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PRELIMINARY STUDY OF THE GEOTHERMAL POTENTIAL OF CARBONIFEROUS STRATA IN THE POMERANIA SYNCLINORIUM, POLAND

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ABSTRACT

Exploration and production of oil, gas and coal in Poland has generated a large amount of data on the Polish sedimentary basins. These data contain information of potential importance for the study of geothermal resources. In order to assess the usefulness of these data in geothermal investigations, a case study was made of the Pomerania Synclinorium, a deep petroleum-producing sedimentary basin within the Teisseyre-Tornquist Zone bordering on the Baltic Sea. Existing borehole data from the Pomerania Synclinorium, acquired by the petroleum industry, were used to investigate the geothermal characteristics and potential of this region. The analysis shows that potential geothermal aquifers are present in Carboniferous sandstones at a depth of 2000–4000 m where temperatures range from 60 to 110°C. In one of the wells, Karsina-1, the sandstones are 260 m thick and have a porosity of 16% and a permeability of about 190 mD. These are promising values from the perspective of geothermal utilization. However, due to the variable quality of the available well logs and a mismatch between the logs and cuttings-based lithostratigraphy, it has proven impossible to correlate this stratigraphic interval across the region and establish how regionally extensive the promising reservoir layer is. The usefulness of the existing borehole data is limited due to a lack of standardization, calibration and information about borehole corrections. This needs to be corrected and defective logs deleted from the database before it can become an effective tool in geothermal investigations.

1. INTRODUCTION

From the early 1980s several tens of research projects have been undertaken in order to assess the geothermal potential of the Mesozoic sedimentary cover in Poland. The Department of Fossil Fuels has been working on a research project evaluating the geothermal resources of Palaeozoic aquifers and possibilities of utilization. The present study is a part of this project. The objective is to assess the usefulness of existing borehole data, mainly geophysical well logs, in the study of Polish geothermal resources. A new software package for interpretation of borehole data from GeoGraphix Software (GeoGraphix, 1997) was used for this purpose. More specifically, the aim is to find a way to increase the chances of success in geothermal investigation in Polish geothermal areas, especially in the development and assessment of potential deep-buried aquifers.

Large amounts of well log data have been acquired during the long-term oil and gas developmental history of the Polish petroleum industry. The data contains information of considerable relevance to the geothermal industry, but only a small part of the data has been interpreted for this purpose. The experience gained during petroleum exploration shows that permeable and porous aquifers are found within Carboniferous rocks in the Pomerania Region. Therefore, it was decided to carry out a case study of potential geothermal reservoir rocks of Carboniferous age within the Pomerania Synclinorium using existing borehole data. Hopefully, the application of the borehole logging techniques and methods would significantly contribute to such investigation.

2. GEOLOGICAL BACKGROUND OF THE POLISH SEDIMENTARY BASIN

2.1 Tectonical outline

The study area is located at the north-east margin of the Polish part of the Palaeozoic Platform in the transition zone with the East-European Precambrian Platform which is called the Pomerania Synclinorium (Figure 1). The Pomerania Synclinorium is located at the northern boundary of the long-lived Teisseyre-Tornquist tectonic zone (TTZ), which runs southeast from the Baltic coast in Poland to the Carpathians-Black Sea area in the Ukraine.

The Tornquist Zone is the longest tectonic lineament in Europe and separates the ancient East European Craton with its Palaeozoic cover from the Phanaerozoic mobile belts of central and western Europe. Geological data collected in the Polish Lowlands and in the central part of the North Sea show that the Caledonian orogenic belt extends into central Europe. This belt links the Scottish-Norwegian Caledonides with the German-Bohemian-Polish Caledonian orogen (Znosko, 1965). Tectonic conditions could influence the distribution of petrophysical parameters of the rocks. This is especially relevant in deep buried Palaeozoic formations, where the main path for fluid flow could occur along cracks or fractures.

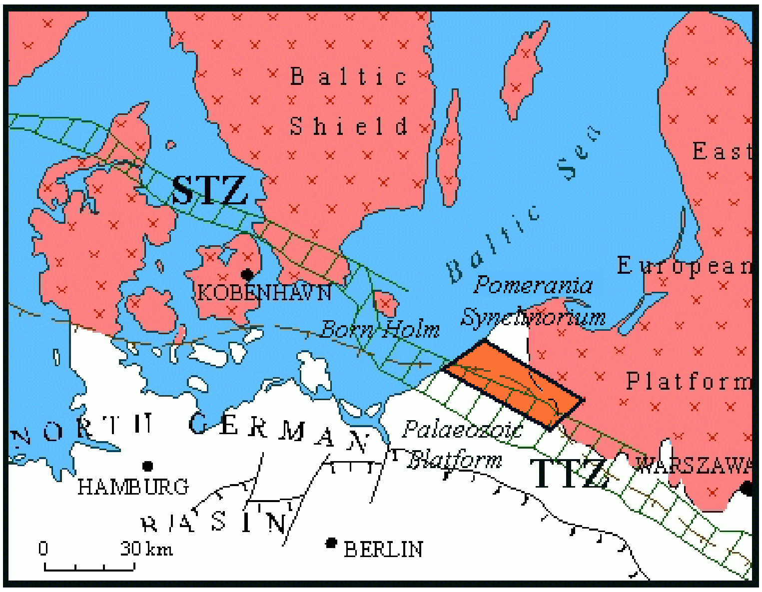

FIGURE 1: Location of the Pomerania Synclinorium, within a tectonic sketch map of Europe; TTZ: Teisseyre-Tornquist zone (modified from Ziegler, 1990)

2.2 Geological evolution of potential aquifers

Over 80% of the Polish territory is built of Mesozoic-Tertiary sedimentary basins with numerous aquifers. From a geological point of view, the Polish Lowlands occupy the area between the Baltic Shield in the northeast, the Sudetian Mountains massif in the southwest and the Lower San River Anticlinorium in the southeast. The Lowlands form an intercratonic deep, filled with Palaeozoic and Mesozoic sediments overlain by a thin Cainozoic cover.

Based on seismic investigations, the total thickness of the sedimentary cover in the deepest area of the Palaeozoic 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 NE-Poland, where the Cainozoic-Mesozoic sediments directly overlie the crystalline Precambrian basement, up to 8 km southwest of the craton.

Two structural complexes are present: a lower unit of Cambrian to Silurian age and an upper unit of Permian to Cainozoic age. The basement of The Permian-Mesozoic sedimentary basin within the Palaeozoic 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 Palaeozoic platform, decreasing to the southwest, south, east and northeast. Upper Permian strata consists mostly of evaporate sediments which were formed during the Laramide tectonic phase, in that time plastic salty sediments. The large Mesozoic sedimentary basin was deformed during the Laramide tectonic phase between the Cretaceous and Tertiary periods. During this phase the plastic salt layer was pressed up to the surface, piercing almost 6 km thick overlying Triassic, Jurassic and Cretaceous deposits. Increasing tectonic movements split the basin into two sub-basins: the Szczecin-Lodz synclinorium and the Grudziadz-Warsaw synclinorium. Between them the Central-Polish anticlinorium was formed. Mesozoic structures were eroded after this deformation, and later covered by flat lying Tertiary and Quaternary horizontally lying sediments.

3. DATABASE AND SOFTWARE

3.1 Database

The Department of Fossil Fuels, University of Mining and Metallurgy collaborates closely with the petroleum industry of Poland, the Polish Geological Institute and the Polish Academy of Sciences. The department has access to all essential geological, hydro-geothermal, geophysical and seismic data in Poland. The well database consists of 1590 wells (carefully separated and verified), which cover the main prospective geothermal areas of the Polish Lowlands (Figure 2).

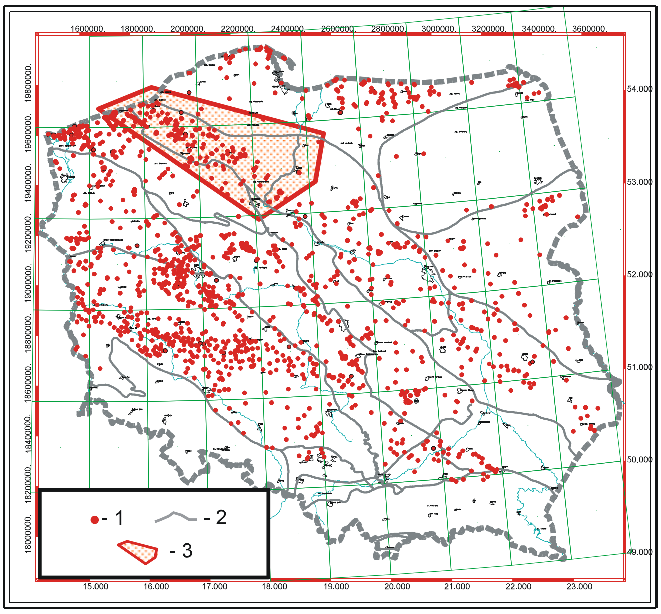

FIGURE 2: Distribution of wells in the Polish Lowlands; in the figure 1) is for wells; 2) for boundaries of structural sub-basins; and 3) the study area

This database is updated yearly. It contains three types of data: geological, geophysical and petrophysical.

- *The geological data* consist of lithostratigraphic profiles, formation tops and descriptive lithology.
- *The geophysical data* consist of geophysical logs. The distribution of well logs depends strongly

on the activities of the oil industry, which is mainly focussed on the most prospective oil and gas areas all over the country. High density of drilling and logging data is connected with oil and gas fields.

- *The petrophysical data* are based on laboratory samples and core measurements. The measurements indicate effective porosity, permeability and specific gravity. The data have still not been compiled into a single database, but are available on demand for several tens of wells.

The database for the Pomerania Synclinorum: In order to evaluate the geothermal potential of Carboniferous strata in the Pomerania Region the extensive database was screened for potential usefulness in the current project. It was filtered to obtain a list of wells reaching into the Carboniferous and for which well logs are available. A total of 165 wells are located within tectonic boundaries of the Pomerania Synclinorium. For 39 of these, well log measurements were available, but only 34 of them reach the Palaeozoic formations. Those 34 wells were analysed for potential of use in the present study (Figure 3). The deepest well, Czlochow IG1, was drilled to a depth of 4919 m and reaches Devonian strata (Givetian). Some additional data were also available for a few wells in the study area, including descriptive lithology along well profiles.

