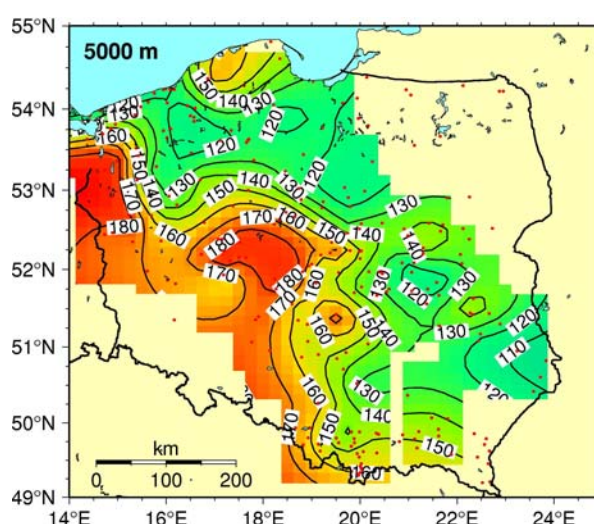
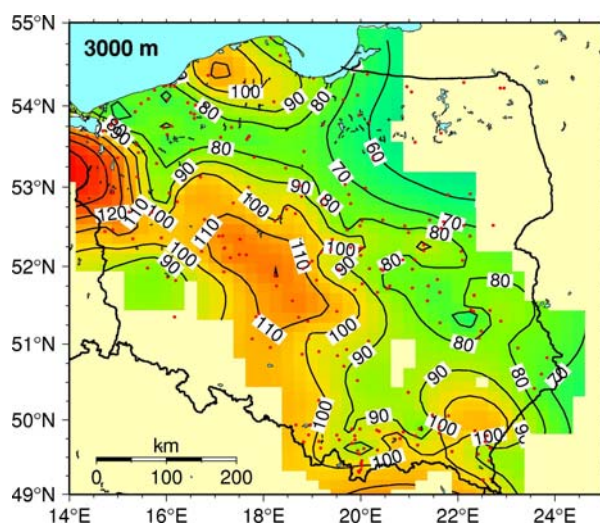
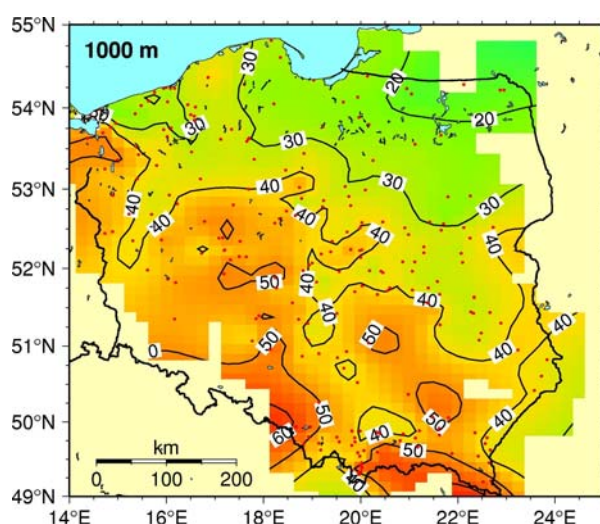


FIGURE 8: Maps of the temperature distribution in Poland at depth levels of 1000, 3000, and 5000 m b.s.l. ( $^\circ\text{C}$ )

to areas of shallow crystalline formations (Majorowicz, 1975). Radiogenic heat production is another element which influences the thermal field distribution. Average values of radiogenic heat for sediments are:  $0.8 \mu\text{W}/\text{m}^3$  for conglomerates,  $0.9 \mu\text{W}/\text{m}^3$  for sandstone and  $1.4 \mu\text{W}/\text{m}^3$  for clays (Plewa, 1994). Other sources of temperature perturbation come from crustal thinning and upwelling of mantle material as a consequence of the continental stretching. Apart from this, heat is usually generated during tectonic movements. It can contribute to the higher temperature found within the Mesozoic-Cenozoic formation, which was disturbed during the Variscian and Alpine tectonic phase.

