Janusz JURECZKA

SUMMARY

The Chełmek IG 1 borehole was drilled in the eastern part of the Upper Silesian Coal Basin (USCB), which is a Variscan geological unit composed of the Cambrian molasse of coal-bearing deposits of the Moravian-Silesian basin. The basement of USCB is built of Precambrian, Cambrian and Devonian rocks. Carboniferous deposits start with the pre-flysch carbonate association that passes into marine clastic sediments of the flysch association, and then into molasse coal-bearing deposits. The characteristic feature of the Carboniferous coal-bearing deposits is their distinct bipartition. The older part of the profile consists of paralic deposits, with periodic marine inundations, lithostratigraphically referred to as the Paralic Series. The remaining, younger part is represented by deposits accumulated in terrestrial conditions, which are the dominant element of the Carboniferous geological structure in the eastern part of the basin. In the area of the Chełmek IG 1 borehole, they are composed of three lithostratigraphic series: the Upper Silesian Sandstone Series, Mudstone Series, and Cracow Sandstone Series. The supra-Carboniferous overburden in the borehole area is thin and composed mainly of Miocene marine molasse deposits of the Carpathian Foredeep, and Triassic Formations.

The geological task of the drilling was to investigate the Carboniferous coal-bearing deposits, in particular stratigraphy, lithology and facies development, petrographic and sedimentological characteristics, total thickness of coal strata, coal potential, coal quality, organic matter metamorphism, and hydrogeological and gas-generation conditions, including field hydrogeological studies. After reaching the geological target (drilling through the base of coal-bearing deposits) the drilling was completed at a depth of 2254.30 m. The borehole section (from a depth of 8.30 m downhole) was fully cored. The drill core has been thoroughly investigated, particularly in terms of lithology, facies types, petrography, mineralogy and geochemistry. Detailed biostratigraphic (fauna, flora and spores) studies, chemical-technological and gas analyses, and petrophysical, geotechnical and geophysical investigations were also carried out.

The stratigraphic column of the borehole is as follows: 0.00–11.60 m Quaternary, 11.60–42.50 m Neogene (Miocene – Badenian), 43.50–50.00 m Triassic, 50.00–2254.30 m Carboniferous, including Moscovian (Westphalian B–D) to ?1229.70 m, Bashkirian to 1455.30 m (Namurian C + Westphalian A) and Serpukhovian (Namurian A) to 2254.30 m. Lithostratigraphically, part of the Miocene has been assigned into the Skawina Formation, while the Carboniferous section consists of the Cracow Sandstone Series (50.00–1143.25 m, Libiąż and Łaziska beds), Mudstone Series (1143.25–1431.25 m, Orzesze Beds *s.s.* + Załęże Beds), Upper Silesian Sandstone Series (1431.25–1455.30 m, Ruda Beds *s.s.*), Paralic Series (1455.30–2145.80 m, Grodziec, Flora and Sarnów Beds) and the Malinowice Beds (2145.80–2254.30 m).

Miocene deposits in the borehole section occur between the Quaternary cover and Triassic deposits. Their upper part is represented by marly claystones lithostratigraphically corresponding to the Skawina Formation. Beneath, to the top of the Triassic, there is a conglomerate of boulders cemented by marly breccia, of uncertain stratigraphic position.

The Triassic deposits, a few metres thick, directly overlie Carboniferous rocks and are composed of limestones and variously grained sandstones. These are Lower Triassic, Rhoetian (carbonate section) and Middle Buntsandstein deposits.

The Triassic deposits are underlain by Carboniferous rocks represented by all coal-bearing formations: the Cracow Sandstone Series, Mudstone Series, Upper Silesian Sandstone Series and Paralic Series, and by marine terrigenous deposits of the Malinowice Beds (of the so-called Culm). Lithologically, the drilled Carboniferous section is composed almost entirely of clastic sedimentary rocks, and of phytogenic rocks in coal-bearing series. The Carboniferous deposits are poorly variable lithologically. The exception is conglomerates that occur only in the Cracow Sandstone Series. Lithological variability is reflected mainly in the proportions of individual lithological types and subtypes, especially in case of sandy deposits. Coarser-grained sandstones occur predominantly in the Cracow Sandstone Series and Upper Silesian Sandstone Series. In the Mudstone Series, they are minor elements, and they are absent in the Paralic Series and marine deposits of the Malinowice Beds. The reason for these differences are facies and palaeogeographic changes that occurred in sedimentary environments during Carboniferous deposition: from the decline of marine sedimentation in coastal plain and deltaic environments, through a period of paralic deposition with a series of marine ingressions into land areas, in which the actual coal-bearing sedimentation took place, to the total

absence of marine influences and deposition of terrestrial deposits in extensive alluvial plains of braided and meandering rivers with numerous peat bogs.