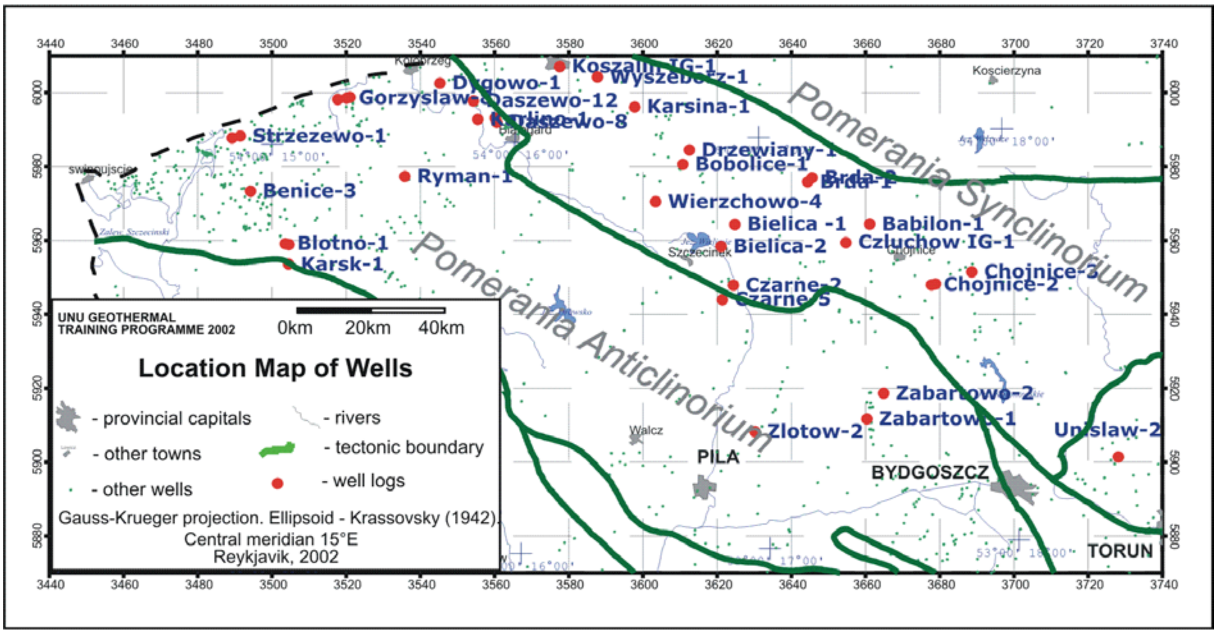

FIGURE 3: Location of petroleum wells in the Pomerania region; borehole data used in this study come from the wells identified by name

3.2 Data management in a multi-well project

3.2.1 Data handling

The well log data was carefully checked, prepared for use with log interpretation software (gaps in header fields checked for possible mistakes) and multiple log suites collected for each well. The second step was to determine the most effective log suite. The most useful logs were selected for further investigation. The processing focussed on the well log data. First a list of the different kinds of well log measurements was made. Thirty-five different types of well logs were found in the Pomerania database. An overview of available measurements for each well is shown in Table 1. Based on the table, it was decided which logs should be used in further analysis.

TABLE 1: Overview of geophysical well logs available for each of the 39 wells

Well name	TYPE OF LOG CURVE																																		
	TEMP	CALX	SP	GR	NEGR	VSHGRI	NPHI	DT	T1	T2	GGDN	LL3	LL3G	MLL	EL00	EL02	EL03	EL07	EL09	EL14	EL19	EL27A	EL28	EN00	EN10	EN16	EN20	EN64	CNL	IL	MIN	MNOR	DEV	SN	RES
1 Babilon-1					X	X																													
2 Banie-1	X	X	X	X	X	X		X	X			X				X	X		X		X		X			X									
3 Benice-3		X	X	X	X			X	X	X		X		X		X	X		X		X		X			X									
4 Bielica-1						X	X																												
5 Bielica-2		X	X	X	X			X	X	X		X	X	X		X	X		X		X		X			X									
6 Blotno-1		X	X	X	X						X	X				X	X		X		X		X			X									
7 Blotno-3		X	X	X	X			X	X	X	X	X		X		X	X		X		X		X			X									
8 Bobolice-1					X	X																													
9 Brda-1					X	X																													
10 Brda-2		X	X	X	X							X				X	X	X	X	X	X		X			X	X								
11 Chojnice-2		X	X	X	X											X	X		X	X		X													
12 Chojnice-3						X	X																												
13 Chojnice-5						X	X																												
14 Czarne-2	X	X	X	X	X			X	X	X	X	X				X	X	X		X			X				X								
15 Czarne-5	X	X	X	X	X			X	X	X	X	X					X			X			X						X						
16 Czluchow IG-1					X	X																													
17 Daszewo-12		X	X	X	X	X	X	X	X	X	X	X		X		X	X		X		X		X			X		X		X					
18 Daszewo-8	X	X	X	X	X	X		X	X	X	X	X				X	X	X		X			X				X								
19 Daszewo-R3P		X	X	X	X			X	X	X		X				X	X		X		X		X			X									
20 Drzewiany-1		X	X	X	X											X	X		X		X		X			X							X		
21 Dygowo-1	X	X	X	X	X			X	X	X	X	X		X		X	X	X		X			X				X			X					
22 Gorzyslaw-8					X	X																													
23 Gorzyslaw-9		X	X	X	X			X	X			X		X		X	X		X		X		X			X									
24 Karlino-1		X	X	X	X			X	X	X		X				X	X		X		X		X			X									
25 Karsina-1		X	X	X	X							X				X	X		X		X		X			X					X	X			
26 Karsk-1		X	X	X	X			X	X	X		X		X		X	X		X		X		X			X							X		
27 Koszalin IG-1		X	X	X	X										X	X	X		X	X		X			X									X	X
28 Ryman-1																																			
29 Sarbinowo-1		X	X	X	X							X				X	X		X		X		X			X									
30 Stargard-1	X	X	X	X	X			X	X	X		X				X	X		X		X		X			X							X		
31 Strzezewo-1					X	X																													
32 Trzebusz-1						X	X																												
33 Unislaw-2	X	X	X	X	X			X	X	X	X	X	X	X		X	X	X		X			X	X		X	X		X			X	X		
34 Wierzchowo-4					X	X																													
35 Wrzosowo-1					X	X																													
36 Wyszeborz-1						X	X																												
37 Zabartowo-1		X		X	X			X																									X		
38 Zabartowo-2		X	X	X	X			X	X	X		X	X	X		X	X		X		X		X			X							X		
39 Zlotow-2	X	X	X	X	X			X	X			X				X	X		X				X			X							X		

According to the literature, the most suitable logs for use in geothermal investigations in sedimentary rock formations are: temperature, spontaneous potential, gamma ray, neutron porosity, sonic log and normal resistivity log. In addition gamma-gamma density logs can be useful.

3.2.2 Data management and computing

The first step was to create a new project in the GeoGraphix software, define the appropriate base map projection parameters, select a coordinate system and the longitude/latitude extent of the study area, cross-sections, etc. In the second step, all available data were imported, in particular stratigraphy, logs and petrophysical parameters. The well logs were then transferred into PRIZM (well logs analysis module) for further analysis. Before any interpreting implementation proceeded, it was necessary to prepare suitable templates to improve managing and editing of the logs on the screen, define the scale of the charts, etc. In the next step all the well logs were plotted out, at the same vertical scale (1:2,000), in order to have a closer look at them, and to evaluate the raw data quality.

The log data were available in LAS format (CWLS v.1.2, which is a Canadian Well Logging Society standard). It is a popular ASCII well data exchange format, widely used in the oil industry.

The evaluation of the geothermal potential of Palaeozoic formations in the Pomerania Synclinorium was carried out with the GeoGraphix software. This package allows simultaneous interpretation of various data types, which can be joined together in a coherent overview. PRIZM, the well log interpretation module, lets the interpreter analyse key wells and then quickly apply the same interpretation to all wells within the project. PRIZM is integrated with GES mapping and other tools within the software package. The data supported by PRIZM are wireline, MWD (measurement while drilling), core, and mud logs, formation boundaries and lithology. PRIZM can handle different numerical data, associated with an index such as depth, or time. Lithologies may be identified and displayed based on user specification, formation tops, and defined by log data.

The data from wells in the project were imported into the *GES* database by using the *WellBase* module. The extensive project database consists of 1590 wells, of which 165 are located in the Pomerania Synclinorium. This database was then used for drawing contour maps for the top of the Carboniferous strata, stratigraphic cross-sections along the tectonic structure (NW-SE) and across them and logs interpretation.

Appendix I gives tables with the abbreviation code for stratigraphic units and nomenclature and acronyms used in the GeoGraphix software.

4. BOREHOLE GEOPHYSICS AND LITHOLOGICAL LOGGING IN GEOTHERMAL PROSPECTING IN SEDIMENTARY ROCK FORMATIONS

Borehole geophysics is the science of recording and analysing measurements of physical properties made in wells or test holes. Borehole geophysics is used in geothermal studies to obtain information on well construction, rock lithology and fractures, permeability and porosity. Typically, multiple logs are collected to take advantage of their synergistic nature. Much more can be learned by the analysis of a suite of logs as a group rather than by the analysis of the same logs individually. The lithological logging technique has been developed in the petroleum industry during the last sixty years. It has only recently been adopted for geothermal logging use. Although this measuring technique can be transferred directly from petroleum wells to geothermal wells, the same will not apply to the methods of interpretation (Stefánsson and Steingrímsson, 1990). These will depend on the kind of rock formations present, igneous or sedimentary. Table 2 lists the common geophysical log suite and main logging parameters, which are measured or can be measured in geothermal wells.

