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SUMMARY

The Narol IG 1 and Narol PIG 2 boreholes were drilled in SE Poland (SE Roztocze region) near the border with Ukraine. The main purpose of the Narol IG 1 drillhole was to acquire a benchmark for determining the lithostratigraphic position of a reflection horizon correlated with sub-Jurassic deposits in the southern part of the Radom–Kraśnik Elevation.

The primary objective of the Narol PIG 2 drillhole was to explore the Cambrian succession in terms of hydrocarbon accumulation.

The drill cores from the Narol IG 1 and Narol PIG 2 boreholes have provided a lot of data for a wide range of research, including: stratigraphic studies, sedimentological investigations, facies and microfacies examinations, ichnological, micro- and macropalaeontological determinations, as well as tectonic and petrologic studies. The second group of work was represented by analytical investigations, including mainly examination of organic matter for both its petrology and geochemistry. Analysis of the rate of deposition was performed, and the burial conditions and thermal history were defined for the Narol IG 1 borehole. Petrophysical characteristics of deposits were determined in both borehole sections. A full range of hydrogeological tests and geophysical borehole measurements were also performed.

In the Narol IG 1, Cambrian strata were drilled at a depth interval of 3269.1–3404.0 m (unpierced), reaching a thickness of 134.9 metres. The Narol PIG 2 borehole also drilled only a portion of the Cambrian succession encountered at a depth interval of 2991.0–3650.0 m, 659.0 m thick. In both boreholes, the pierced portion of the Cambrian succession is represented by Furongian (Upper Cambrian) clastic deposits, mainly sandstone-siltstone-claystone heteroliths, as well as siltstones and claystones. They were deposited on a shelf as storm and tidal sands and muds. The Furongian age of the rocks in both sections is documented by the presence of characteristic species of trilobites, brachiopods and acritarchs. The Cambrian section of the Narol PIG 2 borehole contains associations of trace fossils indicating a differentiation of sedimentary environments. Comparison of microfloral assemblages in the boreholes has allowed a correlation of Cambrian sequences in these sections. The comparisons of acritarch assemblages indicate that the Furongian section in the Narol IG 1 borehole corresponds only to the higher parts of the section in the Narol PIG 2 borehole. Microscopic petrologic studies show that the rocks are represented by quartz arenites (sandstones), quartz and clayey siltstones and claystones to silty claystones.

Ordovician deposits occur at the following depths (logger's depth): Narol IG 1 – 3048.0–3268.0 m, Narol PIG 2 – 2733.0–2990.0 m, with a thickness of 220.0 and 257.0 m, respectively. Both the sections consist of all the standard global Ordovician stages from the Tremadocian through the Hirnantian. The Tremadocian is represented by the Biłgoraj Sandstone and Claystone Formation, comprising the Frampol Sandstone Member and the link with Goraj Claystone and Siltstone Member. Regional geology evidence suggests the presence of the lower Tramadocian corresponding to the Baltic stage of Pakerort, as documented in other drillings from the Lublin region and the Carpathian Foothills. Floian deposits (lower Arenigian) occur probably in theNarol PIG 2 borehole only, comprising the lower part of the Tanew Claystone Formation lying upon the eroded surface of the Biłgoraj Sandstone and Claystone Formation. The claystones contain a very abundant and diverse fauna of graptolites that indicate the presence of graptolite horizons documenting the Floian stage.

The Dapingian stage in the Narol IG 1 and Narol PIG 2 boreholes covers the upper part of the Tanew Claystone Formation, and the lower part of the Susiec Limestone Formation – the Paary Limestone Member. The age of the Paary Limestone Member has been determined based on conodonts that helped to confirm the presence of the equivalents of the upper British Arenigian corresponding to the lower and middle parts of the Baltic stage of Volkhov. Darriwilian deposits in the boreholes are represented by the upper part of the Susiec Limestone Formation – Rebizanty Limestone Member, and the lowermost portion of the Cieszanów Claystone and Limestone Formation.