According to the map by the Robertson Group plc (1991d), the base temperature of the Liassic formation extends from  $20^\circ\text{C}$  at the outcrops and incrops in coastal zones of the basin and on the Precambrian Craton, up to  $140^\circ\text{C}$  in the thickest part of the sedimentary basin.

#### 4. DISTRIBUTION OF RESERVOIR PROPERTIES ALONG A SW-NE CROSS-SECTION

The present study covers a large area, actually too large for the present reservoir engineering training study. It was, therefore, decided to constrain the study to a SW-NE cross-section similar to the one shown in Figure 3, in order to have a general idea about the distribution of the geothermal and reservoir properties. The cross-section runs perpendicular to the axes of the main tectonic structures and through the deepest and hottest parts of the sedimentary basin. In total, the cross-section is 600 km long and 4 km deep. Figure 9 presents the appearance of the Liassic formation in the selected cross-section together with the temperature, heat flow, porosity and dissolved solids. The figure is based on the maps discussed earlier together with a profile of dissolved solids map by Gorecki et al. (1995).

Figure 9a shows the location of the Liassic layer and the temperature distribution. The depth to the Liassic layer ranges from sea level down to 3.5 km. The tectonic deformations; synclines and anticlines, are easily identified on the cross-section, and in their centres, the thickness of the layer is the highest. The temperature isolines, that are based on the

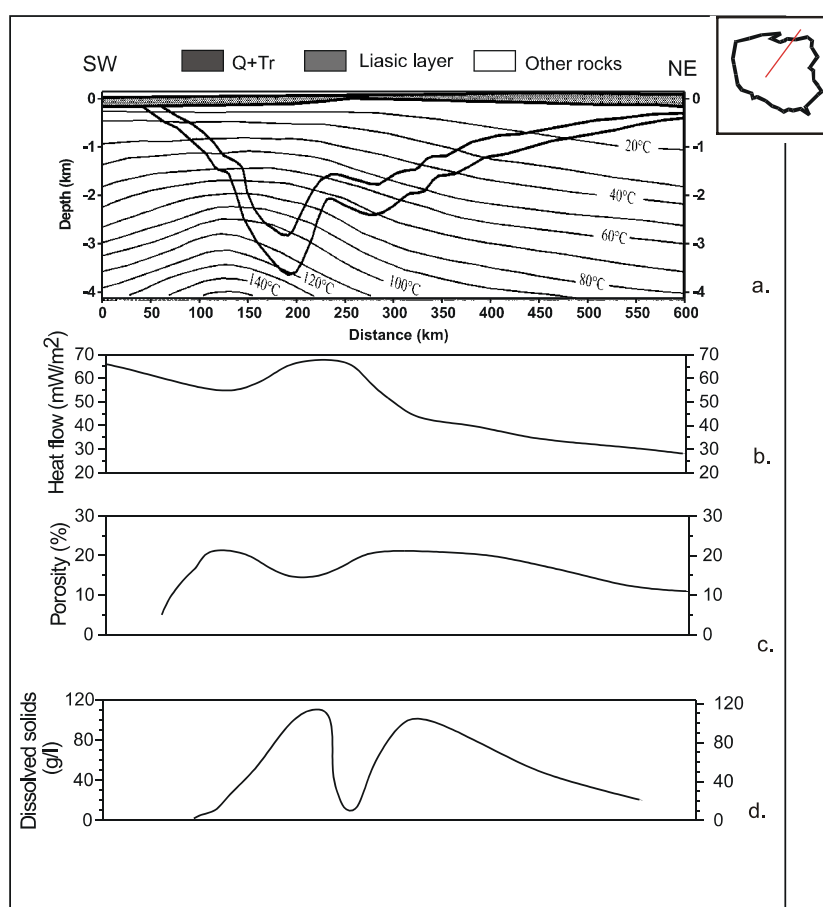


FIGURE 9: Selected parameters for a 2-D reservoir engineering study on a SW-NE cross-section (top right); a) Temperature distribution and main rock units, b) Heat flow, c) Porosity, and d) Mineralisation of the Liassic formation

temperature maps in Figure 8, clearly show the difference between the deep Paleozoic part of the basin and a shallow part, where the basement is the crystalline Precambrian craton. In the southwest, the temperature reaches almost 150°C at 4 km depth. The highest temperature of the Liassic layer is 120°C at its deepest part.

