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SUMMARY

The Nieświń PIG 1 borehole was among a number of exploratory wells drilled in the far north-western margin of the Holy Cross Mountains, in prospecting for Cu, Pb, Zn, Fe and V deposits and hydrocarbon accumulations. This is why the full coring covered only those parts of the borehole section, which were promising for a discovery of these mineral resources. Drill cuttings were taken every 1 m from the remaining parts. This material was used for stratigraphical investigations: litho-, bio-, chrono- and sequence stratigraphic studies, facies, microfacies and sedimentological analyses, and macro- and micropalaeontological (including palynological) determinations, as well as tectonic studies. They were supplemented by mineralogical, petrographic, chemical and geochemical studies. A complete set of geophysical well logs and hydrogeological drillstem tests were performed.

The Nieświń PIG 1 boreholes has provided many fundamental data for the geology of the far north-western margin of the Holy Cross Mountains, which confirm the hypothesis on the occurrence of the Końskie Depresssion in the basement of the Opoczno Megasyncline. The depression is composed of strongly folded Lower Carboniferous deposits, additionally deformed by a fault zone responsible for a repetition of Permian (Zp1 and Ca1) and Carboniferous strata in the stratigraphic section.

Zechstein deposits, which occur in the borehole section in a depth interval of 1765.0–1845.0 m, are developed relatively completely compared with other areas of the Holy Cross Mountains. They attain a thickness of 564.3 m. The PZ1 cyclothem, 401.4 m thick, is represented by all lithostratigraphic units: Zechstein Limestone (Ca1), Lower Anhydrite (A1d), Oldest Halite (Na1) and Upper Anhydrite (A1g). It starts with a thin (2.3 m) complex of detrital rocks represented by the transgressive Basal Conglomerate (Zp1). No Copper-bearing Shales (T1) have been identified in the section, although the basal part of the Ca1, composed of dark grey bituminous, clayey dolomites with pyrite-sphalerite mineralization, may correspond to the shales. Especially thick is the Oldest Halite (Na 1), whose thickness has been increased to 279 m due to halokinetic processes. There is also the synsedimentary anhydrite-dolomite breccia BrA1 (3.7 m), widely distributed in the Upper Anhydrite (A1g) deposits in the marginal zone of the Polish Zechstein Basin.

The second cyclothem PZ2 (38.2 m) is represented by the Main Dolomite (Ca2) attaining a thickness of 30 m, Basal Anhydrite (A2), Terrigenous Series (T2r), and Screening Anhydrite (A2r).

In the third cyclothem PZ3 (44.8 m), a considerable thickness (9.3 m) compared with other sections in the region is revealed by the Grey Salt Clay, while the Platy Dolomite Ca3 is thin (4.5 m). The thickness of the Main Anhydrite A3 is 31 m.

The Permian section is topped by the Top Terrigenous Series PZt (80 m) similar in lithology to that described from the near margin of the Holy Cross Mountains.

The Zechstein deposits represent a record of transgressive-regressive cycles in a lagoon-type basin. The peak of the first transgression is marked by bituminous marly dolomites, being equivalent to the Copper-bearing Shale (T1). During a sea-level stillstand, Ca1 carbonates were deposited on a platform slope, in a zone of barriers that separated a lagoon-type basin from the open sea. Sediment deposition in the basin resulted in its shallowing and transformation into a system of connected shallow-water saline lagoons forming a sulphate platform in which Lower Anhydrite (A1d) deposits were accumulated. The onset of the second Late Permian transgression was marked by deposition of deep-marine anhydrites occurring at the top of the A1d, and of the Oldest Halite (Na 1) deposits, marking the maximum extent of the Zechstein transgression at a depth of ca. 2020 m in the Nieświń PIG 1 borehole (Szulc, this volume). The following period of sea-level stillstand is recorded by A1g sulphate sedimentation on a sulphate platform. The basin shallowing trend is manifested by a few-metre thick packet of clastic deposits represented by the Upper Anhydrite (BrA1) breccia that occurs at a depth of 1941.7–1945.4 m in Nieświń PIG 1, indicating, according to Szulc, pluvialization of the climatic conditions. Kasprzyk (this volume) accepts also an alternative possibility that the BrA1 deposits were accumulated as a result of transgression. The Main Dolomite (Ca2) deposits were accumulated in a high-energy platform environment, while the Main Anhydrite (A2) deposits – on a nearshore plain representing a type of