Based on conodont taxa, it has been found that the lower part of the member can be correlated with the Baltic stages of Kunda–Aseri (= lower Llanvirn),whereas its uppermost part – with the Uhaku stage (= upper Llanvirn). The lowest part of the Cieszanów Claystone and Limestone Formation contains a graptolite fauna association clearly indicating the presence of the uppermost Llanvirn according to the British division. The Sandbian stage (lower Cara-

docian) spans the middle part of the Cieszanów Claystone and Limestone Formation. The age of these deposits is well documented by numerous graptolite species. Deposits included in the Catian (upper Caradocian–lower Ashgill) cover the upper part of the Cieszanów Claystone and Limestone Formation and the lower part of the Narol Calcareous Claystone Formation. The Hirnantian stage (upper Ashgill) includes the upper part of the Narol Calcareous Claystone Formation. Trilobite fauna found in these deposits shows that they correspond to the upper Ashgill, the equivalent of the Baltic stage of Porkuni.

Silurian deposits of the Narol IG 1 borehole occur at a depth of 1954.0–3048.0, attaining a thickness of 1194.0 m. The Silurian succession from the Narol PIG 2 borehole was encountered at a depth interval of 1895.0–2737.0 m, reaching a thickness of 842.0 m.

The development of the Silurian succession in the Narol IG 1 and Narol PIG 2 boreholes shows mutual lithofacies similarity. The dominant lithofacies type is mudstone (clayey calcareous mudstones) and siltstone found mainly in the upper Ludlow. A considerable proportion of carbonates is observed in both boreholes. The Silurian succession in both boreholes also shows similarity to that from the distal areas of the Baltic and Podlasie-Lublin basins; it represents a platformal, deep-neritic type of sedimentation. Like in other areas of the East European Platform, the supply of detrital material was from the west. Carbonate material was derived from erosion of shallow-neritic and littoral zones extending in the east and south of the basin. A considerable role in the sedimentary process was played by the flexural development of the basin during the Silurian, as well as the increase in both accomodation space and supply of detrital material due to erosion of an accretionary prism that formed as a result of collision between Baltica and Avalonia.

The Jurassic in the Narol IG 1 and Narol PIG 2 boreholesis represented by its middle and upper series. Their thicknesses in the Narol IG 1 are 68.0 and 476.5 m, respectively, and in the Narol PIG 2 – 55.0 and 467.5 m. These deposits overlie the Silurian claystones. The Middle Jurassic section is typical of the south-eastern part of the Lublin region and is represented by Bathonian and Callovian deposits. The Upper Jurassic section is complete in both boreholes, and represented by the Oxfordian, Kimmeridgian and Tithonian, passing into the Berriasian of the Lower Cretaceous.

In the Narol area, the Middle Jurassic section is composed of two rock complexes. The lower section is represented by calcareous sandstones and silty sandstones deposited in a nearshore environment – presumably in the intertidal zone. The upper part is composed of fine-grained concise highly calcareous sandstones, passing downwards into more silty. The rock contains sandstone pebbles, forming conglomerate levelsin places. The middle part of the section reveals admixture of limonite and, above, numerous black ferruginous ooids. These deposits accumulated in a shallow-marine environment – their lower part in the shoreface, while the upper part - presumably in a delta area, as indicated by the presence of ferruginous ooids.

The upper complex is included in the Callovian and represented by calcareous mudstones, sandy mudstones and silty limestones. The Callovian deposits from the Narol IG 1 and PIG 2 boreholes also accumulated within a delta or a very shallow-marine basin. In these boreholes, the Upper Jurassic is represented by a complete succession with several formal lithostratigraphic units identified: in the Oxfordian – Kraśnik, Jasieniec and Basznia (Narol IG 1) or Bełżyce (Narol PIG 2) formations; in the Kimmeridgian – Ruda Lubycka Formation; in the Tithonian and Lower Berriasian) – Babczyn Formation. Upper Jurassic deposits in the Narol IG 1 and Narol PIG 2 boreholes accumulated at a high subsidence rate in an extensive and very shallow sea with a depth not exceeding 10 m.

The Jurassic succession in these boreholes is a record of a single major regressive cycle. It began with sedimentation of open-marine, near-barrier deposits (Kraśnik Formation), followed by shallow-water oolitic facies (Jasienica Formation), open-marine lagoonal facies (Basznia Formation), near shore lagoonal facies and tidal flat facies (Ruda Lubycka Formation). The peak regression is marked by the appearance of evaporites in the upper part of the Ruda Lubycka Formation, and the overlying deposits of the Babczyn Formation are a record of a new sedimentary stage – slow deepening of the environment and renewal of sedimentation on oolitic shallows.

