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SUMMARY

The original goal of the Wilga IG 1 borehole was to better explore the north-western extremes of the Lublin Basin, mainly by examining the Carboniferous deposits, their direct basement and the overburden. It was planned to learn more about the stratigraphy and tectonic setting, and the petroleum potential, as well as to find out the lithofacies changes within potentially reservoir rocks. It was intended to better recognize the distribution and stratigraphy of the Devonian deposits and to explore the hydrocarbon potential of the Permian, Triassic and Lower Jurassic formations. The first lithological-stratigraphic profile of the borehole was prepared at the stage of developing the final drilling report. The profile included in this volume has been compiled based on both data from that report and the results of subsequent studies that have been carried out for more than 40 years since the borehole was drilled. The lithology was interpreted based on information from drill cores, geophysical measurements, and auxiliary from drill cuttings. The original stratigraphic units were therefore significantly verified, updated and made detailed. Currently existing stratigraphic schemes have been applied, and most of the chronostratigraphic boundaries have been verified and moved. Up-to-date lithostratigraphic units have been used, which are not highlighted in the final borehole report. The older stratigraphic units have been updated and detailed. This volume also contains a summary of the results of new lithological, sedimentological, stratigraphical, petrographic, geochemical and geophysical studies, as well as modelling of the burial history, thermal evolution, and development of organic matter maturity. The oldest deposits in the Wilga IG 1 borehole are Devonian, and they were encountered at the 3096.7–3552.0 m depth interval. The thickness of the unpierced Devonian system is 455.3 m. The Wilga IG 1 borehole pierced the Frasnian succession, which is underlain directly by the Lochkovian. The characteristic feature is the lack of Pragian, Emsian, Eifelian and Givetian deposits. The chronostratigraphic subdivision of the Devonian is based on microfossil research of ostracods (Lower Devonian) and conodonts (Upper Devonian), and on the correlation with neighbouring boreholes. In the last case, the Lochkovian age of the lower part of the profile was adopted by analogy with the Pionki 4 and Terebin IG 5 boreholes, in which the stratigraphy is based on miospores. In the Wilga IG 1 borehole, such stratigraphic diagnosis is supported by ostracod, tentaculite, trilobite, brachiopod and bivalve assemblages. Analysis of well logs also allowed correlating the characteristic (isochronous) horizons that can be found in neighbouring, better-dated boreholes. The unpierced Lower Devonian deposits (lower and middle Lochkovian) occur at a depth of 3143.0–3552.0 m and their thickness is 409.0 m. The Lower Devonian section consists of two formations – Sycyna and Czarnolas. The lower one – Sycyna Formation (>267 m in thickness, unpierced) – consists mainly of claystones, silty claystones and clayey mudstones, occasionally marly or dolomitic, containing thin interbeds of organodetrital limestones and clayey limestones. In the microscope image, these are siltstones/mudstones, mudstones with bioclasts, and bioclastic packstones. The Sycyna Formation sediments were accumulated in open-marine conditions at a depth below the storm wave base, with a periodic deficit of oxygen in the bottom part of the sediment. In the vertical succession, a record of gradual shallowing of the clay shelf basin can be observed. The Czarnolas Formation (142 m thick) is represented by mudstones/siltstones and clayey siltstones, interbedded with quartz sandstones. In the microscopic image, these are various types of mudstones, wackes and quartz arenites. A characteristic feature is the presence of numerous sedimentary structures and various types of bioturbation. The Czarnolas Formation reflects the later stage of sea shallowing from a deeper siliciclastic basin, through a tidal plain dissected by tidal channels, to an upper tidal plain, shaped by the dynamics of a nearby delta. Deposits of the Zwoleń and Telatyn formations are absent in the Wilga IG 1 borehole.

The Upper Devonian was drilled at a depth of 3096.7–3143.0 m and is represented only by the Modryń Formation (46.3 m thick) dated here to the Lower – Middle Frasnian. The formation is represented by a variety of dolomites, occasionally with anhydrite streaks and laminae. There are also granular limestones containing stromatoporoids, corals, and sometimes brachiopods, ostracods, crinoids and styliolines. The succession also shows intraformational breccia horizons. Petrographically, the Modryń Formation deposits are represented by mudstones, mudstones with bioclasts, intraclastic wackestones, and bioclastic packstones – all in calcareous and dolomite varieties. They were accumulated on a shallow-marine carbonate platform. In the vertical succession of the formation, it is possible to identi-

fy sediments formed successively in the backbarrier shoal zone, on a carbonate platform slope, in an organic buildup, and again on a carbonate platform slope.