The large scale temperature anomaly in Figure 9a is also reflected in the surface heat flow (Figure 9b). The anomaly is most often explained as a result of the different thicknesses of the sediments, and different thermal conductivity of the sediments compared to the old crystalline crust to the northeast. Vertical thermal convection may also partially explain the anomaly, with water from the deeper parts of the basin ascending within fault and crack areas. The maximum value is near 70 mW/m<sup>2</sup>. The heat flow in the East European Craton area is, on the other hand, only in the range 30-45 mW/m<sup>2</sup>.

The Liassic reservoir porosity is shown in Figure 9c. The porosity is lowest (5-10%) in the shallowest parts of the reservoir, where the layer is generally thin. The deep reservoir porosity depends on the relative contributions of porous sandstone and impermeable claystone lenses. When the claystone content is high, the porosity is low. This is observed in the deepest parts of the Liassic reservoir, where the porosity is locally low. In other parts of the reservoir, the content of permeable sandstones is higher, and consequently, the porosity as well.

Water mineralisation (mainly Na-Cl) in the study area is connected to the Zechsteinian salt domes occurring in the central part of the Polish sedimentary basin (Figure 3). The solid concentration varies between 0.3 and 110 g/l. It is clear that the highest mineralisation appears in the deepest part of the reservoir, and that this value decreases in the shallower parts of the Liassic layer, and is at a minimum directly under the Tertiary and Quaternary cover. This decrease in salinity is best explained by recharge of fresh water from the surface (Figure 9d).

## 5. NUMERICAL MODELLING EXAMPLES

### 5.1 Natural state of the reservoir

The TOUGH2 simulator (Pruess et al., 1999) was used for two-dimensional numerical modelling of the temperature distribution of the Liassic reservoir shown in Figure 9. The first step was to create a model grid. The selected cross-section is 600 km long, 1 km wide and 4.25 km deep. It consists of 540 rectangular grid-blocks generated by the meshmaker option of TOUGH2. The grid elements in the top surface and in the base were defined as inactive (constant pressure and temperature), and have dimensions of 20,000×1000×125 m. All other model elements have dimensions 20,000×1000×250 m. These grid elements are obviously very large, but considered sufficiently accurate for this first step of modelling the large Liassic reservoir. The model is intentionally made simple, and grid elements do not completely agree with the actual geometry of the reservoir. Besides this, some assumptions had to be made about rock properties. As an example, no distinction is made between the different kinds of rocks making up the Liassic layer, nor in the rock groups above and below it. Also, thickness accuracy of different layers is limited.

With the model grid at hand, the next step was to simulate the natural state temperature distribution shown in Figure 9a. Two sets of rock properties were defined for this purpose. The first set is divided into 4 groups of rocks which are presented in Figure 10 and in Table 2. These are: 1) Boundary layer, 2) Layer of horizontal sedimentary cap, 3) Liassic reservoir, and 4) Rocks adjacent to the reservoir. In order to obtain the measured temperature distribution shown in Figure 9a, these rock properties had to be iterated until a good match was obtained between the calculated and measured temperatures.



