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SUMMARY

The Czaplinek IG 1 borehole was drilled in the NW part of the Mid-Polish Anticlinorium, in the central, axial zone of its Pomeranian segment, on one of the salt pillows within a string of halokinetic structures stretching from Zalesie to Świdwin.

The primary purpose of the borehole, planned to a depth of 6,000 metres, was to study the stratigraphy, facies development and spatial distribution of Permian and sub-Permian rock formations. The drilling was also intended to provide information on the prospects for oil and gas in Zechstein carbonates, in Rotliegend rocks and in the underlying Carboniferous deposits.

The borehole was completed in Carboniferous (Mississippian) rocks at a depth of 6006.0 m. Its stratigraphic column is composed of the Quaternary, Neogene, Paleogene, Lower Jurassic, Triassic, Permian and Carboniferous, however only fragmentarily cored. One interval was drilled for core in the Jurassic section. More drill cores were acquired from the Triassic, Permian and Carboniferous sections. The lithology and stratigraphy are based on both drill core data and interpretation of well logs.

The Czaplinek IG 1 borehole has a significant thickness of the Carboniferous (Mississippian) section of 960.5 m (logger's depth 5045.5–6006.0 m, unpierced). Based on the results of biostratigraphic and palynological studies, its age has been constrained to the Visean. The Mississippian section is subdivided into three lithostratigraphic units, from the base: the Łobżonka Shale Formation, Czaplinek Limestone Formation and Nadarzyce Shale Formation. The lowermost unit, Łobżonka Shale Formation occurs at a depth of 5703.5–6006.0 (thickness >302.5 m, unpierced) and consists of claystones, siltstones and quartz sandstones. The overlying Czaplinek Limestone Formation (5300.0–5703.5 m, thickness 403.5 m) is dominated by organodetrital, ooidal and lumpy limestones, which are characterized by high diversity of microfacies including lumpy, ooidal and skeletal grainstones, weakly washed, as well as wackestones, packstones and mudstones. The uppermost unit is the Nadarzyce Shale Formation (5045.5–5300.0 m, thickness 254.5 m) dominated by claystones. From this formation, interbeds of tuffs have been reported and described in thin sections.

The data from the Carboniferous section in the Czaplinek IG 1 borehole prove the presence of basinal, deltaic, and rimmed carbonate shelf depositional systems in Western Pomerania during Mississippian (Visean) times. Deposition of clay-muddy-sandy deposits of the Łobżonka Formation took place in a shelf basin area with periodic accumulation of deltaic lobes. The middle part of the section – the Czaplinek Limestone Formation – was most probably deposited on a carbonate shelf. In contrast, the uppermost part of this formation, with slope facies, is associated with the onset of basin deepening and the transition of the carbonate platform into a shelf basin. In this environment, the youngest, Nadarzyce Shale Formation was formed.

The Rotliegend occurs at a depth of 4106.0–5045.5 m (logger's depth), and its thickness is 939.5 m. Petrographic studies facilitated distinguishing of the conglomerate, sandstone and mudstone lithofacies. The Rotliegend section starts with sandstones and probably conglomeratic sandstones of the Drawa Formation (4710.4–5045.5 m). Towards the top of the Drava Formation, there is a change in sedimentation. Deposits of silty-sandy playa are replaced by a complex of sand-gravelly deposits topped by an erosion surface marking a gap in the sedimentary record. Sedimentation of the sandy-gravel platy sediments ends with an erosion gap. The overlying, predominantly fluvial and alluvial (coarse clastic – conglomeratic) rocks represent the Noteć Formation (4106.0–4710.4 m). The Czaplinek Conglomerate Member has been established (4642.0–4710.4 m) in the bottom part of the Noteć Formation. These conglomerates are dominated by carbonate rocks, most probably of Devonian age. Above the Czaplinek Conglomerate Member, the Noteć Formation forms a sedimentary mega-cyclothem divided into two main parts. The lower part consists of fluvial sediments (channel sandstones and gravels) passing into playa mudstones and claystones, forming a simple megacycle composed of a series of reversed cycles. Further towards the top, there is a reversed megacycle composed of a series of simple and reversed cycles.