The Devonian is overlain by the upper Upper Visean deposits, and the stratigraphic gap comprises the upper Frasnian–lower Upper Visean. The Carboniferous deposits, according to geophysical measurements, are at a depth of 2302.0–3094.5 m (792.5 m in thickness), while according to the drilling depth – in the interval of 2304.0–3096.7 m (792.7 m in thickness). Wilga IG 1 is one of the benchmark boreholes for the creation of a sequence stratigraphic model and the subdivision of the Carboniferous in the Lublin Basin and central Poland. The section consists mainly of mudstones and claystones. Sandstones are a minor lithology and occur most often in its lower and upper parts. The rarest lithologies are limestones, marls, conglomerates, carbonaceous claystones (coal shales) and coals. The Mississippian deposits occur at a depth of 2988.0–3096.7 m (108.7 m in thickness), while the Pennsylvanian deposits at 2304.0–2988.0 m (684.0 m in thickness). At the base of the Visean (depth 3038.5–3096.7 m; thickness 58.2 m) there are conglomerates and mudstones deposited during the relative sea-level lowstand (RSL) in a fluvial environment. The upper part of the succession is composed of limestones and marls deposited in a shallow carbonate shelf, and of claystones and mudstones associated with a shallow delta environment and a shallow clay shelf. The Serpukhovian (2988.0–3038.5 m depth; 50.5 m thick) is represented by mudstones and claystones accumulated in a shallow delta environment and a shallow clay shelf during the relative sea-level rise and highstand. At the Mississippian/Pennsylvanian boundary, there is a stratigraphic gap spanning the upper Serpukhovian–lowermost Bashkirian, which corresponds in the West-European stratigraphic scheme to the upper Arnsbergian–lower Marsdenian sub-stages. In the Bashkirian section (depth 2431.5–2988.0 m; thickness 556.5 m), sandstones dominate in its lower and upper parts. They were deposited during the filling of riverbeds and incised valleys at the end of the relative sea-level lowstand. In this type of sandstones, belonging to sequences 12, 16 and 17, there are three gas-bearing horizons of the Wilga deposit. The middle part of the Bashkirian is dominated by claystones, mudstones, stigmarian soils, carbonaceous claystones and coals deposited in areas of river floodplains, occasionally interlayered by river channel sandstones. These sediments were formed during the lowstand, rise and highstand of relative sea level. The uppermost part of the Carboniferous section, included in the Moscovian (depth 2304.0–2431.5 m; thickness 127.5 m), is composed mainly of claystones, mudstones and accompanying minor sandstones, which were also deposited in a fluvial environment.

Results of biostratigraphic (conodonts, calcareous algae, foraminifera) studies of the Carboniferous section have revealed the presence of the Upper Visean in its lowest part. On the other hand, the revision of results of palynostratigraphic studies confirmed the presence of the uppermost Visean and upper Bashkirian in the profile. Petrographic studies have shown the presence of grainstones with bioclasts among carbonate rocks, and predominantly arenites and subarkose wackes among Bashkirian sandstones. Within them, the spaces between detrital grains are partially filled with the matrix and/or cements, *i.e.* quartz, kaolinite and carbonates, occasionally also with gypsum and pyrite. The effects of diagenetic processes, *i.e.* compaction, cementation, replacement, alteration and dissolution, are observed. Compaction and cementation had the greatest influence on the reduction of porosity. These sandstones show very good reservoir properties; their porosity is 2.3–23.33%, and the permeability can reach 893.81 mD.