The Lower Cretaceous succession (Upper Valanginian–Upper Albian) occurs at a depth of 1371.5–1409.5 m in the Narol IG 1, and at 1341.0–1372.5 m in the Narol PIG 2 borehole. The thicknesses are 38.0 and 31.5 m, respectively. In these boreholes, there is probably a sedimentary gap spanning the Upper Berriasian–Lower Valanginian. Younger Lower Cretaceous units (Barremian–Middle Albian in the Narol IG 1, and Hauterivian–Middle Albian in the Narol PIG 2) are also missing, indicating an erosional truncation.

Lower part of the Lower Cretaceous is represented by the Cieszanów Formation (Upper Valanginian–Hauterivian). The Upper Valanginian section is composed of carbonate-marly-sandy rocks with oolitic limestones. The Hauterivian section (found only in theNarol PG1 borehole) consists of marly mudstones.

A new sedimentary megacycle starts with the Upper Albian and ends with the Maastrichtian deposits. The Upper Albian section is represented by quartz-glauconitic sandstones, likely containing phosphatic concretions.

The Upper Cretaceous succession in the Narol IG 1 borehole was drilled at a depth of 0.0–1371.5 m, and in the Narol PIG 2 – at 0.0–1341.0 m. In both boreholes, it is represented by all stages from the Cenomanian through the Maastrichtian. Worth noting is the presence of Upper Maastrichtian deposits. Lower part of the succession: Cenomanian, Turonian and Coniacian, is composed of heavily lithified micritic and marly limestones. Upper part of the Upper Cretaceous succession (Santonian, Campanian and Maastrichtian) is represented by carbonate-siliceous rocks, predominantly opokas (siliceous marl), exceeding

1040 m in thickness. In the Upper Campanian and Maastrichtian, gaize is also a significant rock type.

In the Cambrian section, the most organic matter-abundant deposits (1.00–1.20%) are mudstones occurring at the top of the Furongian. In the Ordovician section, the greatest concentrations of organic matter are found in some clay shale horizons (Tremadocianin the Narol PIG 2 borehole, and Tremadocian, Darriwilian and Hirnantianin the Narol IG 1) containing from 1.0 to 2.8% of organic matter. In the Silurian section, the greatest amount of organic matter are found in the clays of the Llandovery (Narol PIG 2 – 3.50%), Wenlock and Ludlow (Narol IG 1 – 2.80 and 1.20%).

Thermal maturity of the Upper Cambrian, Ordovician and Silurian deposits corresponds to the gas generation phase and to the so-called "overmature" phase, when only high-methane dry gas can be generated. Thermal maturity of organic matter in the Lower Paleozoic section from the Narol IG 1 borehole is 1.60–2.50% R_o. In the coeval complex from the Narol PIG 2 borehole, the mean values of vitrinite-like material range from 1.73 to 2.36% R_o. The reflectance coefficient of vitrinite-like autogenic material varies between 1.60 and 2.50% R_o and indicates high peak palaeotemperates of diagenetic processes, of the order of 180 to over 200°C.

The results of geochemical studies of organic matter show that, in the Narol IG 1 borehole, only the Silurian (Wenlock) deposits contain enough organic carbon to be called "good" source rocks for hydrocarbon generation. Other deposits tested in the borehole are "very poor" or "poor"source rocks. Generally, the content of labile components is small in the analysed deposits; they are syngenetic to the sediments. Only in the lower parts of the Upper Jurassic section, labile components are epigenetic. Organic matter in the Lower Paleozoic is sapropelic and well transformed, but it underwent strong degradation. Organic matter in the Upper Cretaceous rocks is sapropelic and poorly altered.

The Ordovician and Cambrian rocks in the Narol PIG 2 borehole are generally "poor" source rocks for hydrocarbon generation. The value of migration coefficient indicates that labile components in the Cambrian formations of this borehole are syngenetic. In the Silurian formations, the organic carbon content varies widely from 0.20 to 2.68%. Some intervals contain good source rocks and rocks devoid of such qualities. The value of migration coefficient suggests that the bitumens are syngenetic. Epigenetic bitumens are found only in the Pridoli deposits. Upper Jurassic deposits from these boreholes contain an average of 0.30% of organic carbon. The amount of organic carbon is unevenly distributed. The content of organic carbon in the Lower Cretaceous deposits is 0.80%, allowing for considering these carbonate sediments as "good" source rocks for hydrocarbon generation.