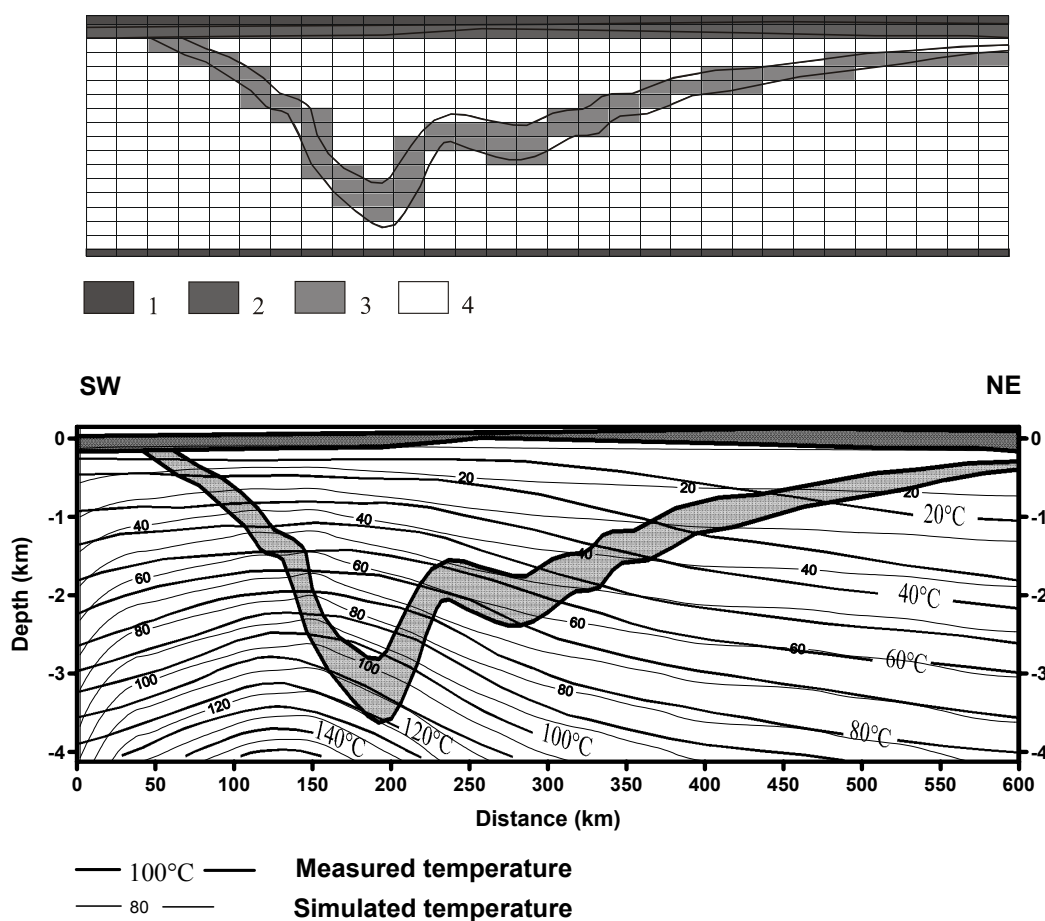


FIGURE 10: Rock properties in the first grid (top) with simulated and measured temperatures (bottom); the rock properties and their numbers are defined in Table 2

TABLE 2: First model case reservoir properties; thermal conductivity is 2.5 W/m°C for all rocks, and the heat capacity is 1000 kJ/kg;  $k_x$  - horizontal permeability,  $k_y$  - vertical permeability

Rock no. in model	Rock type	Porosity (%)	$k_x$ (m <sup>2</sup> )	$k_y$ (m <sup>2</sup> )	Density (kg/m <sup>3</sup> )
1a	Boundary layer on the top of grid	20	$4 \times 10^{-50}$	$0.1 \times 10^{-15}$	2400
1b	Boundary layer on the base of grid	1	$4 \times 10^{-50}$	$0.04 \times 10^{-70}$	2600
2	Horizontal cover	20	$50 \times 10^{-12}$	$0.01 \times 10^{-15}$	2400
3	Reservoir (Liassic reservoir)	20	$500 \times 10^{-15}$	$50 \times 10^{-15}$	2620
4	Rock above and below reservoir	5	$1 \times 10^{-15}$	$0.01 \times 10^{-15}$	2600

This first model case shows too low temperatures in the southwest, and to the northeast the temperatures are too high. Therefore, it was decided to make a second set of rock properties to better simulate temperatures in these two sub parts of the cross-section. Two additional domains were, therefore, added to the grid. The first one consists of elements representing the crystalline basement of the sedimentary basin, with a higher value of thermal conductivity in the northeast (Precambrian Craton). The second one consists of elements representing a vertical high-permeable zone in the southwest part of the basin. The temperature anomaly in the southwest part of the cross-section is, therefore, allowed to be partially caused by vertical convection within permeable faults or crack zones, where geothermal water can migrate from deeper to shallower parts of the basin.