The Carboniferous is overlain by the Permian deposits (?2034.5–2304.0 m; thickness 269.5 m), and a stratigraphic gap at the boundary spans the Kazimovian–Gzelian and the Lower Rotliegend. The top of the Carboniferous section is overlain by sandstones with interbeds of conglomerates, representing the Upper Rotliegend (depth 2286.0–2304.0 m, thickness 18.0 m). The lower part of the section is composed of fluvial deposits, while the upper part consists of aeolian sediments with reservoir potential. These deposits were accumulated in the south-western part of the Permian Podlasie Basin, filling a paleomorphological depression that formed as a result of erosion affecting the East European Platform cover. In the Zechstein section (depth 2034.5–2284.6 / 2286.0 m; thickness 250.1 m), cyclothems (PZ1)–(PZ4) have been distinguished. Cyclothem (PZ1) consists of the following units: Basal Conglomerate (Zp1), Copper Shale (T1), Zechstein Limestone (Ca1), Lower Anhydrite (A1d), Oldest Halite (Na1) and Upper Anhydrite (A1g). Cyclothem (PZ2) is represented by the Main Dolomite (Ca2). Cyclotem (PZ3) consists of the Grey Salt Clay (T3) and Platy Dolomite (Ca3), while cyclothem (PZ4) is represented by the Top Terrigenous Series (PZt). The Zechstein section bears numerous stratigraphical gaps due to the location in the eastern, marginal part of the Polish Zechstein Basin, in the Podlasie Bay.

The triassic rocks occur at a depth of 1591.0–?2034.5 m (thickness 443.5 m). The position of its base is debatable, while the other chronostratigraphic boundaries are conventional and approximated by lithostratigraphic boundaries. The Buntsandstein (depth 1887.5–?2034.5 m; thickness 147.0 m) is represented mainly by claystones, mudstones and sandstones deposited in an alluvial system. Near the top, there are sandstones and claystones deposited in the littoral zone during an early phase of marine transgression. Quartz and/or subarcosic arenites have been described among the sandstones. They contain granular components, *i.e.* quartz and feldspar, as well as small amounts of rock clasts. The grains are cemented with the matrix and orthochemical cement. The cement constituents include carbonates (dolomite, calcite), locally authigenic quartz or small concentrations of kaolinite and chlorites. The effective porosity is 20.8–30.3%, while the permeability varies widely from negligible to a maximum of 485.0 mD. The middle part of the Triassic, assigned to the Muschelkalk, occurs at a depth of 1831.0–?1887.5 m (thickness 56.5 m) and is represented by alternating limestones, claystones and mudstones. Deposition took place in a nearshore zone located in the eastern part of a shallow sea basin that periodically underwent remarkable shallowing. The Upper Triassic section, referred to as the Keuper (depth 1591.0–1831.0 m; thickness 240.0 m), is dominated by claystones and mudstones probably of fluvial origin, deposited on a mud plain. The Triassic is separated from the Jurassic deposits (depth 1095.1–1591.0 m; thickness 495.9 m) by a stratigraphic gap spanning the upper Keuper. The Lower Jurassic (depth 1521.0–1591.0 m; 70.0 m in thickness) is represented by mudstones and claystones of the Zagaje Formation, deposited in a limno-marshy environment, while the overlying complex of mudstone-sandstone heteroliths (Ostrowiec and Drzewica/Gielniów formations) represents deposition during the transgression and then during the regression of a marine basin. The uppermost part of the Lower Jurassic deposits (mainly claystones and mudstones with sandstone interbeds, Ciechocinek Formation) were deposited in a shallow and extensive brackish basin. The Middle Jurassic section (depth 1470.0–1521.0 m; thickness 51.0 m) is reduced and comprises only the Bathonian and Callovian. The lower part of this section is dominated by sandstones, mudstones and claystones, frequently dolomitized, followed upwards by organodetrital limestones, frequently sandy. The observed interfingering of organodetrital limestone facies with sandstone and mudstone-claystone facies indicates variable dynamics in the marine basin, while the decrease in the proportion of clastic fractions towards the top of the section may be related to a gradually increasing distance from the shoreline. The presence of bryozoan fauna indicates a normal degree of salinity, as well as a shallow and warm Late Callovian marine basin with a moderate hydrodynamic regime. The Upper Jurassic (depth 1095.1–1470.0 m; thickness 374.9 m) comprises the Oxfordian and Kimmeridgian deposits with four formations: Kraśnik, “Coral”, Bełżec and Głowaczów. The Oxfordian section is represented at the bottom by organodetrital spongy limestones, whereas in the middle part by organodetrital coral-bryozoan limestones. The uppermost Oxfordian and Lower Kimmeridgian are composed of oolitic and micritic limestones. The Upper Kimmeridgian is represented by marls and marly limestones with coquina layers. Infrequent faunal evidence, mainly foraminifera, suggests occurrence of Oxfordian, Upper Kimmeridgian, and probably Lower Tithonian deposits, however, it does not provide the basis for establishing the biostratigraphy. The Jurassic is separated from the Cretaceous (depth 250.0–1090.0 m; thickness 840.0 m) by a stratigraphic gap spanning the Tithonian–Valanginian. Both the Lower (Hauterivian and Albian – depth 1059.0–1090.0 m; thickness 31.0 m) and the Upper (Cenomanian through Upper Maastrichtian – depth 250.0–1059.0 m; thickness 809.0 m) Cretaceous are represented by marine deposits. In this area, no typical carbonate facies were deposited in the Early Cretaceous, and the section is represented only by clayey mudstones of the Włocławek Formation, overlain by sandstones and mudstones of the Kruszwica Member of the Mogilno Formation. The Upper Cretaceous section is dominated by carbonate lithofacies, with minor marly and carbonate-siliceous ones. Chalk appeared relatively late, because only in the early Early Maastrichtian and continued into the earliest Late Maastrichtian. The Cretaceous is overlain by Paleogene deposits (150.0–250.0 m depth; 100.0 m in thickness) with some internal stratigraphic gaps. The lower part of the section is composed of calcareous gaizes with limestone interbeds, included in the Danian Puławy Formation. The deposition took place in a marine basin that retreated at the end of the Danian. The upper part of the Paleogene, corresponding to the Lower Oligocene Lower Mosina Formation, is represented by sands and muds with glauconite admixture, which were accumulated in a marine basin during a relative sea-level highstand. The Neogene section (depth 24.0–150.0 m; thickness 126.0 m), preceded by a stratigraphic gap, is composed of sands and muds of the Adamów Formation, dated at the Middle Miocene.