The Zechstein deposits are characterized by significant thickness (1503.0 m), complete stratigraphic section, and the presence of a specific zuber facies in its upper part, at a depth of 2635–2928 m. The Zechstein section in the Czaplinek IG 1 borehole consists of three carbonate-evaporite cyclothems: PZ1, PZ2, PZ3 and the terrigenous-evaporite cyclothem PZ4, subdivided into sub-cyclothems PZ4a to PZ4e. The Copper Shale comprises sediments composed of laminated fine-grained terrigenous rocks (more than 50% of grains less than 0.062 mm in diameter) exhibiting platy parting. The Copper Shale occurs at a depth of 4105.6 to 4106.0 m (logger's depth) and is merely 0.40 m thick. It overlies immediately the Rotliegend and represents the mature stage of

Zechstein marine transgression, related to basin deepening. The alternating deposition of black and dark grey clayshales/mudshales and grey mudshales indicates periodic variations in water oxygenation and energy and in the supply of sedimentary material, depending on changes in basin depth and distance from shallower zones supplying carbonate material.

The Zechstein limestone occurs within a depth interval of 4096.5–4105.6 m (thickness 9.1 m). It is bipartite lithologically: the lower part is represented by a complex of dark grey marly limestones (micrite complex) and the upper part is composed of light grey granular limestones (oncolithic complex). The Zechstein limestone was deposited in a basin plain. The dominance of granular limestone in the section indicates sedimentation within an extension of the Gryfice Shoal. The Main Dolomite is about 12.5 m thick and occurs in a depth interval of 3872,5–3885,0 m. It is composed exclusively of mudstones, mostly heavily marly, i.e. highly enriched in clay-bituminous matter (locally these are close to clay shales). The mudstones are represented by two interbedding subfacies – these rocks are either horizontally laminated or more or less massive (at most with slightly marked streakiness). Sedimentological investigations of salt horizons in the cored intervals of Zechstein deposits were made mainly on some parts of three sub-cyclothems PZ4e, PZ4d and PZ4a, and supplemented with geochemical data. They enabled detailed interpretation of sedimentary environments.

Investigations of the ore mineralization in the Zechstein copper-bearing series, based on reflected light microscopic observations of 22 polished rock preparations, indicate the presence of the following ore mineral assemblages: bornite (Cu5FeS4), chalcopyrite (CuFeS2), digenite (Cu9S5), covellite (CuS), galena (PbS), sphalerite (ZnS) and pyrite (FeS2). The ore mineralization of the Zechstein copper-bearing series is not intense and dominated by zinc and lead sulfides (sphalerite and galena), while the copper mineralization is poor and represented by bornite, chalcopyrite, digenite and covellite. The most heavily ore-mineralized interval is the Copper Shale, the overlying carbonate rocks, and the top part of the Rotliegend, described as the Weissliegend deposits. Ore minerals are present here in the form of fine-grained disseminations and variably sized lenses, nests, and void fills, or replacements of rock-forming minerals. Ore minerals are distributed generally in a disorderly manner; however, in places (usually in shales and in the lower part of the Zechstein limestone) they are concentrated in the form of linear and lenticular aggregates, or horizontally arranged streaks or clusters of mineral aggregates. No rich ore mineralization has been found in the Czaplinek IG 1 borehole.

The contents of metals in the individual lithological units of the copper-bearing series are variable. The highest copper concentrations were found in the uppermost part of the Rotliegend Noteć Formation, where copper content is up to 0.65%. The Copper Shale and Zechstein Limestone contain only trace amounts of Cu, up to 0.04%. Elevated contents of zinc (up to 1.34% Zn) were found only in the Copper Shale. The highest contents of lead (up to 0.11% Pb) were recorded in the Zechstein Limestone. In general, the characteristics of ore mineralization in the Zechstein copper-bearing series confirm earlier assessments that the Pomeranian zone is not prospective for Zechstein ores of economic importance, both because of low metal contents and considerable depth of the bottom of the copper-bearing series, exceeding 4000 m.