The burial model for the Narol IG 1 borehole indicates a Late Cambrian burial. From the beginning of the Ordovician, there was a period of stagnation and slow burial, which continued into the Late Ordovician. During that period, the sedimentary cover reached a thickness of approximately 370 m. With the beginning of the Silurian, a rapid burial phase systematically continued, with the maximum lasting from the Wenlock to the Early Devonian, accumulating approximately 2000 m of sediment.

In the Narol IG 1 borehole, Devonian and Carboniferous deposits are missing due to erosion associated with uplifting movements during the Bretonian phase. Subsequently, in the Visean, there was another phase of rapid burial, which lasted almost until the end of the Carboniferous (Westphalian), thereby increasing the thickness of the sedimentary cover to about 2420 m. At the end of the Carboniferous (Stephanian) and at the beginning of the Permian, there was a significant phase of uplift and erosion that resulted in the removal of the whole thick Carboniferous succession of about 800 m.

The two Mesozoic burial phases include the Late Jurassic and Late Cretaceous. The former, when the thickness of the sedimentary cover had reached a similar figure to that of the late Carboniferous, was followed by the Early Cretaceous phase of low subsidence rate. At the beginning of the Late Cretaceous, there was another very intense phase of burial, which continued into the early Paleogene. The beginning of the Cenozoic is a period of stagnation and decelerating sedimentation rate, possibly along with a small erosion phase at the beginning of the Miocene.

Thermal maturity distribution in the Mesozoic and Paleozoic sediments provides a consistent pattern of high maturity gradient. It can be considered that there is no contradiction between the maturity of the Paleozoic and Mesozoic rocks. The anomaly associated with a decrease in thermal maturity within the lower part of the Ludlow deposits is due to the development of maturity under an overpressure regime. The fast rate of deposition of clastic sediments in the Ludlow and their mechanical compaction affected the formation of overpressure within these deposits. The modelling enables determining the zones of hydrocarbon generation phases, as well as tracing this phenomenon over time.

One-dimensional modelling in the Narol IG 1 borehole shows that the zone of hydrocarbon generation encompasses the interval from the bottom of the borehole (Upper Cambrian) to the Campanian (Upper Cretaceous), inclusive. The Cambrian to the top-Upper Jurassic deposits are in the gas generation window. Generation of natural gas from these deposits probably started at the beginning of the Paleogene. The Upper Jurassic, Lower Cretaceous and Upper Cretaceous (up to the Campanian)deposits fall in the late, middle and early window of oil generation, respectively. The onset of oil generation for these rocks took place at the Late Cretaceous/ early Paleogene transition.

The analysis of petrophysical data suggests that there are only three lithological intervals out of all tested meet the standards of good reservoir rocks (porosity greater than 15.0%, and permeability greater than 5.0 mD). These intervals fall on the Middle Jurassic (1924.5 and 1917.5–1916.3 m) and Upper Jurassic (1439.0 m).

Petrophysical data of the whole section suggests that none of the tested lithological intervals meets the standards of good reservoir rocks. The standard is met in one case, with the effective permeability of 25.5 mD observed in a Jurassic interval from a depth of 1373.2 m.

Formation tests were carried out in four reservoir horizons from the Furongian section (Upper Cambrian). Three of them yielded flows of brine with combustible gas, and one of them did not yield any flow. The properties of three reservoir horizons have been defined as medium, and dependent on fracture permeability. The average discharge rates varied between about 1 and 5 m^3/h. The Cambrian reservoir horizons are in low formation pressure zones with the gradients of 0.1–0.102 MPa/10 m. The tested deposits host sodium chloride and iodi debrines with the dry residue content from about 222 to about 225 g/dm^3. The brines were metamorphosed, which is expressed by the values of hydrochemical indicators rNa/rCl = 0.70–0.76, and by the increased content of calcium ion of about 17–18% mval. Their high bituminous potential is confirmed by the composition of free gas. This is a high-methane gas containing 80.0–86.5% vol. of methane and a very high content of helium – about 1.9–2.2% vol. The gas composition and noticeable alteration of the brines prove favorable conditions for the hydrocarbon accumulations in the Furongian deposits.

The Narol IG 1 and Narol PIG 2 boreholes met most of the tasks associated with the exploration of the geological structure and hydrocarbon accumulations in the Narol area.

Translated by Krzysztof Leszczyński