Above, there are clays, muds and sands of the Upper Miocene Poznań Formation. The near-top part is included in the Gozdnica Formation, probably of Pliocene age. The Neogene deposits were accumulated on alluvial plains. The near-surface section of the borehole consists of the Quaternary sands, gravels, muds and glacial tills.

Petrological studies of organic matter were carried out within the Lower Devonian–Lower Cretaceous interval. The content of organic matter is variable, and its elevated concentrations are found in the Lower Cretaceous (2.20%) and Carboniferous (Bashkirian: 2.0–11.6%), (Visean–Serpukhovian: 1.5–2.0%). The maceral composition includes mainly the humus type – vitrinite (colotelinite) with a much smaller proportion of liptinite and inertinite groups. Thermal maturity increases with the burial depth from the early stage of oil generation in the Cretaceous and Jurassic (0.48–0.50% R_O) to the main phase of oil generation in the Permian–Devonian formations (0.52–0.90% R_O). Some horizons in the Carboniferous section can be proved as potential source rocks for crude oil generation. The results of geochemical studies have shown that the Devonian deposits are “poor” source rocks, so are the poorly studied deposits of the Lower and Middle Jurassic. The Serpukhovian deposits are considered “good” source rocks, while the remaining Carboniferous and Permian deposits are “poor” source rocks because there are only single point samples with increased organic carbon content. In the Lower Devonian, the amount of bitumens is low, while a considerable quantity of bitumens syngenetic with the sediment was found in the Upper Devonian, Serpukhovian and Zechstein. The main constituents of the organic matter are algae and bacteria, and the only organic matter developed as a result of decay of higher plants due to biodegradation comes from the Pennsylvanian. Based on pyrolytic analysis, three levels of source rock have been distinguished: Visean, Serpukhovian and Bashkirian. In the Visean and Serpukhovian deposits, the organic carbon content (TOC) is 0.31–3.24 wt%, while in the Bashkirian deposits – 0.02–70.04 wt%. The whole section is dominated by type III kerogen, with the exception of the top part of the Serpukhovian, where type II kerogen also occurs. Measured temperature values T_{max} are in the range of 419–447°C, which indicates that the organic matter is immature or is in the initial range of “oil window”.