TABLE 2: Types of well logs used in geothermal well logging

	Log type	Measured formation parameter
Mechanical measurements	• Caliper	Hole diameter
Spontaneous measurement	• Temperature	Borehole temperature
	• Self-potential	Spontaneous electrical currents
	• Gamma ray	Natural radioactivity
Induced measurement	• Resistivity	Resistance to electrical current
	• Induction	Conductivity of electrical current
	• Sonic	Velocity of sound propagation
	• Density	Reaction to gamma ray bombardment
	• Neutron	Reaction to neutron bombardment

4.1 Temperature log (TEMP)

The temperature log records the water temperature in the borehole. It is the fundamental parameter in geothermal investigation. Temperature logs are useful for delineating water-bearing zones and identifying vertical flow in the borehole between zones of differing hydraulic head penetrated by wells (Doveton, 1994). Borehole flow between zones is indicated by temperature gradients.

In the present project, temperature logs were available only for a few boreholes and, in particular, zones along the wellbore. Unfortunately, they have not been adopted in Poland on the scale necessary for geothermal exploration.

4.2 Caliper logs (CAL)

The caliper log records the borehole diameter. The ordinary type of measuring sonde is a three-arm caliper, but tools with up to 60 arms are being used. Changes in borehole diameter are related to well construction, such as casing or drilling-bit size, and to fracturing or caving along the borehole wall. Because the borehole diameter commonly affects log response, the caliper log is useful in the analysis of other geophysical logs, including interpretation of flowmeter logs. In geothermal drilling activities, caliper logs are mainly used for

- determination of cavities in the well;
- estimation of borehole influence on the log measurements;
- measurement of wellbore volume (for estimation of cement volume);
- determining the placing of the casing;
- inspecting the casing for damage either during drilling or production;
- establishing a depth reference for depth calibration of lithological logs.

4.3 Spontaneous potential log (SP)

The spontaneous potential log records potentials or voltages developed between the borehole fluid and the surrounding rock and fluids. Spontaneous potential logs can be used in the determination of lithology.

The SP results from the potential difference measurable in the borehole produced by the flow of currents in the hole. These currents are generated by the electrochemical and electrokinetic potentials. In impermeable shales, the SP tends to follow a fairly constant shale base line. In permeable formations, the deflection depends on the contrast between the ion content of the formation water and that of the following: drilling mud filtrate, the clay content, the bed thickness and resistivity, hole size, invasion, and bed boundary effects, etc. In thick, permeable, clean, nonshale formations, the SP value approaches the fairly constant static value. The SP value will change if the formation water salinity changes. In clayey reservoir rocks, the SP will not reach the same value, and a pseudo-static SP value will be recorded (Doveton, 1997).

The SP is most useful when the mud is fresher than the formation water, a good contrast exists between mud filtrate and formation water resistivities, and formation resistivity is low to moderate. In these cases, it indicates permeable beds by large negative deflections, permits easy sand-shale discrimination, is useful for correlations, and under favourable conditions, can be used for the estimation of formation water resistivity (Doveton, 1994).

The curve still remains useful in some saline muds. If the formation water is less saline than the mud filtrate, the SP deflection will be positive. However, when the mud column becomes so conductive it will not support a demonstrable potential difference, the SP curve becomes featureless. Collection of spontaneous-potential logs is limited to water- or mud-filled open holes.

4.4 Normal-resistivity logs (EN)

The normal resistivity log records the electrical resistivity of the borehole environment and surrounding rocks and water as measured by variably spaced potential electrodes on the logging probe. Typical spacing for potential electrodes is 16" for short-normal resistivity and 64" for long-normal resistivity (Figure 4).

Normal resistivity logs are affected by bed thickness, borehole diameter, and borehole fluid and can only be collected in water- or mud-filled open holes. They need to be corrected. The normal resistivity log is a four-electrode array with two electrodes fixed on the logging sonde in the well. The third electrode is placed at the surface, but the armour of the logging cable is usually used as a fourth electrode (Figure 4). During logging a constant current *I* is driven between the electrode *A* on the sonde and the cable armour (*B*), and the voltage *V* between electrode *M* and the surface electrode *N* measured. For the normal electrode array the resistivity of an infinite homogeneous medium is given by the relation:

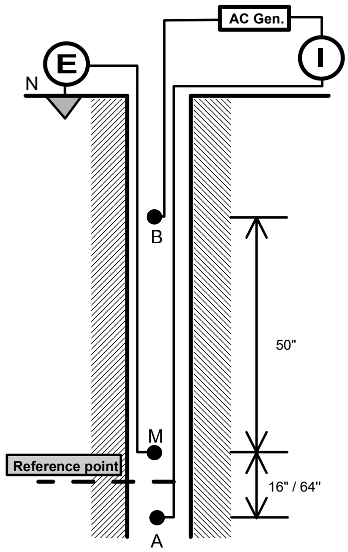

FIGURE 4: Electrode arrangement for a normal resistivity log

$$\rho = 4\pi \, \overline{A}\overline{M} \, V / I \qquad \textit{(apparent resistivity)} \qquad (1)$$

The determination of the true rock resistivity will include elimination of well effect (fluid resistivity and well size) as well as the effects of limited bed thickness of the adjacent lithological units (Doveton, 1997). Resistivity well logs are the best method available to check the results of geoelectrical surveys, and are therefore of great importance in geothermal investigation. Because of the difference in electrical properties between different formations the resistivity will show lithological variations clearly.

4.5 Gamma logs (GR)

Gamma logs record the amount of natural gamma radiation emitted by the rocks surrounding the borehole. The most significant naturally occurring sources of gamma radiation are potassium ^{40}K and daughter products of the uranium ^{238}U and thorium ^{232}Th decay series (Stefánsson and Steingrímsson, 1990). Clay- and shale-bearing rocks commonly emit relatively high gamma radiation because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion absorption and exchange. The activity of nuclear radiation is related to the mineral composition and generally to the type of rock formation. In sedimentary rocks, it is due to significant abundance of potassium ^{40}K, and in volcanic rock to SiO_2 content of the rock. Geochemical evidence supports the above relationship, as the content of radioactive isotopes increases when going from basic to acidic igneous rock. The four basic types of detectors used since the inception of radiation logging are

a) Ionisation chamber;
b) Geiger-Muller (G-M) detector;
c) Proportional counter;
d) Scintillation detector.

The G-M counter measures the total gamma intensity, and the scintillation counter can register the energy spectrum of the gamma radiation (Jarzyna et al., 1997). The log often functions as a substitute for the SP for correlation purposes in nonconductive borehole fluids in open holes, for thick carbonate intervals, and to correlate cased-hole logs with open-hole logs. The "API Gamma Ray Unit" has been adopted industry-wide as the official unit of gamma ray measurement. The detector-measurement system of all primary service companies are normalized to this unit in the American Petroleum Institute test pit at the University of Houston. The API gamma ray unit is defined as 0.5% of the difference of the count rate registered between zones of low and high radioactivity in the test pit.

4.6 Neutron porosity logs (PHIN, NPHI)

Neutron porosity logs were introduced in the early 1940s. The first tools were known as neutron-gamma tools (raw neutron porosity logs) (GRN, NEGR). The capture of neutrons in this tool results in the emission of secondary gamma rays, which are captured by the sonde. Other tools detect intermediate (epithermal) neutrons or slow (thermal) neutrons (both referred to as neutron-neutron logs) (AnaLog Services, 2000). Neutron-neutron tools, using a thermal neutron detector were introduced in about 1950 (Schlumberger, 2002).

Modern neutron porosity logs are sensitive to the density of the hydrogen nucleus and respond to the contents of water in the formation. It should be pointed out that neutrons don't distinguish between protons that belong to formation water and those water-bound in minerals. This is of particular interest in geothermal logging, as hydrothermal alteration is a process of forming minerals with bound water. A downhole chemical neutron source (typically: beryllium ${}_{4}Be^{9}$ and radium ${}_{88}Ra^{226}$) emits a continuous flux of energetic neutrons. These neutrons are reduced in energy as they migrate spherically away from the source. At a very low energy level, the neutrons are eventually absorbed by the nuclei of the wellbore and formation constituents. A radiation detector senses either the low-energy neutrons or the gamma radiation resulting from slow neutron absorption. The elastic collision of neutrons with nuclei in the borehole and surrounding rocks leads to a gradual loss of energy (as a function of: angle of collision and relative mass of the struck nucleous). Since hydrogen atoms are both relatively abundant and nearly equal in mass to the neutron, they are primarily responsible for reducing high-energy neutrons to their thermal state. A neutron at thermal energy level finds itself in a state of equilibrium with the surrounding atoms. The detector is responsive to captured gamma rays or slow neutrons, the measurement is indicative of the relative amount of hydrogen in the rocks. Thus, high porosity is indicated by a low neutron-counting rate and vice versa. The units of such measurement are usually counts per minute. The NPHI log is used for estimation of porosity.

4.7 Density logs (RHOB, GGDN)

The bulk density registered by the gamma-gamma log is an essential parameter of the reservoir rock. The density log is one of the three "porosity logs"; this group also includes the sonic and neutron logs.

The density tool is usually run in an open hole and is pushed against the side of the hole by an arm on the tool, or a decentralizer spring. The radiation from a radioactive source (Cesium ${}^{137}Cs$) that is placed in the tool is scattered by the formation. Dense formation causes more scattering and a lower count rate, corresponding to higher density values. In less dense formation there is less scattering, a higher count rate corresponding to lower density values.

The logging tool consists of a gamma-ray source (e.g. ${}^{137}Cs$) and a detector shielded from the source so that it records backscattered gamma rays from the formation. The backscattering depends on the electron density of the formation, which is roughly proportional to the bulk density. The source and detector usually are mounted on a skid, which is pressed against the borehole wall. The compensated density logging tool includes a secondary detector, which responds more to the mud cake and small, borehole irregularities. Units for the density are in g/cm^3 (gm/cc) or in counts per second (CPS) or counts per minute (CPM). The response of the second detector is used to correct the measurements of the primary detector (Figure 5). Log quality of the decentralized density log greatly decreases in washouts and varies if the tool is run inside the casing.