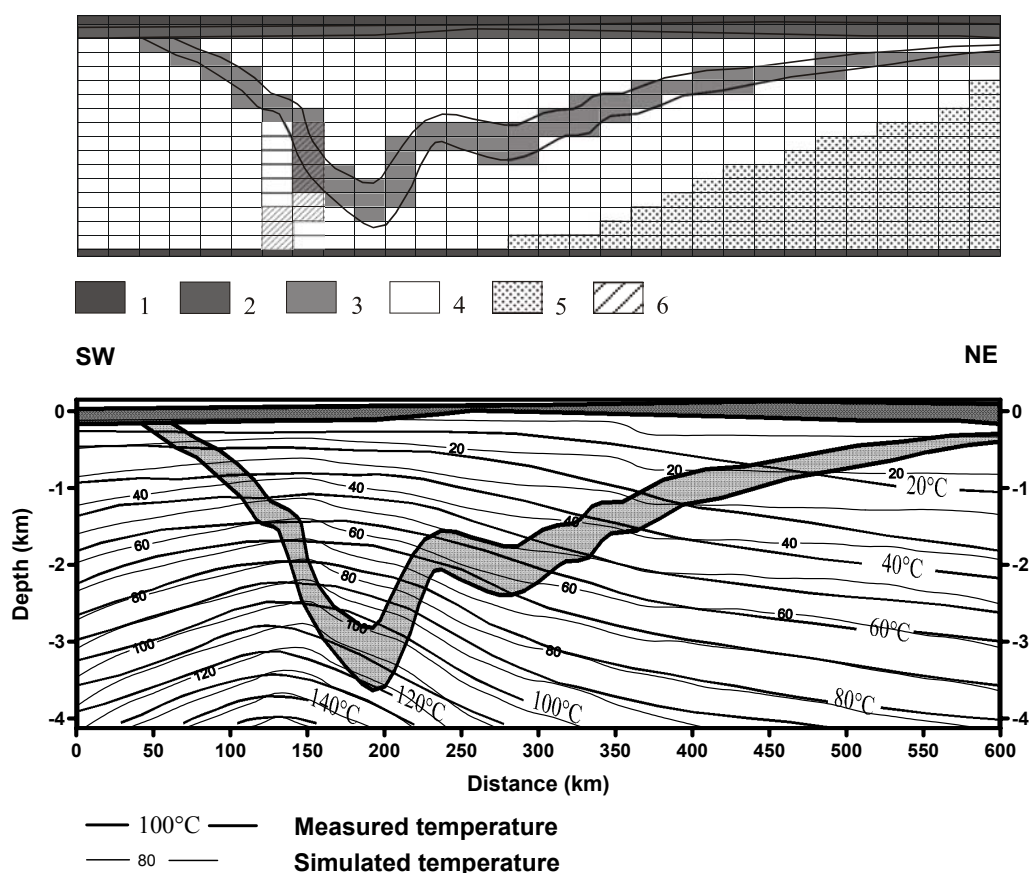


FIGURE 11: Rock properties in the second model grid (top), with simulated and measured temperatures (bottom); the rock properties and their numbers are defined in Table 3

This “best” model grid and the simulated temperature are shown in Figure 11. The final rock properties are listed in Table 3. Figure 11 shows that higher temperatures are indeed obtained in the southwest part of the cross-section, but to the northeast the temperature did not decrease as much as wanted. This discrepancy may be attributed to the fact that the fluid is basically stagnant in the numerical model, whereas in reality, the measured temperature is possibly influenced by regional groundwater flow perpendicular to the cross-section. Nevertheless, the second case temperature model is closer to the actual temperatures than case 1, so this model was chosen to represent the natural state, and used in a simulation study of long term production and reinjection.