carbonate-sulphate sabkha, in very shallow-water to subaerial conditions. The final stage of the regressive stage was the emergence of much of the peripheral part of the Zechstein Basin and the formation of classic T2r deposits bearing a record of weathering and calichefication processes. The A2r sulphate deposits, representing a siliciclastic-carbonate sabkha, reflect the transgression related to the Permian last depositional sequence dominated by sabkha (T3), hypersaline lagoon (A3), playa and alluvial (PZt) deposits accumulated in subtropical climates. The most common deposits are clastic rocks: variegated claystones and mudstones accompanied by sulphates and dolomites with frequent caliche-type paleosol horizons, e.g. at a depth of 1886 m in the Nieświń PIG 1 section. These deposits continue upward in the section at least to a depth of 1735 m. Therefore, in the case of lack of guide fossils, determination of the chronostratigraphic boundary between the Permian and Triassic remains an open question.

The Buntsandstein (413.7 m) section is incomplete in Nieświń PIG 1 and disturbed by a fault zone that has eliminated thick sandstone series of its lower part, known from many other areas of the Holy Cross region. Variegated mudstone-claystone deposits with calcite and sulphate nodules, found in this section, are typical of the Middle Buntsandstein Samsonów Formation. They were deposited in a wide range of environments, starting from lacustrine and intermittent playa, through floodplains of meandering rivers, to crevasse splay environments.

Röt deposits (175.3 m) are represented mainly by two facies: sandy-clayey-marly and calcareous-marly-sulphate. The bottom part consists of the Radoszyce Beds showing intermediate characteristics between the typical Radoszyce Beds described by M. Pajchlowa (1970), and the Wąchock Beds. They are overlain by the Lower Gypsum Beds, Inter-Gypsum Beds, Upper Gypsum Beds and Dalejów Beds. The Radoszyce Beds were deposited on a fluvial plain and may represent deltaic sediments. The Lower Gypsum Beds represent a sulphate lagoon/sabkha environment, while the Inter-Gypsum Beds were formed in the nearshore zone of marine basin, where periodic events of emergence above sea level took place. The Upper Gypsum Beds were deposited in a siliciclastic-sulphate sabkha. The Dalejów Beds, accumulated in the foreshore and beach zones, mark the onset of the Middle Triassic transgression.

The Nieświń PIG 1 section includes the Lower, Middle and Upper Muschelkalk (140 m). The Lower Muschelkalk is represented by the Wallenkalk Beds, while the Upper Muschelkalk – by the Entolium discites Beds. These are epicontinental sublittoral deposits with recorded sabkha influences, especially in the Middle Muschelkalk dominated by dolomites with sulphates.