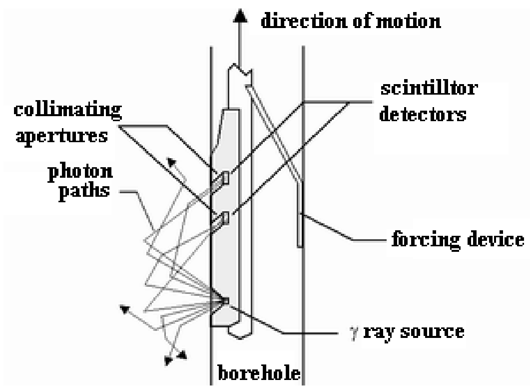

FIGURE 5: Gamma-gamma density tool

The density log is primarily applied to uncased holes. The RHOB log is used for estimation of porosity. The number of gamma rays that reach the detectors is directly related to the number of electrons in the formation, which is in turn related to the bulk density. The bulk-density value measured by the sonde can be used to calculate the total porosity using Equation 2.

$$\phi = (\rho_{gr} - \rho_b) / (\rho_{gr} - \rho_w) \qquad (2)$$

where ρ_{gr} = Mean grain density, given by physical properties measurements (typically 2.7 g/cm^3);
ρ_w = Pore water density, taken to be 1.03 g/cm^3 for seawater;
ρ_b = Bulk density, given by the sonde.

4.8 Sonic logs (DT)

Acoustic travel time (delta-T), also called "slow-travel time or variable density log", records the travel time (interval transit time) of the compression wave over a unit distance and hence, is a record of the reciprocal of the compressional wave velocity. The time for acoustic energy to travel a distance through the formation equal to the distance spanned by two receivers is the desired measurement (Doveton, 1997). The units of such measurement are usually expressed in μs/m. The interval transit time can be integrated to give the total travel time over the logged interval. For the borehole sonic log - dual receiver (Figure 6), one transmitter above the two receivers is pulsed to produce an improved log; averaging the measurements tends to cancel errors due to sonde tilt or changes in hole size.

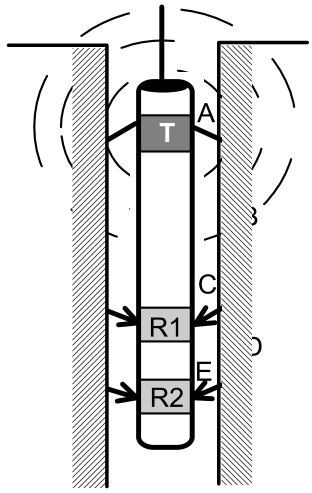

FIGURE 6: Sonic tool (T is the transmitter; R1 and R2 are receivers)

There are a few other types of sonde with more complicated sets of transmitters and receivers. For instance Borehole compensated sonic (BHC) with two transmitters and four receivers; and long spacing sonic tool (LSS) with two transmitters and two receivers. The Sonic is one of the "porosity logs" along with the neutron and density logs; it does not need a radioactive source so it can be used in water source wells when radioactive sources cannot be run (Doveton, 1997). The sonic log is used in combination with other logs (e.g. density and neutron) for estimation of the *(total) porosity*:

There is an approximately linear relationship between the transit time and porosity (Doveton, 1997). Porosities could be estimated from a linear interpolation between the transit time of the matrix mineral (zero porosity) Δt_{ma} and the transit time of the porosity fluid (100% porosity) Δt_f. Thus,

$$\Delta t = \Phi\, \Delta t_f + (1 - \Phi)\, \Delta t_{ma} \qquad (3)$$

where Δt = Transit time of the zone
Φ = Porosity of the zone

which gives the *Wyllie time average equation*,

$$\Phi = (\Delta t - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma}) \qquad (4)$$

5. CASE STUDY

5.1 Geothermal features of the Pomerania Synclinorium

5.1.1 Geothermal conditions in Carboniferous strata

The distribution of the terrestrial heat flow in Poland varies with geological structure. The heat flow in the Precambrian East European Craton is lower than in other geological provinces. An average value for the heat flow is 48 mW/m^2. Within the Teissere-Tornquist Zone, where the study area is located, the heat flow is more diverse, but on average 52 mW/m^2 (Plewa, 1994).

The variability of temperature conditions is shown clearly on the geothermal gradient map of the Pomerania Synclinorium region (Figure 7). The gradient varies between 25 and 30°C/km and it is within the range of average temperature gradients observed in Poland (12-38°C/km). Minima in the gradient extends from northwest to southeast along the axis of the Synclinorium, whereas maxima, expressing different geological conditions, are found on both sides.

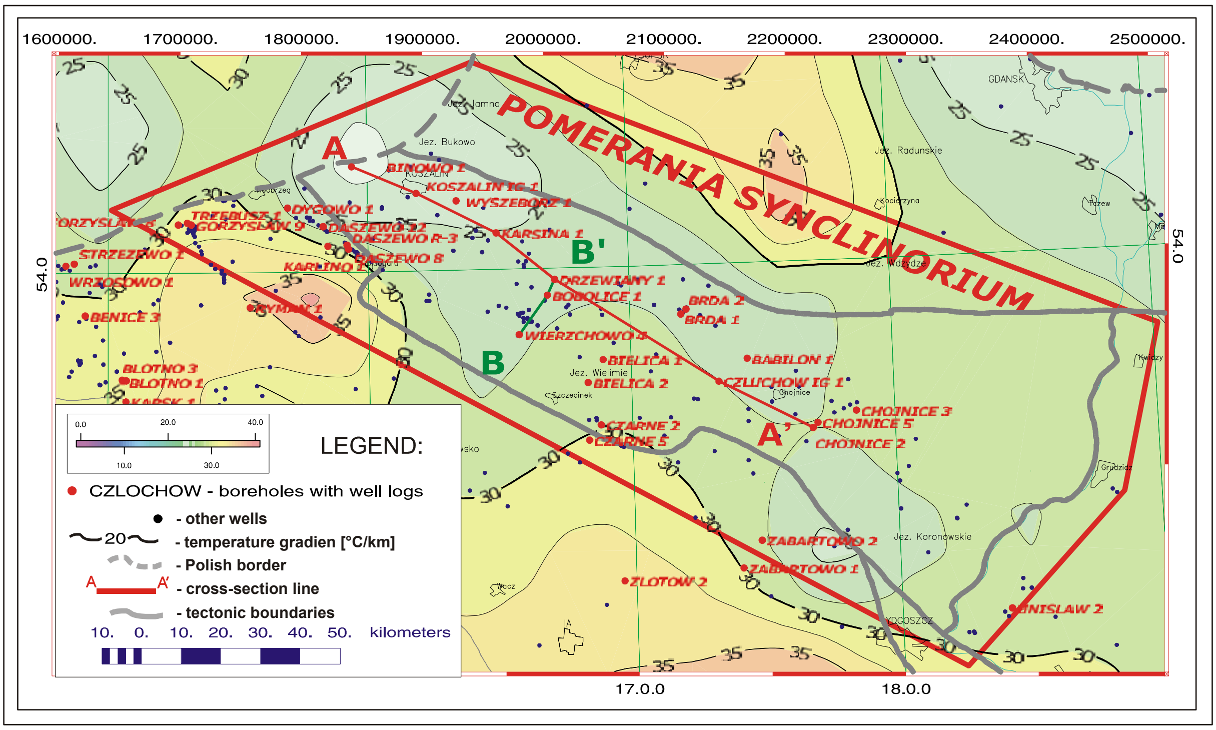

FIGURE 7: Map of the geothermal gradient in the Pomerania region

The study area is located in a contact zone between the Palaeozoic Platform (on the southwest side of the Teisseyre-Tornquist Zone), and the Precambrian Craton, with a thin cover of sediments on the northeast side of the zone. On average the older crustal areas appear to have a lower heat flow than the younger crust. The heat flow in the cratonic shields, as in the East European Precambrian Craton, may almost entirely be accounted for by radiogenic heat production within the surface rocks themselves. This may imply depletion of radiogenic heat-producing elements in the crust and upper mantle beneath these areas, whereas the Mesozoic and Tertiary orogenic areas, with thick sedimentary cover, may still have a great radiogenic potential.

Equation 5 is Fourier's law of heat conduction in homogeneous, isotropic media. It applies for 1-dimensional, steady-state systems. The equation has wide application in porous media systems, e.g. in sedimentary basins.

$$q_x = -k \frac{\partial T}{\partial x} \tag{5}$$

where q_x = Heat flow in the x direction [W/m^2];
k = Thermal conductivity [W/m°C];
$\partial T/\partial x$ = Temperature gradient in the x direction [°C/km]

According to Equation 5, variable heat flow can affect the distribution of the temperature gradient anomalies on both sides of the Teisseyre-Tornquist Zone, assuming a constant value for the thermal conductivity.

5.1.2 Distribution of temperature in Carboniferous strata

There were very few temperature measurements for the top of the Carboniferous strata. Hence, the temperatures for this horizon were obtained by extrapolating the geothermal gradient at the top of the Lower Triassic, for which there is geothermal data coverage, down to the top of the Carboniferous strata. These data are from an unpublished study carried out at the Department of Fossil Fuels. It is based on temperature measurements in boreholes during stable state conditions, as well as on laboratory studies and heat flow measurements not presented before.

The first step, in this part of the analysis, was to prepare the structural map for the top of Carboniferous strata in the Pomerania Synclinorium (Figure 8). The map was prepared based on the lithostratigraphic profiles gathered from the GeoGraphix database. The mathematical model of the top of Carboniferous surface was constructed using the IsoMap module. During computation, the extent of the Carboniferous strata was taken into consideration. The study area is located in the northeast marginal zone of Carboniferous sediments in Poland.