TABLE 3: Second model case reservoir properties; Heat capacity is 1000 kJ/kg for all rocks,  $k_x$  - horizontal permeability,  $k_y$  - vertical permeability

Rock no.	Rock type	Porosity (%)	$k_x$ ( $m^2$ )	$k_y$ ( $m^2$ )	Thermal conductivity ( $W/m^{\circ}C$ )	Density ( $kg/m^3$ )
1a	Boundary layer on the top of grid	20	$4 \times 10^{-50}$	$0.1 \times 10^{-50}$	2	2400
1b	Boundary layer on the base of grid	1	$4 \times 10^{-50}$	$4 \times 10^{-70}$	2	2600
2	Horizontal cover	20	$300 \times 10^{-12}$	$0.1 \times 10^{-12}$	2.25	2400
3	Reservoir	20	$350 \times 10^{-15}$	$3.2 \times 10^{-15}$	2.25	2620
4	Rock above and below reservoir	5	$50 \times 10^{-15}$	$0.02 \times 10^{-15}$	2.25	2600
5	Rock of crystalline basement	1	$1 \times 10^{-15}$	$0.1 \times 10^{-15}$	2.75	2700
6	Fractured zone	50	$250 \times 10^{-12}$	$50 \times 10^{-12}$	2.10	2600

## 5.2 A simple exploitation study

A simple study of water extraction and reinjection from the Liassic reservoir has been carried out based on the “best” model. The primary objective was to see if reservoir temperature would decline, during long term exploitation and reinjection, assuming variable production and reinjection rates. Water was produced from the deepest and hottest ( $\sim 100^\circ\text{C}$ ) part of the Liassic layer (about 3 km depth), from the center of the syncline. A  $10^\circ\text{C}$  water was reinjected to the same Liassic layer, but at 20 km distance from the exploitation well and at 2 km depth. A sketch showing the well configuration is given in Figure 12.

The assumed time of operation was 1000 years, considered sufficient to show changes on a regional scale. The initially steady-state temperature profiles for the production and reinjection area are shown in Figure 13. The profiles are straight lines, which indicates that temperature increases with depth according to a temperature gradient without any disturbances, but the thermal gradient in the production area ( $3.39^\circ\text{C}/100\text{ m}$ ) is a little higher than in the reinjection area ( $3.23^\circ\text{C}/100\text{ m}$ ) because of the regional thermal anomaly mentioned in previous chapters.

The expected production from wells within the deepest parts of the Polish sedimentary basin is about  $60\text{ m}^3/\text{h}$ . This value of production and reinjection was, therefore, assumed in the first

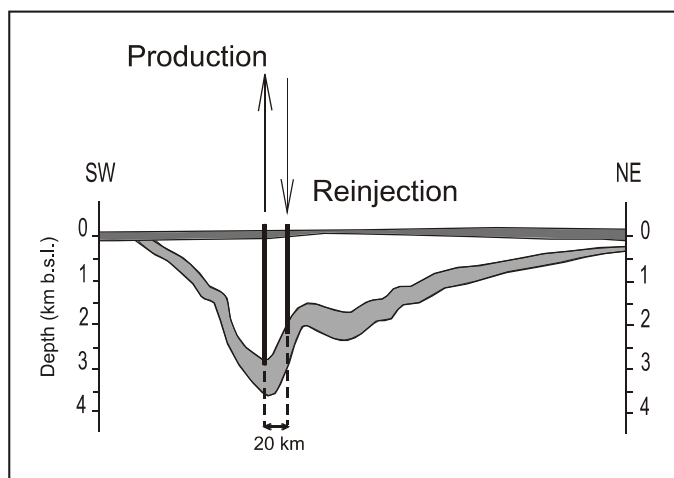


FIGURE 12: Configuration of production and reinjection wells for exploitation study

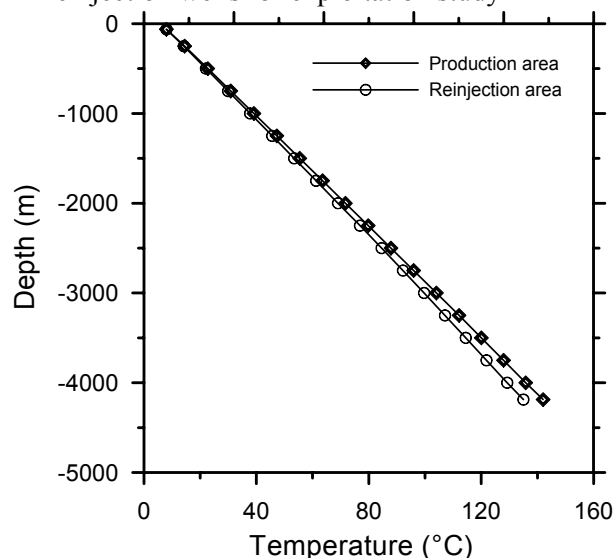


FIGURE 13: Temperature of production and injection wells at steady-state conditions