The Nieświń PIG 1 borehole is the first one where the lithological succession of thick Keuper deposits (656 m) has been thoroughly studied in the far Mesozoic margin of the Holy Cross Mountains. Petrographic and palynological studies provided the basis for distinguishing the following lithostratigraphic units: Sulechów Beds, Boundary Dolomite of the Lower and Upper Gypsum Beds, Studzianna Beds, and variegated and grey Parszów Beds. The Sulechów Beds (119 m) show the typical tripartite division (cf. Gajewska, 1978) – grey mudstones and claystones occurring at the base and top are separated by variegated mudstones with paleosols whose presence is indicated by numerous carbonate nodules. They were deposited in a brackish lagoon passing into a coastal alluvial plain. The assumed thickness of the Lower Gypsum Beds is 148 m. While the determination of their base was easy owing to the presence of the Boundary Dolomite containing sandstone interbeds, the lack of a clear horizon of the Reed Sandstone made it difficult to define their top. The boundary between the Lower and Upper Gypsum Beds has been drawn at a depth of 750 m, based on both the change in the colour of rocks from variegated at the top of the Lower Gypsum Beds to brownish-chocolate at the base of the Upper Gypsum Beds, and the presence of sulphate clasts in the latter. The lower part of the Lower Gypsum Beds contains bioclastic limestones (coquina), so far unknown from the Holy Cross region. They are overlain by dark grey dolomitic claystones and mudstones with anhydrite. Upward within the unit, sulphates disappear and the colour of the rock changes to variegated. Thin interbeds of sandstones start to appear and the deposit is strongly bioturbated. Deposits of the Lower Gypsum Beds were accumulated in a lagoonal, locally sulphate environment. The Upper Gypsum Beds, 150 m in thickness, are clearly bipartite in terms of both lithology and origin. The brownish-chocolate claystones and mudstones with sulphates, occurring in the lower part of the unit, were deposited in a lagoon, while the grey mudstones and sandstones, composing its upper part, were accumulated in a brackish basin. The Studzianna Beds, which are a new lithostratigraphic unit proposed by A. Fijałkowska-Mader and M. Kuleta, encompass the Middle Keuper recognised in the Nieświń PIG 1 borehole above the Upper Gypsum Beds and below the variegated Parszów Beds of the Upper Keuper. These are usually variegated mudstones and claystones containing paleosol horizons developed as caliche (calcisols) and occurring within the 502–511 m depth interval. Deposits of the Studzianna Beds were accumulated in a wide range of alluvial plain environments. The Keuper section is terminated by variegated (7 m) and grey deposits of the Parszów Beds (20 m) that were accumulated in boggy and meandering river environments.

Lower Jurassic deposits (350 m) are represented by the Zagaje and Skłoby formations and the Przysucha Ore-bearing Formation. Their lithologies are typical of the NW margin of the Holy Cross Mountains (cf. Pieńkowski, 2004). The lithology of the Zagaje Formation, separated from the grey Parszów Beds by an erosional boundary, reflects a transgressive systems tract, ranging from meandering rivers through limnic-boggy basins to nearshore environments with storm or barrier deposits. The Skłoby Formation reflects a further development of transgression followed by a regressive trend. Deposits of its lower part were accumulated in proximal deltaic environments. Above a depth of 192.0 m, there is a change to more distal environments with a smaller proportion of distributary channel deposits.

The upper part of the formation was deposited in middle shelf environments. The maximum flooding surface can be interpreted to occur at a depth of 147.0 m. The Przysucha Ore-bearing Formation reflects a continuation of the regressive trend in migrating delta environments of a brackish basin. The lower part of the section can be interpreted as deltaic deposits interbedded with nearshore storm strata.

No Early Cimmerian unconformity has been found near the Triassic/Lower Jurassic boundary. The Triassic and Lower Jurassic succession forms a single structural complex in this area, jointly deformed by faulting and folding. It probably also includes Permian strata whose original tectonic structure was later affected by halokinetic and discontinuous deformations.

The rocks from the borehole were also analysed for the presence of sulphide mineralization. It has been found in the deposits marking the onset of the Zechstein marine sedimentary cycle: the Basal Conglomerate (Zp1) and the Zechstein Limestone (Ca1). Pyrite, sphalerite, and traces of galena and chalcopyrite have been recognised here. The maximum level (ca. 7.28% FeS_2 and 1% ZnS) of this meagre mineralization is observed in dark bituminous, dolomitic marls equivalent to the Copper-bearing Shale.

The Main Dolomite Ca2 is practically non-mineralized. Pyrite appears in small amounts only in the lower part of this unit. It is accompanied by trace amounts of sphalerite. More interesting copper mineralization, although very weak, has been encountered in mudstones and sandstones of the Middle Buntsandstein and Lower Keuper. The presence of small bornite and chalcocite crystals is observed occasionally in the Lower Triassic deposits, while of chalcopyrite in the Keuper.