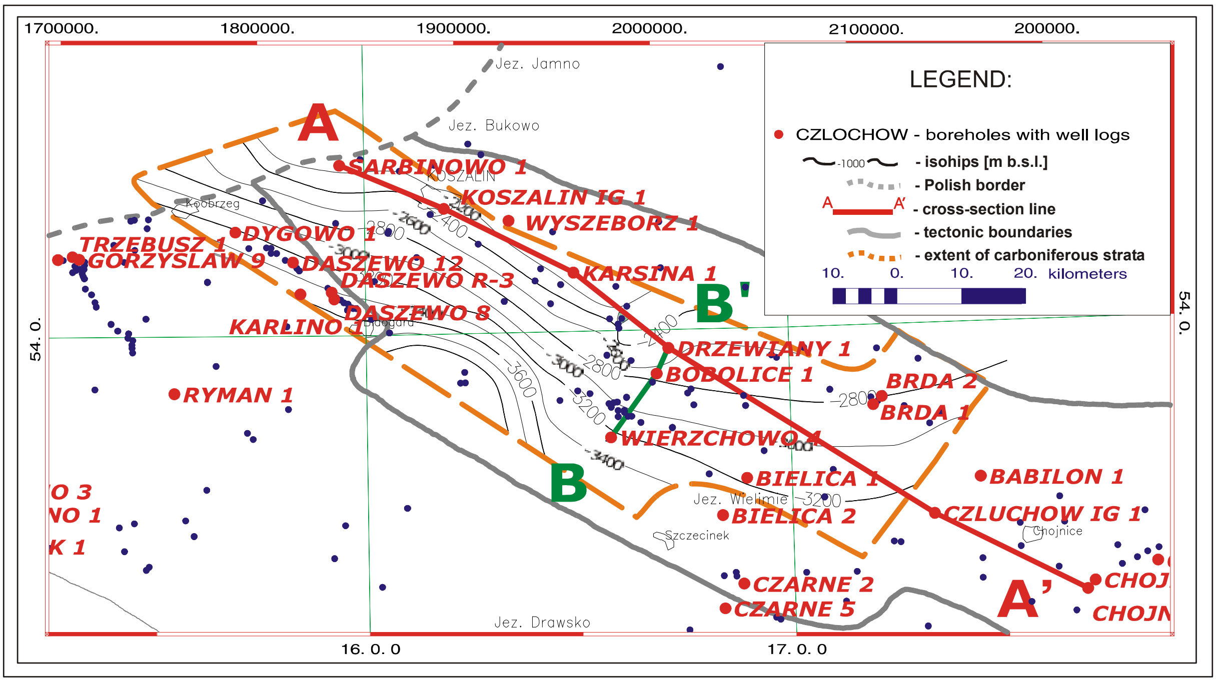

FIGURE 8: Structural map of the top of the Carboniferous strata in the Pomerania Synclinorium

Analysis of the map shows that the depth to Carboniferous strata generally increases from northeast to southwest, toward the centre of deposition in the Palaeozoic Platform. The southwest part of the Synclinorium is deeply buried and reaches a depth of more than 4000 m. The shallowest depths are found

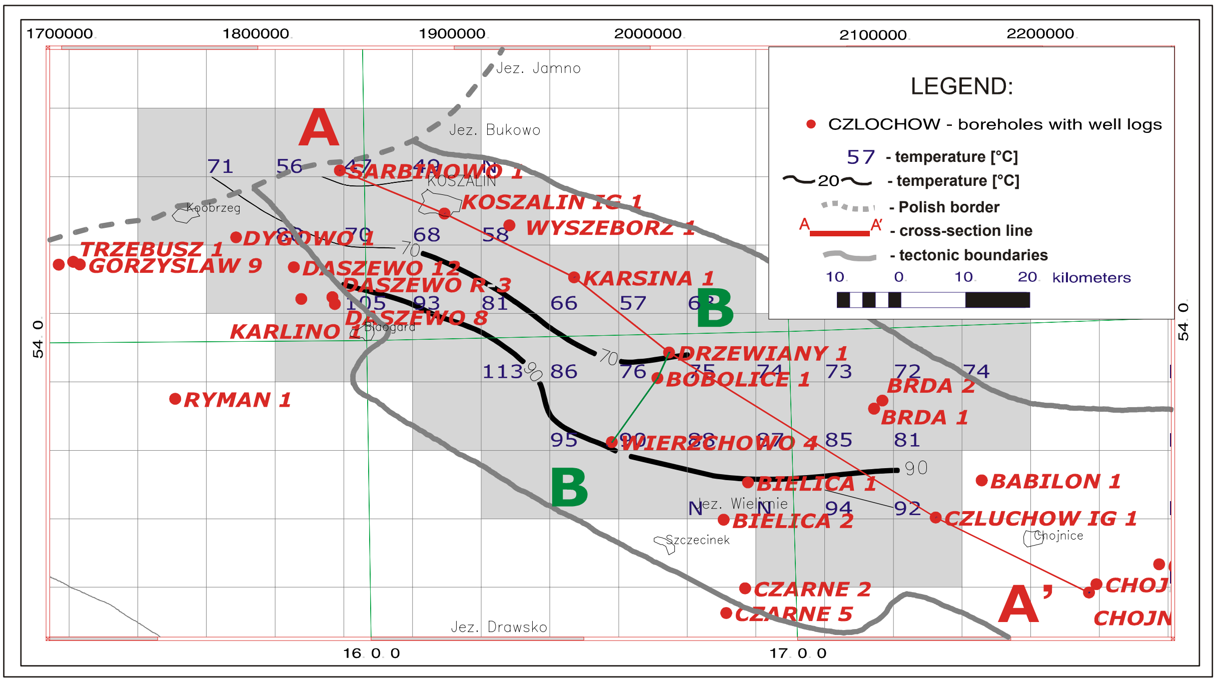

FIGURE 9: Map of estimated temperature at the top of the Carboniferous strata

along the northeastern boundary of the Synclinorium, where a minimum depth of 2200 m is reached close to the Karsina-1 well. In order to obtain a map of the temperature in the top of the Carboniferous strata, the map of the geothermal gradient was superimposed on the structural map of the top of Carboniferous. The result is given in Figure 9 which shows the estimated distribution of temperature at the top of the Carboniferous strata. The estimated temperature at the top of the Carboniferous strata varies from about 60°C in the northeast part of the Synclinorium, to 110°C in the southwest part, where the top of the Carboniferous layer reaches 4000 m. These estimated temperatures indicate that the geothermal water from the Carboniferous formations will be classified as low-enthalpy resources.

5.2 Lithological features of potential aquifers in Carboniferous strata

Carboniferous strata are widespread in some parts of the Polish Lowlands, such as in the lower and upper Coal Basins, Lublin Region. Other information about the presence of Carboniferous rocks comes from deep wells and geophysical borehole data. Carboniferous strata are, for instance, well known from boreholes drilled in the Pomerania Region. Here they are located at large depths, below a thick Permo-Mesozoic cover.

An important problem during initial investigations of potential geothermal areas in sedimentary rocks is to identify possible aquifers and cap rocks within the lithostratigraphic section. Based upon the experience on the geothermal behaviour of aquifers within the Mesozoic sedimental cover of the Polish Lowlands, especially the petrophysical parameters of aquifers, the present study should be focused on evaluation of the porosity and permeability of sandstone beds. However, permeability due to fissures in limestones and other carbonate rocks cannot be neglected. It could play a significant role in fluid circulation, especially in deeply buried rocks connected with fault zones (related to the Teisseyre-Tornquist lineament).

5.2.1 Lithological description of the Carboniferous sedimentary succession

The Lower Carboniferous sequence (Tournaisian, Visean) includes a wide spectrum of lithology from claystones to conglomerates and sandstones. In both the Pomerania Synclinorium and Anticlinorium, the

Tournasian sequence is present in the southern and central parts where it is directly overlain by Zechstein strata. In the Wierzchowo-Bobolice area the Tournasian complex is developed as claystones with sandstone and mudstone intercalations and with minor dark dolomites and dolomitic limestone. In both the northern and northwestern part of the Pomerania Synclinorium the percentage of sandstones and arkosic sandstones in the sequence increases (Karnkowski, 1999).

From a lithological point of view, the most suitable reservoirs are probably connected with porous sandstones.

5.2.2 Petrophysical characteristics of the Carboniferous strata

Available data on porosities and permeabilities in the Palaeozoic strata do not allow for an extensive statistical analysis of petrophysical parameters. However, some descriptive information and quantitative data collected for a few wells (Figure 10) clearly point to Carboniferous (Visean) sandstones as the most promising reservoir interval. Figure 10 demonstrates that the porosity and permeability of the rocks increase from Devonian (Famennian) rocks to the Lower Carboniferous profile, reaching a maximum in Visean sandstones.

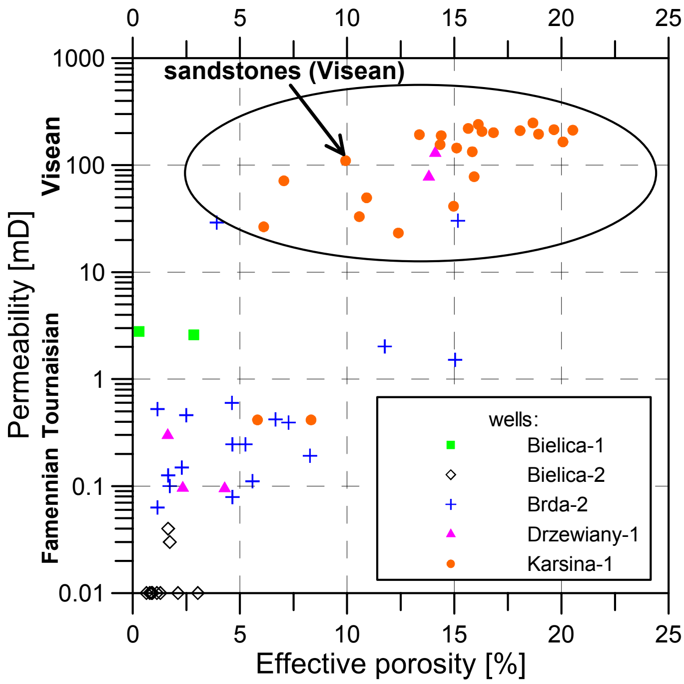

FIGURE 10: Permeability vs. porosity measured in cores from Devonian and Carboniferous strata rocks from wells in the Pomerania Synclinorium

The core samples from Famennian and Tournasian strata rarely exhibit more than 10% porosity and 1.0 mD permeability. By comparison, the whole profile of Visean strata shows anomalously high effective porosity and permeability. Based on measurements of core samples from the Karsina-1 well profile, the most promising possible aquifers within the Carboniferous strata are porous and permeable sandstones of Visean age (Table 3). Apparently, there are two main zones. The upper zone at a depth of 2214-2236 m has an average porosity of 16.5% and permeability of 188.3 mD. The lower zone at a depth of 2425-2427 m has a porosity of 16% and permeability of 145 mD (Table 3).