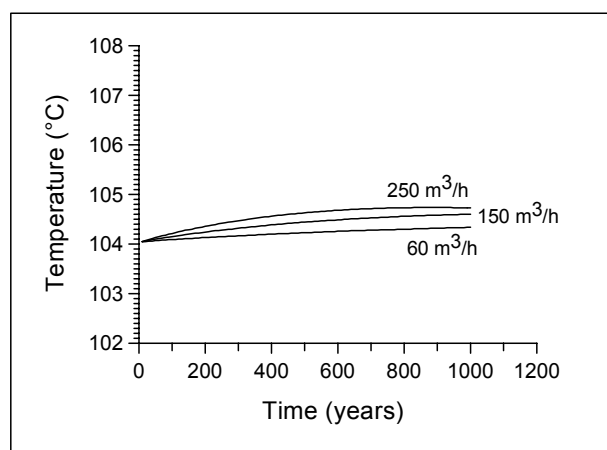


FIGURE 14: Temperature history of the model element where production took place

simulation example. In the second example the flowrate was increased to  $150\text{ m}^3/\text{h}$  and then increased up to  $250\text{ m}^3/\text{h}$ , which is one of the highest values of production within the Polish Liassic basin (Gorecki et al., 1995). These three production examples predict temperatures after 1000 years of hot water extraction and cold water injection. It was also possible to get a history of temperature changes for the model elements, where production and injection took place. These histories are shown in Figures 14 and 15.

The initial temperature of the production area is  $104^\circ\text{C}$ . A temperature increase is predicted for all

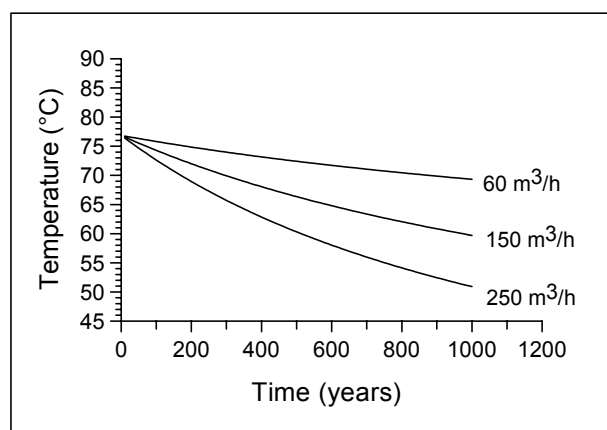


FIGURE 15: Temperature history of the model element where reinjection took place

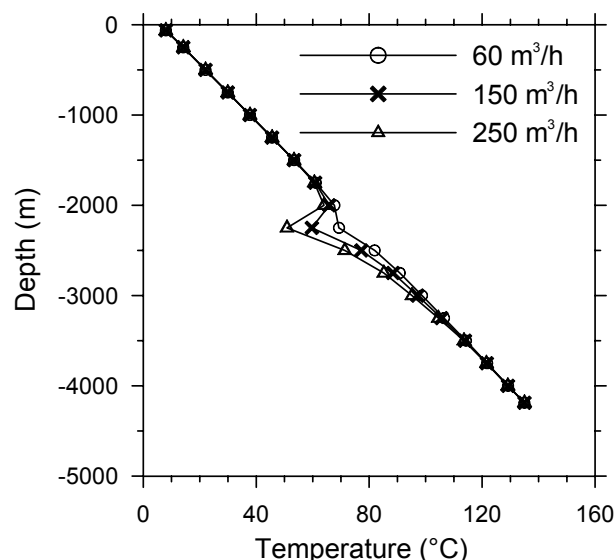


FIGURE 16: Temperature in the vertical model column containing the reinjection well after 1000 years of 10°C water reinjection at variable rates

and the temperature profile after 1000 years of production looks very similar to the original one shown in Figure 13.