Most of the coal-bearing Carboniferous deposits in the Chełmek IG 1 borehole are represented by the Cracow Sandstone Series and the Mudstone Series. Their characteristic feature is a cyclic succession consisting of clastic and phytogenic rocks, but the Cracow Sandstone Series is dominated by braided river deposits with relatively infrequent peat bogs, while the Mudstone Series is composed mainly of meandering river deposits with numerous peat bogs and frequent changes in sedimentary conditions. A similar cyclic succession, like the Mudstone Series, is also observed in the Paralic Series; however, the presence of sediments deposited in a coastal deltaic plain (brackish) environment (rarely in a marine environment) is characteristic for this part of the borehole section. These rocks commonly contain abundant faunal remains forming the so-called faunal levels or horizons. Compared with the western part of the Upper Silesian Coal Basin, the Paralic Series of the Chełmek IG 1 borehole contains much less marine horizons. Horizons of broad lateral extents, large thicknesses and abundant faunal assemblages are represented only by one thick cycle of marine deposits corresponding probably to the Barbara (V) level combined with the Enna (VII) marine level. The lack of other marker marine horizons and the Polierschiefer horizon makes it impossible to use the so-called western subdivision of the series into minor lithostratigraphic units. Instead, lithostratigraphic units of the so-called eastern subdivision have been determined. Lithology of the individual lithostratigraphic units of the Paralic Series is poorly variable. Along the entire section, sand-muddy rocks are dominant. A greater proportion of sandstones is observed only in the Grodziec Beds. Notable is also clearly higher sandiness of the basal part of the series, in the Sarnów Beds, which start the coal-bearing sedimentation.

The total thickness of coal strata (in %) in the coal-bearing Carboniferous rocks is 4.04%. There are 142 coal seems with a thickness of 0.05–5.80 m and the total thickness (without intercalations) of 84.68 m. The highest total thickness of coal strata is found in the thin Upper Silesian Sandstone Series (23.24%) with one thick coal seam (5.80 m). Disregarding this particular case, the greatest total thickness of coal strata is found in the Mudstone Series (8.15%) that contains 9 coal seams of balance reserves, and thicknesses ranging between 1.00 and 3.00 m. The lowest total thickness of coal strata is observed in the Cracow Sandstone Series (Libiąż Beds – 3.45%, and Łaziska Beds 3.99%). This series can be prospective for potential production (18 coal seams ranging in thickness from 1.00 to 5.00 m). The relatively small total thickness of coal seams is due to the large thickness of the series. The lowest proportion of phytogenic rocks is a characteristic feature of the Paralic Series (Grodziec Beds – 0.83%, Flora Beds – 2.55%, Sarnów Beds – 0.13%); this series contains only one 1.10-m thick coal seam of balance reserves.

Marine terrigenous deposits – lithostratigraphically referred to as the Malinowice Beds – occur beneath the coal-bearing Paralic Series down to the well bottom. The borehole drilled through only the uppermost part of the Malinowice Beds, which are very poorly explored in this part of the basin. They are represented by sand-muddy and silty clay deposits.

The drill core material was analysed for the presence of fossils and sampled for extensive biostratigraphic studies of Carboniferous deposits: floristic, palynological and macrofaunal. Based on floristic studies, palaeobotanical characteristics and phytostratigraphy have been developed for the Carboniferous deposits spanning the Early Serpukhovian – Late Moscovian (Namurian A–Westphalian D). Analyses were made on 4420 samples from 372 sampling intervals that contain very well-preserved and taxonomically determinable fossil flora, as well as various fragments of plants with coal-bearing flora affinity. In total, the whole Carboniferous section has provided 5740 plant fragments representing stratigraphically significant taxa.

Miospore investigations were made on 86 samples of coal, coal shales and carbonaceous shales from the interval of 109.40–2048.00 m where miospore assemblages representative of the standard biozones of the West European Carboniferous palynostratigraphic division have been identified: upper Lower Namurian A (Serpukhovian), Westphalian A (Bashkirian), part of the Westphalian B (Moscovian), Westphalian C (Moscovian), and upper Westphalian D (Moscovian), and their local equivalents in the USCB. Six megaspore assemblages characteristic of the Upper Visean, Serpukhovian, Bashkirian and Moscovian have also been distinguished.