5.2.3 Well logging application

A qualitative analysis of the well logs does not give a clear confirmation of the petrophysical anomalies observed in the core measurements. Some local perturbations in the GR and NEGR logs can be seen between 2220 m and 2435 m in well Karsina-1 (Figure 11). The correlation is rather poor, probably due to the quality of the input data (geophysical logs). High-porosity zones should give a clear response in the gamma and neutron logs, but this is not observed. However, the central and lower part of the Visean profile of Karsina-1 (Figure 11, and Appendix II) is characterized by high gamma-ray values. Analysis of volume shale curve (VSHGR) in Wierzchowo-4, which describes the amount of shale minerals in the total volume of rocks, confirms that the lower parts of the Visean are more shaly.

TABLE 3: Petrophysical properties of Visean sandstones in well Karsina-1 (archives of the Department of Fossil Fuels)

Karsina-1 Stage	Lithology	Depth of sampling [m]	Effective porosity [%]	Permeability [mD]
Visean	quartzity sandstone	2203.1	15.927	77.927
Visean	quartzity sandstone	2204.1	7.05	71.298
Visean	quartzite sandstone	2205.1	6.11	26.53
Visean	sandstone	2207.5	14.39	188.659
Visean	sandstone	2208.5	14.34	155.367
Visean	sandstone	2209.5	15.84	133.634
Visean	sandstone	2213.7	15.65	220.100
Visean	sandstone	2214.7	16.12	240.114
Visean	sandstone	2215.7	16.29	206.348
Visean	sandstone	2221.1	18.07	210.098
Visean	sandstone	2222.1	19.65	214.600
Visean	sandstone	2226.5	18.67	247.616
Visean	sandstone	2227.5	13.37	192.590
Visean	sandstone	2235.9	18.93	195.091
Visean	sandstone	2236.9	12.39	23.214
Visean	sandstone	2238.9	14.97	41.269
Visean	sandstone	2242.1	10.91	49.523
Visean	sandstone	2249.8	10.57	33.015
Visean	sandstone	2250.3	15.11	144.442
Visean	claystone	2251.3	9.93	110.051
Visean	quartzity sandstone	2424.2	22.38	NULL
Visean	quartzity sandstone	2425.3	20.53	212.242
Visean	quartzity sandstone	2426.3	20.07	165.077
Visean	quartzity sandstone	2427.2	16.83	201.180
Tournaisian	claystone	2591.7	5.82	0.415
Tournaisian	sandstone	2592.7	8.32	0.415

In order to show the lateral extent and thickness of the Visean strata in comparison with geophysical borehole measurements, two stratigraphic cross-sections with geophysical datasets were constructed (Figures 12 and 13, which show SP logs from the wells). The stratigraphic cross-sections differ from structural cross-sections in that underground structure or elevation is not considered in the stratigraphic one. In this case, horizon P2Z1 was chosen as the reference level. The well logs were "hung" from this level in order to show the formation thickness and log relationship more clearly. Horizon P2Z1 corresponds to the top of the Zechstein - Werra cyclothem, which could be traced through almost all the wells in the Pomerania Synclinorium region (Appendix II).

Each SP log was hung on the reference level though the formations in each well are at different depths, due to underground structure Hanging the line on the marker-horizon (reference level) shows the lateral extent and thickness relationship of Visean strata more clearly. The software can determine this correlation automatically.

The two stratigraphic cross-sections in Figures 12 and 13 illustrate a vertical view along A-A' (Figure 12) and across B-B' the structure (Figure 13). Spontaneous potential logs are laid out in a line. The stratigraphic borders between individual formations were identified in the well database.

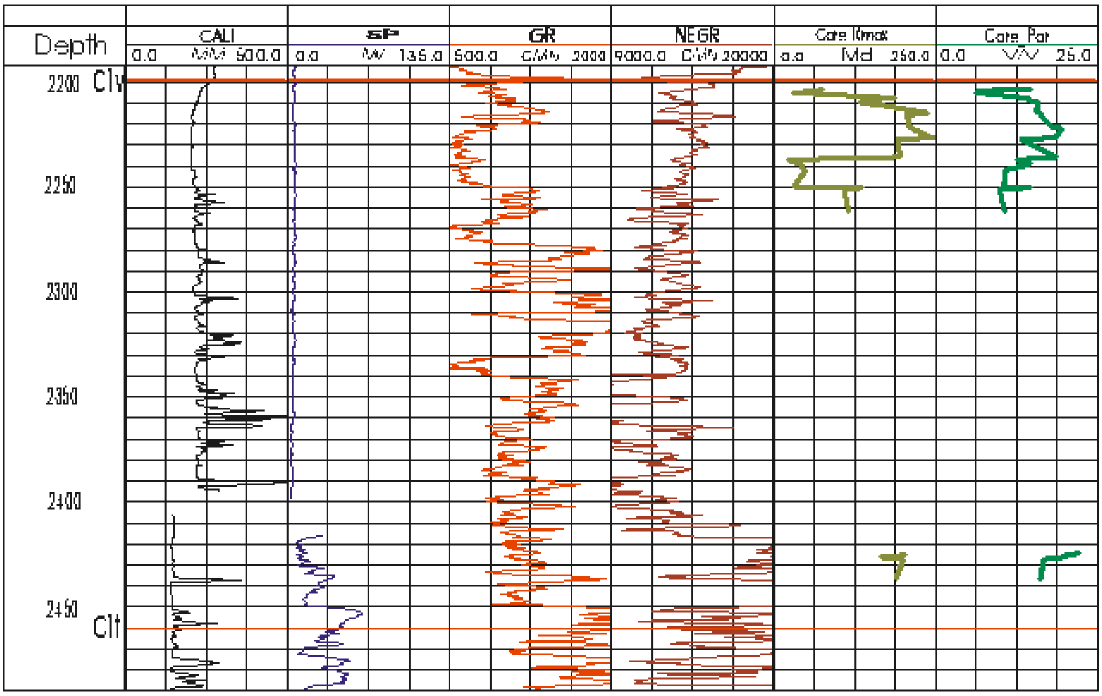

FIGURE 11: Part of a composite well log from well Karsina-1

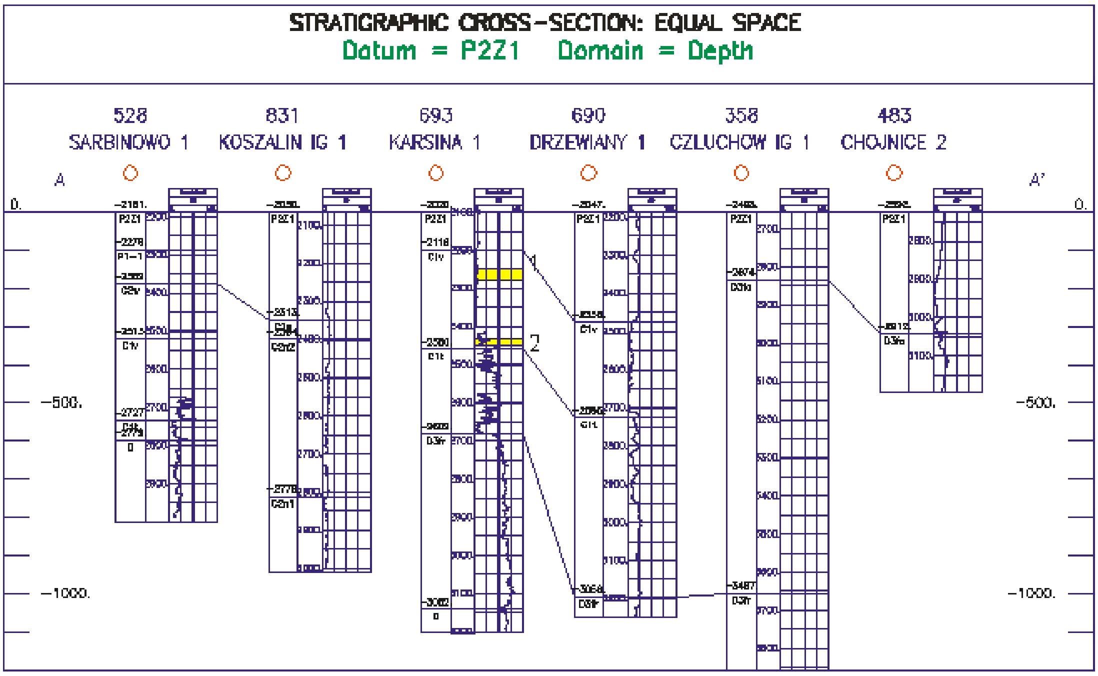

FIGURE 12: Lithostratigraphic cross-section A-A' along the Pomerania Synclinorium, showing correlation of pre-Permian strata (location see Figures 7-9)

The lithostratigraphic boundaries identified in the well database were adjusted to fit the corresponding boundary depths determined from the depth on geophysical logs (Figures 12 and 13). Unfortunately there is no clear relationship between the geophysical logs and stratigraphical boundaries and the thickness of individual lithostratigraphic units. In Figure 12 the two most prospective zones of Carboniferous sandstones were marked (zone 1, zone 2) according to Table 3. The high porous sandstones distinguished as zones 1 and 2 in the Karsina-1 well do not correspond even with the SP curve, which based on the screen analysis of the logs, fits best with the stratigraphic boundaries in almost all the wells. Unfortunately, the SP log curve is not present in Czlochow-1 well.

The maximum thickness of Visean strata, 260 m, is present in the Karsina-1 well. In other wells the thickness varies over a wide range. The most interesting thing about cross-section A-A' (Figure 12) is the way the Visean layer disappears along it, between Koszalin-IG1 – Karsina-1 and Drzewiany-1 – Czlochow-IG1 wells.

The Visean deposits are not present in the Bobolice-1, Koszlin-IG1, and Czlochow-IG1 wells. In Chojnice-2, the whole Carboniferous sediments entirely disappear. These pinch-outs of the Visean layer may be due to both sedimentary and tectonic geological conditions in the Pomerania Synclinorium region. It could possibly affect the extent of aquifers and determine if it is a confined or unconfined type of aquifer. These suggestions should be taken into consideration in further, detailed studies.