## 6. CONCLUSIONS.

In this study, a comprehensive well data-base concerning the Polish sedimentary basin has been developed. It includes the temperature measurement from 224 wells at up to 5000 m depth, the values of heat flow measured in 83 wells, the depth intervals of the Liassic layer occurrence in most wells, the pressure values at the top surface of the Liassic reservoir, and the values for porosity and permeability for the Liassic reservoir.

Temperature distribution maps at 500 m depth intervals between 0 and 5000 m, and a map of the heat flow in Poland show clearly the differences in temperature and heat flow between Precambrian and Paleozoic basement areas. It is clear from these data that the best prospective sites for geothermal heat utilization

the three production cases. After 100 years of exploitation this temperature has increased by 0.05, 0.11 and 0.16°C for production rates of 60, 150 and 250 m³/h, respectively. After 1000 years of continuous production and injection, the temperature has increased correspondingly by about 0.3, 0.55 and 0.69°C. This minor temperature increase may be due to vertical recharge of hot water via the fracture zone, defined in the model near the extraction point.

In the reinjection area (element), where the initial temperature at injection point is about 77°C, considerable temperature decrease is predicted (Figure 15). After 100 years of 10°C water reinjection to the reservoir at a rate of 60 m³/h, the temperature decreased by about 1°C, for rates of 150 m³/h the temperature would decrease by 3°C, and for rates of 250 m³/h the temperature would decrease by 4°C. After 1000 years of reinjection, the temperature decline around the reinjection well would be, accordingly, 8, 17 and 26°C.

Figure 16 shows the predicted model temperatures in a vertical column containing the injection well. The most noticeable changes in model temperatures are predicted when the reinjection is 250 m³/h. These changes are observed over the depth interval 2000-3500 m, which is the vertical range of the Liassic layer in that part of the reservoir model. The changes are not observed outside the Liassic layer, because in the simulation it was assumed that the permeability of rocks next to the reservoir is very low. Thus, the cold reinjected water could not migrate outside the highly permeable Liassic layer. For the production well, a vertical temperature profile has not been drawn, because changes are very small,

are within the sedimentary basin deposited on the Paleozoic platform.

It also appears that the central part of the sedimentary basin, i.e. the Szczecin-Lodz sub-basin and the Grudziadz-Warsaw sub-basin, are the best prospects for geothermal water utilization from the Liassic reservoir, because of high temperature and porosity. The detailed permeability distribution of the Liassic reservoir is, however, still a question to be addressed in future research, which is necessary for detailed recognition of the Lower Jurassic geothermal potential.

A simple numerical model study in a greatly simplified grid, suggests a massive production and reinjection potential for the Liassic layer, possibly in the range of  $\text{m}^3/\text{s}$ . The model study also indicates that vertical permeability may be present near the deepest and hottest section of the Liassic reservoir, where water temperatures are as high as  $120^\circ\text{C}$ .

Better recognition of the Liassic reservoir properties will enable more precise modelling in order to predict future reservoir performance. The simulation of production performed in this paper indicates that numerical models are useful for the prediction of temperature and pressure. It also appears possible to use them to define optimal conditions for long term utilization and for other aspects of reservoir engineering and environmental assessment, which have not been considered in this work.

### ACKNOWLEDGEMENTS

I am very grateful to Ingvar B. Fridleifsson for giving me the opportunity to participate in the UNU Geothermal Training and to see the beauty of Iceland. I would like to thank Lúdvík S. Georgsson and Gudrún Bjarnadóttir for their good organisational work. I am thankful to my supervisors: Grímur Björnsson and Sigvaldi Thordarson for sharing their knowledge and time. Thanks to all staff members of Orkustofnun for their kindness.

I am also grateful to Leszek Pajak and Pawel Wojnarowski for their great help and friendship, as well as to all the year 2000 UNU Fellows for their good company during the six months of this course.

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