Inflows of natural gas and brine from the Carboniferous sandstones at a depth of 2972.0–2985.0 m, as well as the presence of natural gas in the nearby Wilga deposit, may be genetically related to the Carboniferous levels of source rocks in a deeper, more thermally mature part of the Lublin Basin. It does not exclude the possibility of hydrocarbon migration from older rocks, *e.g.* Silurian. Based on the assumed model, it was found that the sediment deposition rate was high in the Devonian and Pennsylvanian and amounted to over 150 m/my and over 100 m/my, respectively. In the Permo-Mesozoic succession, its highest rate is calculated for the Late Permian–Early Triassic (about 50 m/my) and the Middle and Late Jurassic (40–70 m/my). In the Late Cretaceous, the deposition rate was variable, initially lower, to reach more than 60 m/my in the Maastrichtian. The burial depth and thermal evolution model developed for the area of Wilga IG 1 borehole indicates that there was a rapid depth increase to below 800 m in the Devonian, and an increase in temperature at the base of the Lochkovian deposits to more than 50°C. Subsequently, at the end of the Carboniferous, the base reached a burial depth of below 2050 m and a temperature above 100°C. The Late Carboniferous inversion of the Lublin Basin stopped the increase in the burial depth and temperature. In the Late Permian and Mesozoic, there is again a rapid increase in burial depth, and, from the early Paleogene, a moderate deposition rate and low burial rate. The maximum burial depth is observed at present. The porosity of Jurassic deposits is 1.8–29.28%. They are dominated by almost impermeable lithologies, but some permeability measurements show values reaching 1780 mD. The Triassic Buntsandstein deposits have been analysed on a limited basis obtaining the porosity of 9.84–30.30% and the permeability within the limits of 180–4100 mD. Some of the Zechstein deposits are impermeable, with a low porosity of 0.2–3.9% up to a maximum of 18.4% in the Main Anhydrite. High porosity (26.5%) was recorded in the Main Dolomite, the deposits of which are characterised by varying permeabilities of <0.2–1200.0 mD. In the Rotliegend, the porosity varies in the range of 10.5–35.1%, and the permeability reaches its peak value in the entire tested borehole section, which is 5150 mD. The Visean and Serpukhovian deposits (Huczwa and Terebin formations) are characterised by low porosity and lack of permeability. Good reservoir properties are found in the Lower Bashkirian deposits (lower and upper parts of the Dęblin Formation). The maximum porosity is 18.6% and the permeability 450 mD. The Upper Bashkirian deposits (Lublin Formation) have low porosities and are practically impermeable.

The uppermost Bashkirian–Moscovian (Magnuszew Formation) is characterised by varying measurement results; the porosity can attain 24.5% and the permeability is up to 1560 mD. Lower porosities have been found in the Lower Devonian deposits (Sycyna Formation). In the Upper Devonian (Modryń Formation) the measurements indicated a porosity of 0.07–9.40%. The majority of rocks are impermeable, and the observed permeability values reach merely 6.7 mD. Within the Czarnolas Formation, the porosity is in the range of 2.1–19.0%. Some of the deposits are impermeable, and some are characterised by a permeability reaching 530 mD. Three characteristic reflecting boundaries, which are marker horizons, have been identified in the Paleozoic succession, based on analysis of seismometric measurements, *i.e.* the top-Zechstein, lower Bashkirian sandstones, and Frasnian/Lower Devonian interface. The limited range of well log curves from the Wilga IG 1 borehole, as well as their poor quality, definitely differs from the current sets of measurements and their quality standards. However, the qualitative and quantitative interpretation of these data allows for a better knowledge of the lithologies, determination of physical parameters and reservoir properties of the rocks, and identification of aquifers and impermeable layers.

Drill cores from the Devonian (Frasnian) section revealed traces of crude oil in cracks and microfractures of limestones and dolomites. Some parts of the dolomites are saturated with crude oil as well.

Well tests were performed at nine reservoir horizons to find out the possibility of natural gas and crude oil occurrence and to make hydrochemical analyses of waters. The testing of five levels in the Devonian deposits showed inflows of gasified brine with combustible gas and, in one case, with traces of crude oil. A single sampling of the Carboniferous and Main Dolomite rocks also showed the flow of gasified brine with combustible gas, while the lowermost Lower Jurassic deposits revealed the presence of moderately mineralised thermal water with a temperature of 32°C, which is classified as 0.35% hypothermic, chloride-sodium, boron water. The borehole was made available to municipal authorities to use the water in balneotherapy or recreation. A safe-yield determination for the water resources in category C was finally prepared.

Translated by Krzysztof Leszczyński