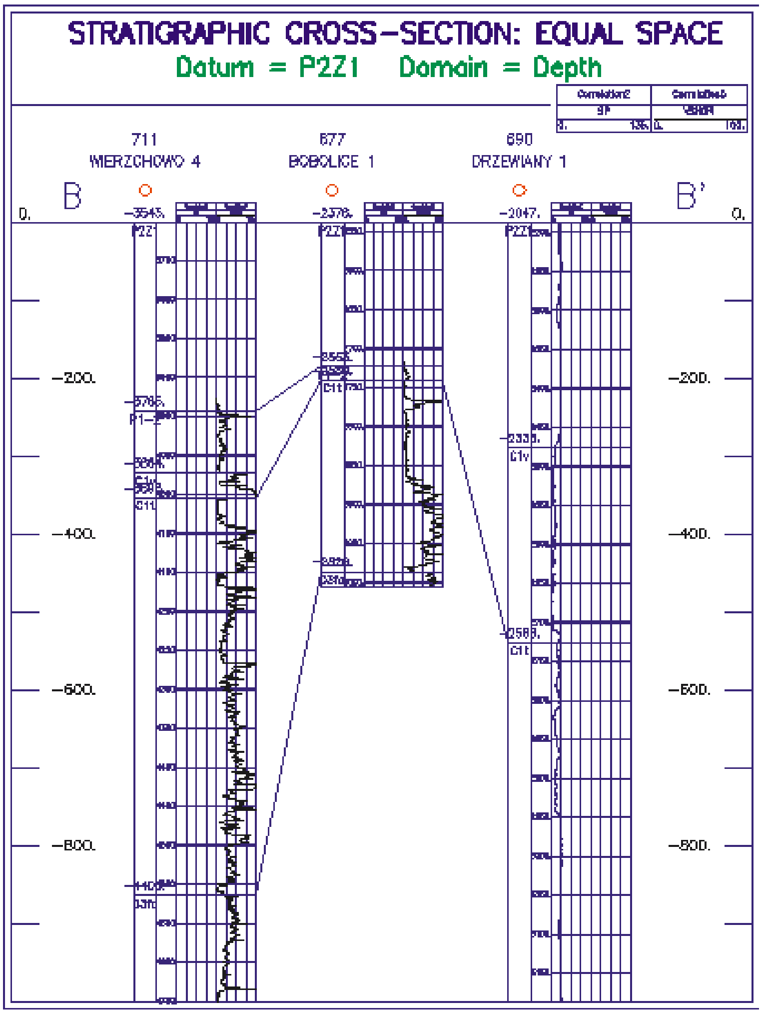

FIGURE 13: Lithostratigraphic cross-section B-B' across the Pomerania Synclinorium, showing correlation of pre-Permian strata (location see Figures 7-9)

The Visean succession discordantly overlies various Tournaisian units (Figures 12, and 13). In the central part of the Synclinorium, its lithology includes dolomites and claystones with sandstone and limestone interbeds. The western part is dominated by sandstones. Namurian and Westphalian strata are reported from the northwestern part of the Synclinorium. Westphalian is present in well Sarbinowo-1 and Koszalin-IG1 (Figure 12) and Namurian strata is present in Koszalin-IG1 (Figure 12).

6. CONCLUSIONS

The main conclusions that can be drawn from the study are as follows:

1. Good permeability and porosity for potential aquifers exist in the Carboniferous (Visean) sandstones within the Pomerania Synclinorium at a depth of 2214-2236 m with a porosity of 17% and permeability of 188 mD, and at a depth of 2425-2427 m with a porosity of 16% and permeability of 145 mD.
2. The geothermal gradient in the Pomerania Synclinorium varies between 25 and 30°C/km.
3. The temperature at the top of the Carboniferous strata varies between 60 and 110°C. Any geothermal resources will therefore be of the low-enthalpy type.
4. Existing geophysical borehole log data available in the project are of poor quality. Calibration processes must be applied before analysis and comparison of data can proceed. Almost all logs,

especially nuclear radiation logs (gamma ray, neutron-gamma, etc.), need to be normalized into API standard units, before any quantitative interpretation can be undertaken.

5. Lithological profiles cannot be accurately identified on the basis of gamma and neutron logs. A clear anomaly on one log, is usually not accompanied by a corresponding response on the other. This applies to the gamma ray and neutron-gamma curves.
6. Within the same stratigraphic unit, log readings in one well are often inconsistent with the readings in neighbouring wells.
7. Misidentification of lithological boundaries and lithological correlation of potential aquifers, based only on those curves, can be a source of considerable error.

Future activities should be undertaken in order to improve the quality of the borehole data, due to their possible use in future geothermal investigation, such as

1. Calibration of old logs into API standards, which is necessary.
2. Use of temperature logs (recorded during and after drilling), as a tool to localize aquifers, should be taken into consideration. It may improve exploration techniques and possibly show location of feed zones in the deepest parts of the wells.

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APPENDIX 1: Stratigraphic nomenclature and nomenclature and acronyms in GeoGraphix

TABLE 1: Stratigraphic nomenclature (abbreviation codes)

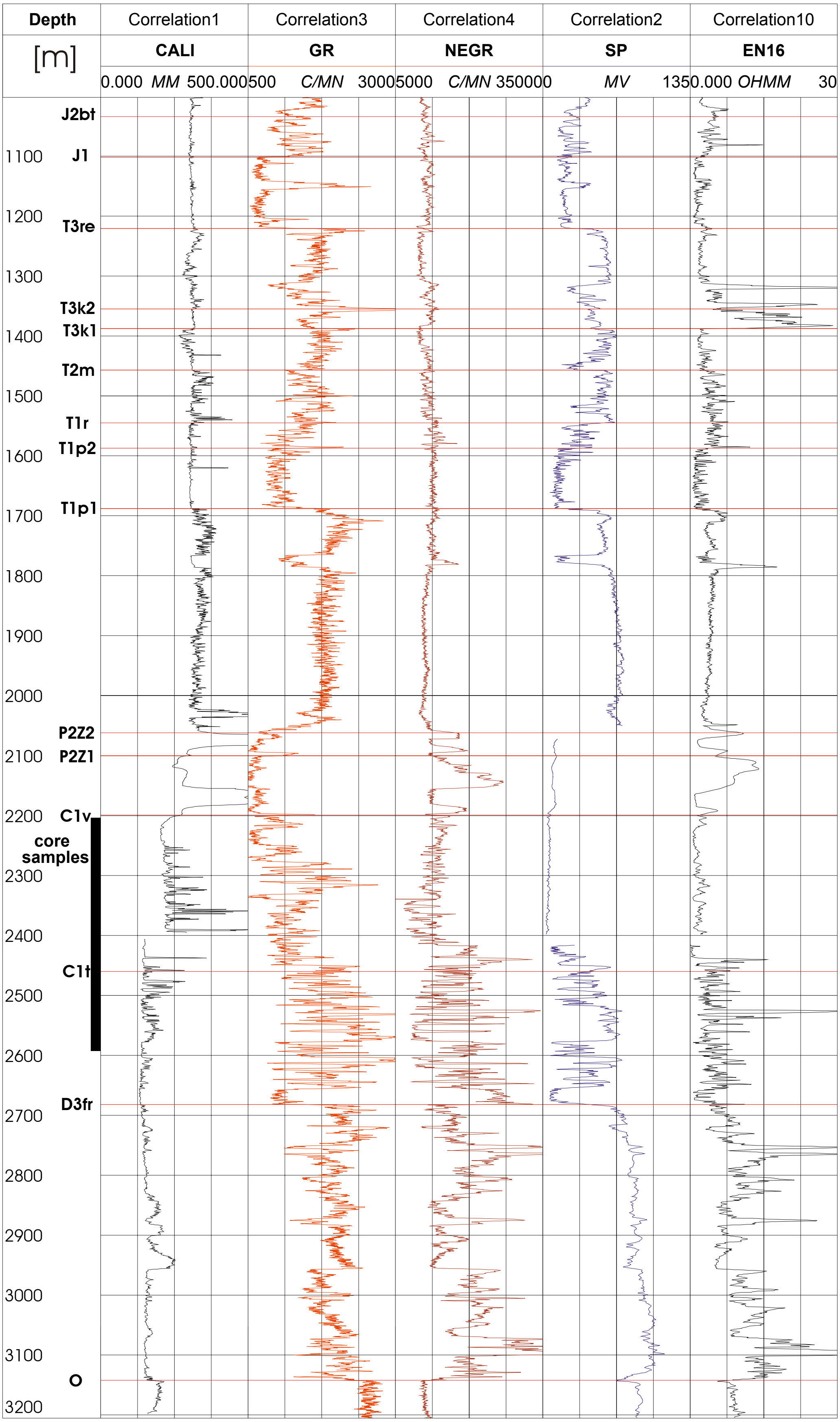
Abbreviation	Explanation
J3p	Jurassic/Malm/Portlandian
J3km	Jurassic/Malm/Kimmeridgian
J3o	Jurassic/Malm/Oxfordian
J2c1	Jurassic/Dogger/Callovian
J2bt	Jurassic/Dogger/Bathonian
J2w	Jurassic/Dogger/Bajocian- Bathonian (Wezul)
J1h	Jurassic/Lias/Hettangian
J1	Jurassic/Lias
T3re	Triassic/Rhaetian
T3k2	Triassic/Norian
T3k1	Triassic/Carnian
T2m	Triassic/Anisian- Ladinian
T1r	Triassic/Scytian - local subdivision
T1p2	Triassic/Scytian - local subdivision
T1p1	Triassic/Scytian - local subdivision
P2Z4	Permian/Zechstein - Aller
P2Z3	Permian/Zechstein - Leine
P2Z2	Permian/Zechstein - Stassfurt
P2Z1	Permian/Zechstein - Werra
C1v	Carboniferous/Visean
C1t	Carboniferous/Tournaisian
D3fr	Devonian//Frasnian
J2k3	Jurassic/Dogger/Callovian - subdivision
Pzt	Lower Permian (terrigenic succession)
O2l	Ordovician/Llandeilo
O	Ordovician