Triassic deposits occur at a depth of 626.0–2603.0 m, reaching a thickness of 1977.0 m. All three Triassic lithostratigraphic groups are present in the section, i.e. the Buntsandstein, Muschelkalk and Keuper, with the Buntsandstein accounting for more than half of the entire section, and the Keuper being reduced, especially in its middle part. The Buntsandstein is dominated by claystones and siltstones of the Baltic, Pomeranian, Clayey and Barwice formations. Lithology of the Clayey Formation, not formally established, is characterized by a fairly significant proportion of thin sandstone interbeds, the total thickness of which, however, is too small to incorporate this succession into the Połczyn Formation, which is equivalent to the Clayey Formation in boreholes located slightly further north and northwest. Major sandstone levels are represented only by the Drawa Sandstone Member in the bottom of the Pomeranian Formation and by the Świdwin Member at the top of the Clayey Formation. Carbonate interbeds are characteristic of the Barwice Formation that forms a gradual transition between the Buntsandstein and the Muschelkalk. The Triassic succession is terminated by the Keuper Group, dominated by claystones and siltstones except for its uppermost part – the Wielichowo Beds (with *Trileites*) – which form a prominent sandstone complex, several tens of metres in thickness. The Reed Sandstone and the Upper Gypsum Beds have not been distinguished in the Keuper section. Comparison of the Triassic lithologies in the boreholes of Czaplinek IG 1 and Piła IG 1, drilled 36 km to the south, indicates that the deposition of the System was tectonically controlled in this region.

The Lower Jurassic succession is truncated at the top, and only its lower part, 414.5 m thick and attributed to the Hettangian and Sinemurian, has been preserved. In the Czaplinek IG 1 borehole, three lower lithoformations of the Kamienna Group can be distinguished (from the bottom): Zagaje, Skłoby and Ostrowiec formations. The Lower Jurassic succession is overlain by Paleogene deposits. The upper Lower Jurassic, Middle and Upper Jurassic, as well as the entire Cretaceous, are absent here.

The Paleogene section consists of the Czempiń and Upper Mosina formations (Oligocene, Rupelian). The Neogene is represented by the Gorzów Formation (Lower Miocene). All these formations are represented by clastic deposits with interbeds of brown coals.

The Quaternary is represented by tills and sands deposited during the South Polish (Sanian), Middle Polish (Odranian and Wartanian) and North Polish (Vistulian) glaciations.

Detailed petrographic studies of the Carboniferous and Permian rocks have revealed that reservoir properties of the Visean sandstones of the Łobżonka Shale Formation are poor. The Lower Carboniferous carbonates also lack reservoir potential due to strong compaction, cementation and neomorphic recrystallization.

Interpretation of vitrinite reflectance values of the Mississippian rocks in the Laska–Czaplinek zone, which are in

the range of 1.3–2.9% R_O, indicates a gas generation phase to a dry gas generation phase and suggest very high palaeotemperatures. Temperatures affecting the Carboniferous deposits in the Czaplinek IG 1 borehole are 200°C (R_O = 2.9%).

The main geophysical task of the borehole was to examine the reflection horizon Vgr 5600 m/s, running at a depth of ca. 5800 m in this region. The other objectives were to determine reservoir horizons and their characteristics on the basis of borehole geophysics, to identify lithologies of the formations drilled, and to assess the technical condition of the drill hole. The measurements were made with non-calibrated measuring instruments, so that the obtained values give different results due to different technical parameters of the device even in the same depth interval, which significantly hinders further mathematical analysis of the data. The results are subject to additional error resulting from the poor condition of the borehole walls, numerous caverns, or drill collars left in the borehole due to the sticking of the drill string.