Faunal fossils (freshwater, brackish and marine fauna) in the Carboniferous section are found at a depth of 952.00–2241.45 m; in terrestrial deposits, freshwater fauna occurrences are rare. In this part of the section, two freshwater fauna horizons are of stratigraphic importance – at the base of the Cracow Sandstone Series and in the Mudstone Series (Moscovian). The remaining faunal fossils occur in the Paralic Series and Malinowice Beds. These fossils document the Serpukhovian (Namurian A). Faunal assemblage analysis enabled identification of a number of faunal horizons important for stratigraphy and correlations. The Malinowice Beds contain the Štur (XVI) horizon, while the Paralic Series contains (from the base) the Bruno (XII), Franciszka (X), Roland (IX), Barbara (V) and Koks (IVa) horizons.

Detailed petrographic-mineralogical studies of gangue were performed along the entire Carboniferous section. These included the following analyses: microscopic – 207, planimetric – 136, X-ray diffraction – 209, and thermal – 53. Determinations of effective porosity and permeability of 80 sandstone samples were also used. The following types of clastic rocks have been identified: sandstones, mudstones, claystones and tuffogenic rocks (tuffs). Sandstones are the most significant rock types for petrographic variability in the section. These are predominantly arenites and arkosic and lithic wackes, fine-grained to coarse-grained. The grain framework is composed of quartz, potassium

feldspars and plagioclases, lithoclasts (mainly quartz, quartz-mica schists, and acid igneous rocks) and micas. It contains carbonate and quartz matrix and/or cement. Effective porosity of the sandstones varies between 1.3 and 22.1%, and their permeability ranges from below 0.1 to 600 mD. Their permeability and porosity decrease with depth and is the greatest at the top of the Cracow Sandstone Series. Diagenesis of the Carboniferous rocks was affected primarily by mechanical compaction, carbonate and quartz cementation, kaolinization and sericitization of feldspars, and carbonatization of feldspars and lithoclasts.

Petrographic studies were also performed on 70 coal seams and interbeds at a depth interval of 226.55–2095.20 m. The scope of the study included analysis of macerals and microlithotypes and determination of vitrinite reflectance coefficient R_o. The studies show that macerals from the vitrinite group are the main constituent of the coals. In this group, colinite is definitely more common than telinite. Among microlitotypes, the most abundant is vitrinite, followed by duroclarite. The predominant microfacies type is the trimacerite-vitrinite type. The vitrinite reflectance coefficient increases with depth from 0.53% (226.55 m) to 0.87% (2048.00 m), and the vitrinite contents indicate a low degree of coal metamorphism.

Technological and chemical analyses were performed for 70 coal seams and beds ranging in thickness from 0.10 to 5.80 m. The scope of this research included: technological analysis (moisture, ash, volatiles, heat of combustion and calorific value), coking and semi-coking properties, coal type determination, grinding ability, apparent density, sulphur content (total, ash, combustible and pyritic sulphur) and elemental analysis (carbon, hydrogen, oxygen and nitrogen). There are the following coal types found: 31.1 and 31.2 (flame coal), 32.1 (gas-flame coal), 33 (gaseous coal), 34 and 34.2 (gas-coking coals).

Geochemical analyses of coal ashes were performed for 68 coal seams and layers to determine the content of major, minor and trace elements. The scope of the analyses also included determination of sulphur, phosphorus, chlorine and fluorine contents directly in coal. Main elements (Si, Al, Fe, Ca, Mg, Na, K and S) were determined for the ashes obtained at the temperature of 815°C. In turn, for low-temperature ashes (525°C), minor and trace elements were analysed: As, Ba, Br, Co, Cr, Ga, Ge, Mn, Mo, Nb, Ni, Pb, Rb, Sr, Th, Ti, U, V, Y, Zn and Zr. The average ash content in the studied coals is 12.1%. The basic chemical composition is alumino-silicate, the average pyrite content is 6.7%, and the total sulphur content is 1.32%. The content of minor and trace elements is similar to their average contents in coals from the central part of the basin.

The study of mineralization in the Carboniferous rocks was carried out on 106 samples from the depth interval of 48.6–2253.4 m. The most common forms of mineralization are infillings of tectonic fissures and siderite and pyrite concretions. Fissures are most often found in sandstones and are filled with pyrite, anhydrite and calcite, more rarely by gypsum, galena and magnesite. Septaria in siderite concretions are filled with calcite and pyrite, more rarely by magnesite and dolomite.