TABLE 2: Nomenclature and acronyms for the Geographix software

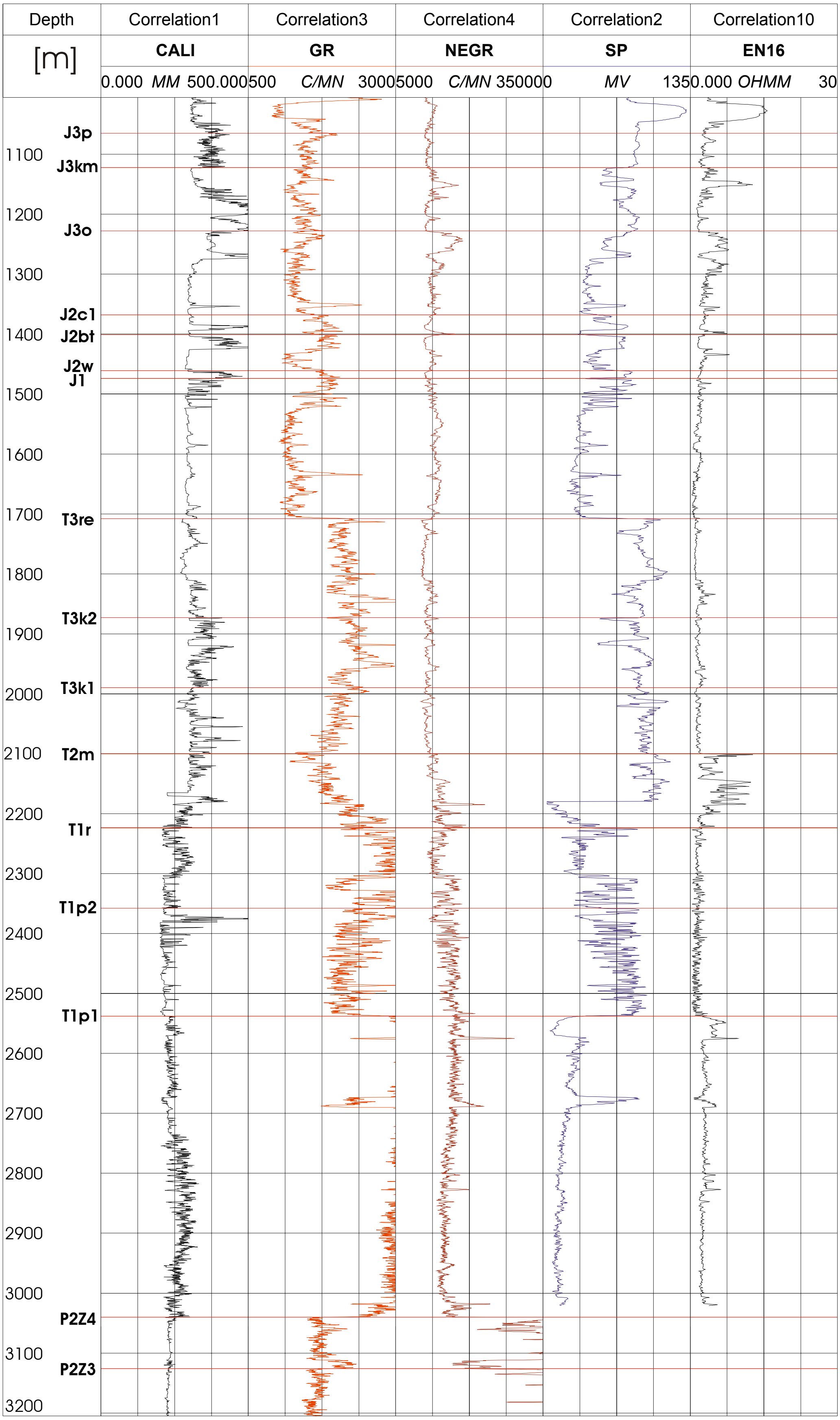
Well log codes	Units		Description
DEPT	M	Metre	Depth
TEMP	DEGC	Centigrade	Formation Temperature
CAL	MM	Millimetre	Caliper
SP	MV	Millivolt	Spontaneous Potential
GR	C/MN	Count per minute	Gamma Ray
NEGR	C/MN	Count per minute	Neutron-Gamma
VSHGRI	PCNT	Percent	Shale Volume/Gamma Ray
NPHI	PU	Porosity units	Neutron porosity
DT	US/M	Microseconds per minute	Sonic DT
GGDN	C/MN	Count per minute	Gamma-Gamma Density
EN16	OHMM	Ohmmeter	Normal 0.4m, 16in
T1	US	Microseconds	SonicT1
T2	US	Microseconds	SonicT2
LL3	OHMM	Ohmmeter	Laterolog-3, Guard eq.
LL3G	OHMM	Ohmmeter	Laterolog-3, Guard eq. Gron
MLL	OHMM	Ohmmeter	Microlaterolog
EL00	OHMM	Ohmmeter	Lateral
EL02	OHMM	Ohmmeter	Lateral 0.55m, 2ft.
EL03	OHMM	Ohmmeter	Lateral 1.05m, 3ft.
EL07	OHMM	Ohmmeter	Lateral 2.25m, 7ft.
EL09	OHMM	Ohmmeter	Lateral 2.625m, 9ft.
EL14	OHMM	Ohmmeter	Lateral 4.25m, 14ft.
EL19	OHMM	Ohmmeter	Lateral 5.9m, 19ft.
EL27A	OHMM	Ohmmeter	Lateral 8.25m, 27ft.
EL28	OHMM	Ohmmeter	Lateral 8.5m, 28ft.
EN00	OHMM	Ohmmeter	Normal
EN10	OHMM	Ohmmeter	Normal 0.25m, 10in.
EN20	OHMM	Ohmmeter	Normal 0.5m, 20in.
IL	OHMM	Ohmmeter	Induction Log
EN64	OHMM	Ohmmeter	Normal 1.62m, 64in.
MINV	OHMM	Ohmmeter	Microinverse 1"x1"
MNOR	OHMM	Ohmmeter	MicroNormal 2"
SN	OHMM	Ohmmeter	Normal 0.25m
RES	OHMM	Ohmmeter	Lateral 1.05m
CNL	C/MN	Count per minute	Compensated Neutron Log

APPENDIX II: Composite well logs from 3 wells

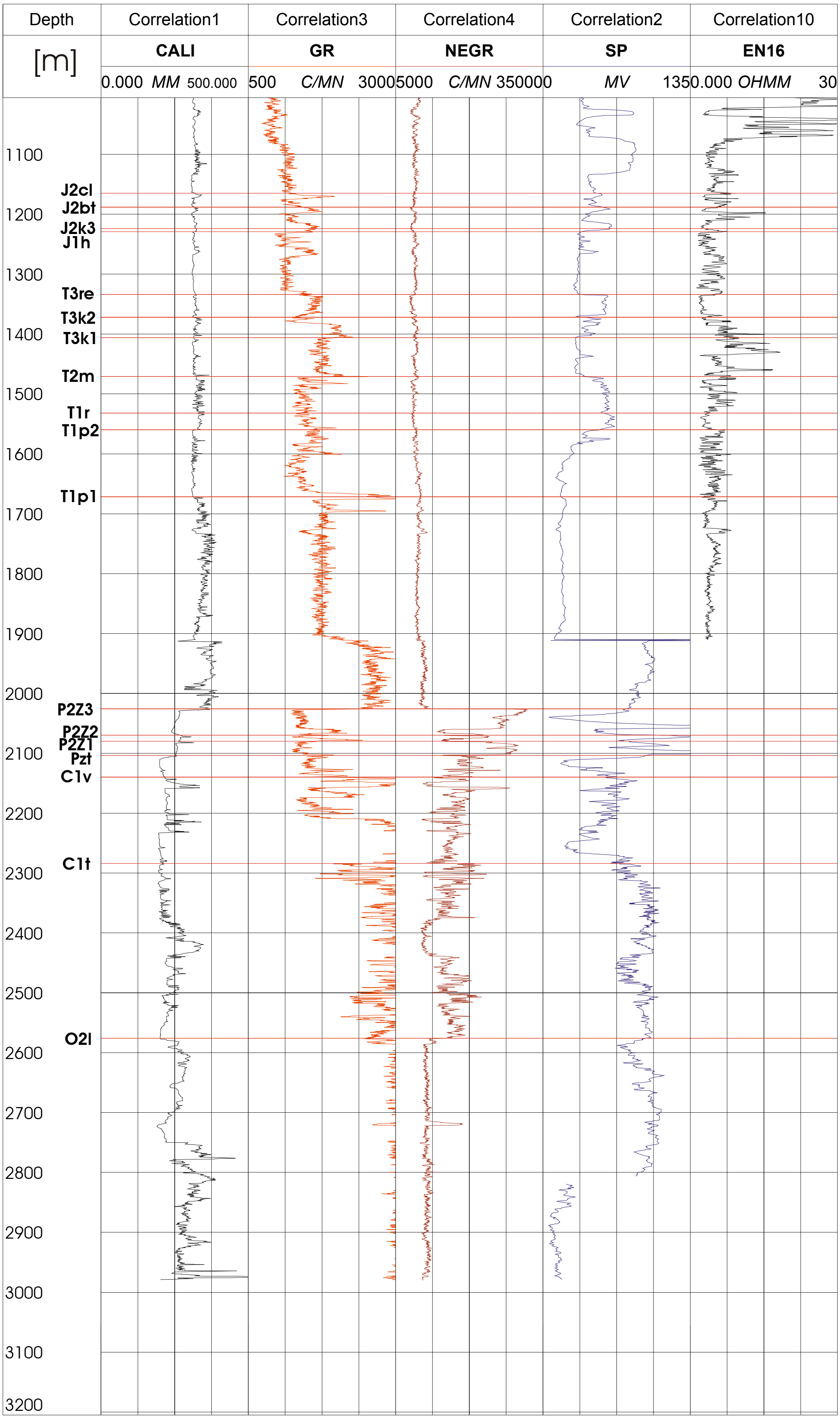
Well Karsina-1



Well Bielica-2



Well Brda-2


Depth
[m]
Correlation1
CALI
0.000 MM 500.000
Correlation3
GR
500 C/MN 3000
Correlation4
NEGR
5000 C/MN 350000
Correlation2
SP
0 MV 135
Correlation10
EN16
0.000 OHMM 30
1100
1200
1300
1400
1500
1600
1700
1800
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2100
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3100
3200
J2cl
J2bt
J2k3
J1h
T3re
T3k2
T3k1
T2m
T1r
T1p2
T1p1
P2Z3
P2Z2
P2Z1
Pzt
C1v
C1t
O2l