Only 21 thin rock layers that show potential for being reservoir horizons have been identified. This proves that the region of the Czaplinek IG 1 borehole is characterized by low values of reservoir parameters. The highest porosities are recorded for the Keuper and Rhaetian sandstones. The average geothermal gradient in the 5–5750 m interval was 1.8°C/100 m, and the average geothermal degree was 55.44 m/°C.

The results of vertical seismic profiling enabled the determination of a number of velocity complexes. The values of interval, complex and smoothed velocities made it possible to determine the boundaries between successive formations, indicating lithological changes within the stratigraphic units from the Quaternary to the Zechstein base. The greatest contrast of complex velocities is observed within the Middle Triassic formations, at the boundary between the Lower Keuper and Upper Muschelkalk. A remarkable reflection within the Triassic formations is also the velocity contrast related to the lithological variability within the Middle Buntsandstein (Lower Triassic). In addition to the Mesozoic horizons, well pronounced velocity contrasts are observed also within the Zechstein at the boundaries between the Younger Halite (Na3) and the Main Anhydrite (A3) and between the Older Halite (Na2) and the Basal Anhydrite (A2). The boundaries of the complexes will allow us to relate the most prominent reflections on seismic profiles to the corresponding lithostratigraphic units and develop correct seismic interpretations in the region of this borehole.

The rocks drilled in the Czaplinek IG 1 borehole do not exhibit the characteristics of high quality source rocks for hydrocarbon generation. In general, they can be considered "poor" or "weak" source rocks. Only some of the Zechstein carbonate rocks can be called "good" source rocks.

Given the small amount of organic carbon, the bitumen found in the studied rocks is generally considered epigenetic. Syngenetic bitumen is present only in the Zechstein and lower Lower Carboniferous.

Detailed geochemical studies have shown that organic matter in the studied rocks is mainly of marine origin. In all rock formations, biodegradation of organic matter is common.

The Rock-Eval pyrolysis was done on 36 samples of Lower Carboniferous, Permian, Lower Triassic and Lower Jurassic rocks. The resulting geochemical profile covers a depth interval of 356.5–5998.0 m, within which no source rocks for hydrocarbons have been found. Signs of rocks of such characteristics are observed only in a single Jurassic sample, but these rocks are characterized by thermal immaturity of kerogen dispersed in them.

Organic matter in the Czaplinek IG 1 borehole is dominated by low-quality kerogen. The Lower Jurassic deposits are the only ones that contain gas-forming type III kerogen. The remaining samples in the section contain heavily transformed kerogen currently showing the characteristics of non-generative type IV kerogen.

Thermal maturity of the rocks, determined for a single Lower Jurassic sample, corresponds to the final stages of diagenesis. The remaining results do not allow an accurate determination of the degree of thermal alteration of rocks lying deeper in the borehole section.

Physical and chemical properties of the rocks suggest that the lithologic intervals analysed in the Czaplinek IG 1 borehole do not meet the standard of so-called good reservoir rocks, which means that the porosity values here are below 15.0%, while the permeability is generally lower than 5.0 mD. The maximum recorded porosity is 5.45%, and the maximum permeability is 5.43 mD.

The drill stem tests (DST) prove poor reservoir properties of Rotliegend deposits in this part of the Permian Basin. There was only one case that the minimum brine inflow rate was 0.07 m^3/h. The brines in the Rotliegend formations are characterized by a high degree of metamorphism, indicating favourable conditions for hydrocarbon accumulations.

Slightly higher inflow rates were obtained from the Buntsandstein horizon, characterized by medium reservoir properties. This horizon occurs in a zone of elevated pressures with a gradient of more than 1.3–103 hPa, the highest recorded in Poland at the time of the DST in this well. The Buntsandstein brines yielded gas containing elevated methane levels, which may indicate the prospectivity of these deposits in deeper zones of the Mesozoic basin.