Analysis of sediment deposition rate and modelling of thermal history and burial conditions was performed using the Schlumberger PetroMod 1-D program. There are two burial stages: in the Carboniferous and in the Miocene. The Carboniferous stage was associated with the formation of sedimentary cover due to flexural bending of the Variscan foreland plate. This created an accommodation space in a foredeep basin and enabled its high degree of filling with detrital material. Based on modelling results, zones of hydrocarbon generation phases have been determined in the borehole. Deposits of the Upper Silesian Sandstone Series, Paralic Series and Malinowice Beds are probably in the gas generation phase.

Geochemical studies of organic matter in the Carboniferous section were performed using the Rock-Eval method that provides parameters and indicators allowing determining the kerogen type in rocks, degree of thermal maturity, and hydrocarbon potential. The studies were conducted on 44 samples (mudstones, claystones and carbonaceous shales) from the 227.0–2250.6 m interval. The study results indicate a generally low degree of thermal alteration of organic matter. Organic matter in the terrestrial part of the Carboniferous section appears to be immature for hydrocarbon generation, as opposed to organic matter from the Paralic Series, which is in the initial phase of hydrocarbon generation.

Hydrological conditions were determined from laboratory tests of drill cores and direct field observations during and after drilling. Laboratory investigations of physical and hydrogeological properties of the Carboniferous rocks were made on 107 samples. They indicate their wide range of permeability values, from impermeable to poorly permeable rocks (<0.1–1000 mD), and their low and moderate effective porosity. Direct hydrogeological tests were performed using a formation tester (intervals: 1506.0–1658.8 m, 1799.5–1863.0 m and 2071.0–2116.9 m), and a compressor and a well bailer (intervals: 550.0–600.0 m, 700.0–750.0 m, 920.0–980.0 m, 1192.0–1418.0 m). The Carboniferous aquifers show a subartesian nature. The groundwater is represented by 4.03–23.38% Cl–Na brines. A high degree of metamorphism of these brines (rNa/rCl=0.764–0.878) indicates relict waters strongly altered during long-term geological processes under prolonged isolation from the ground surface.

The gaseous conditions were determined based on methane content and gas quality in coal seams using the vacuum degassing method (45 determinations) and the desorbometric method (42 determinations). The methane content was also determined in the drilling mud (4 determinations). Down to a depth of 1100 m, there are non-methane coal seams. In the interval of 1100–1650 low- and medium-methane seams were encountered (with a maximum of 4.41 m^3 CH_4/t daf), and below these depths, there are high-methane coal seams (up to 9.42 m^3 CH_4/t daf).

A set of well logs were run in the borehole, including the standard logs that are used for coal-bearing formations. Drilling mud resistivity, temperature, spontaneous potential, and acoustic logs were also performed. In the Carboniferous sandstones, interpretation of well logs was made to determine the hydrogeological properties: water mineralization, sandstone porosity, and formation water saturation. Temperature logging was performed under near-steady state conditions. The geothermal gradient in the Carboniferous section is 47.4 m. The bottom hole temperature at 2250 m depth was 62°C.

Seismometric measurements covered average seismic velocities and vertical seismic profiling. The results indicate a relationship between depth and recording time and average velocity. A constant increase in velocity with depth was observed. Four velocity complexes have been identified based on the results of seismic velocity measurements in the borehole: the overburden and the Libiąż Beds to a depth of *ca.* 400 m with an average velocity of 2300 m/s; the Upper Łaziska Beds to a depth of *ca.* 830 m with an average velocity of 3200 m/s; the Lower Łaziska Beds, Mudstone Series and Upper Silesian Sandstone Series to a depth of *ca.* 1520 m with an average velocity of 3400 m/s, and the Paralic Series with an average velocity of 4000 m.

Samples of the Carboniferous rocks were analysed for their physical properties. The scope of the studies covered bulk density, acoustic wave velocity, thermal properties and geotechnical parameters. Bulk density measurements were performed on 7125 samples taken at 25-cm intervals. Within the intervals of individual lithological types, the average bulk density increases with depth. Acoustic (longitudinal and transverse) wave velocity measurements were performed on 96 sandstone and mudstone samples. For the individual lithological types, the acoustic wave velocities increase with depth. Measurements of thermal properties (conductivity and capacity) were conducted on 198 samples; no correlation with depth was observed. Studies of geotechnical parameters were carried out on drill core samples from the upper Carboniferous, to a depth of 1000 m. The scope of the studies covered the following physical properties of rocks: uniaxial and triaxial strength, elastic properties, and rheological parameters. In total, 73 samples from the Cracow Sandstone Series were analysed.