The geochemical studies show distinct differences in the content of examined elements, depending on the lithology of rocks: the highest contents are associated with carbonate and clay rocks, while the lowest contents are observed in gypsum, anhydrite and salts. Greater concentrations of most elements are found in the Zechstein Limestone (Ca1); however, the concentrations of zinc (1966 g/t), lead (615 g/t) and silver (2.8 g/t) are several times greater than the clark values. In the other Permian and Triassic complexes, excluding the Ca1, the concentrations of all elements oscillate around average values. A correlative analysis indicates a clear dependence in the occurrence of non-ferrous metals and iron group elements and between barium and strontium.

Both the Permian and Triassic deposits in the Nieświń PIG 1 are very poor in organic matter. Its greater amounts occur only in the Lower Carboniferous rock, bituminous deposits at the base of the Zechstein Limestone (Ca1), some horizons of the Main Dolomite (Ca2), Lower Gypsum Beds, and Lower Jurassic deposits. According to I. Grotek, these rocks are considered potential source rocks for hydrocarbon generation. In the Lower Carboniferous, predominantly humic matter has reached the main phase of gas generation (1.70–1.73% R_o). In the Ca1 deposits (1.56–1.73% R_o) and in single Ca2 horizons (1.37–1.40% R_o) the thermal maturity corresponds to the phase of wet gas and condensate generation. Deposits of both the Lower Gypsum Beds (0.82–1.00% R_o) and Lower Jurassic (0.56% R_o) contain organic matter that has reached the main phase of oil generation. Similar results of the degree of organic matter maturity have been obtained by Z. Szczepanik using the TAI method and by I. Dyrka using thermal history modelling. Investigations of organic matter conducted by M. Janas with use of the Rock-Eval method show that interbeds enriched in dispersed organic matter occur only in the Ca2. They have features of source rocks, but currently show no hydrocarbon potential. To summarise: in the Nieświń region, there were no favourable conditions for liquid or gaseous hydrocarbon accumulation, neither in the contact zone of the Lower Carboniferous with the Permian Basal Conglomerate (Zp1), nor in the Zechstein Limestone (Ca1), Main Dolomite (Ca2), and upper formations of the Zechstein and Buntsandstein. Slight hydrocarbon shows, detected in the laboratory in the drilling mud and core, are discussed in Chapter „Results of reservoir formation tests". Well log analysis indicates that all horizons with poor reservoir properties have appeared to be waterlogged, as is also confirmed by formation tests. Potentially the most predisposed formation for hydrocarbon accumulation, Zechstein Limestone, is represented in this borehole by dolomitic-marly facies and is characterised by very poor reservoir properties, and very low values of effective porosity (0.5–2.7%) and permeability (ranging from 0.3 to commonly below 0.1 mD). The Basal Conglomerate (Zp1) has better reservoir properties (conglomeratic sandstones) and was saturated with brine.

Burial modelling performed by I. Dyrka for the Nieświń IG 1 borehole shows a number of phases of increased burial depth and high deposition rates (in the Early Carbonifeorus, Late Permian, Triassic, Jurassic, Early Cretaceous – the maximum burial of the sedimentary cover of ca. 3570 m, and in the Late Cretaceous). These phases were followed immediately by periods of erosion or stagnation (in the Early Permian, Late Carboniferous, end-Early Cretaceous – the maximum erosion of ca. 1250 m, related to the Asturian phase, and Late Cretaceous – Laramide Phase).

From the geological point of view, the Nieświń PIG 1 borehole achieved its main exploratory objectives and provided comprehensive material about the lithology, age, tectonic settings, geochemistry, and ore mineralization and bitumen content in the Permian, Triassic and Lower Jurassic deposits in the far northern margin of the Holy Cross Mountains, which was a poorly explored area before. However, it is a pity that it was impossible to study a longer interval of the Carboniferous section due to technical drilling problems.

Translated by Krzysztof Leszczyński