SUMMARY

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The Piła1/IG 1 borehole section is located in north-western Poland, in the area of the Mid-Polish Anticlinorium, in the southern part of its Pomeranian Segment. The main objectives of the drilling were to investigate Permian (Rotliegend and Zechstein) deposits of the elevated Wałcz–Piła–Szamocin structure in order determine their lithological and facies development, reservoir properties, potential hydrocarbon accumulations and a burial depth of the pre-Permian rock complex.

Carboniferous, Permian (Rotliegend and Zechstein), Triassic, Lower–Middle Jurassic, Paleogene, Neogene and Quarternary deposits have been documented in the Piła 1/IG 1 borehole section. Upper Jurassic and Cretaceous deposits are lacking from this section as a result of its location within the Mid-Polish Anticlinorium, which underwent tectonic inversion and significant erosion at the Cretaceous and Paleogen transition.

Upper Carboniferous (Pennsylvanian) deposits were drilled at the depth of 5468.3–5482.0 m. They are mostly represented by mudstones and massive claystones, which are horizontally laminated and intercalated by siltstones, and occasionally, by tuff layers. The Upper Carboniferous (Pennsylvanian) deposits have been dated on the basis on rare palinological data and by analogy of their petrographic composition (quartz wackes) with the lithological record of other Carboniferous borehole sections from Western Pomerania. They were deposited in a lacustrine environment as evidenced by the lack of marine organisms and marine trace fossils.

Mesostructural analysis of the Carboniferous deposits has shown the presence of common tectonic disturbances i.e. slickensides, slickenlines, veinlets, small faults as well as steeply inclined beds, whose dips range from 45 to 90°. The presence of these structures points to tectonic deformation of Carboniferous rock complex in the regime of reverse faults. There are indications that it underwent multiphase deformations with initial deflection, tilting and compression by reverse faults, which was followed by transpressive re-activation (chapter p. 74, this volume).

The base of the **Permian** is marked by the occurrence of Lower **Rotliegend** facies (Wielkopolska Volcanogenic Formation). An erosional gap probably occurs between the Upper Carboniferous and Lower Permian deposits as shown by red colouration of the rocks, which may be linked to their subaerial weathering.

One of the principal goals of geologic-exploratory studies of the Piła 1/IG 1 borehole section was documentation of Rotliegend deposits. They were cored at a depth of 4384.9–5468.3 m (according to drilling measurements) and their thickness amounts to 1083.4 m. The Rotliegend section of the Piła 1/IG 1 borehole is divided into two rock complexes. The lower complex corresponds to the Wielkopolska Volcanogenic Formation (Lower Rotliegend). It is represented by volcanic rocks, mostly basalts and to lesser extent by rhyolites. Sandstone-conglomerate deposits of the epiclastic-piroclastic series occur in lowermost and uppermost parts of the lower rock complex. A total thickness of the lower rock complex amounts to 192.3 m. An erosion surface and hiatus occur on the top of the Lower Rotliegend deposits. The overlying strata are assigned to the upper part of the Rotliegend. Their lowermost portion (Drawa Fm) consists of sandy-gravel marginal playa deposits, which are overlain by an interval of clayey playa deposits, intercalated with eolian sandstone covers and, occasionally, with layers of fluviatile, riverbed deposits. They were deposited in a vast, playa depression under cyclic climatic variations including cycles of dry, semi-dry and wet climatic conditions. An erosion surface and hiatus occurs on the top of the Drawa Formation. Younger sandy-clayey playa deposits of the upper Rotliegend part (Noteć Fm) are intercalated with layers of fluviatile, riverbed deposits, which become upsection less frequent. All the sandy-clayey playa deposits are 373.85 m thick. Upper Rotliegend deposits pass without any discernible erosion surface into the Zechstein evaporites and carbonates, which points to a continuous process of sedimentation (chapter p. 81, this volume).

Zechstein deposits occur at a depth of 3099.0–4384.9 m. They are characterized by a significant thickness of 1285.9 m. Zechstein section is relatively complete and comprises three evaporite-carbonate cyclothems (PZ1, PZ2 and PZ3), a terrigenous-evaporite cyclothem PZ4, divided into subcyclothems PZ4a–PZ4d and the terrigenous Rewal Formation. Cored intervals of the Zechstein, which include a boundary of the Upper Rotliegend and the Zechstein along with the Kupferschiefer (chapter p. 116, this volume), carbonate rocks of the Zechstein limestone (CA_1) and the Main Dolomite (CA_2) (chapter p. 121, this volume), halite deposits of the cyclothems PZ2 and PZ4 (chapter p. 136, this volume) and anhydrite deposits of the

cyclothems PZ1–PZ3 (chapter p. 134, this volume) have been studied, in details, using sedimentological and microfacies methods. A separate chapter is devoted to ore-bearing mineralization of the Rotliegen-Zechstein boundary and the mineralization of the Kupferschiefer and the Zechstein Limestone (chapter p. 115, this volume). A so-called Permian copper-bearing series is mineralized by iron minerals (pyrite and marcasite) along with secondary occurrences of chalcopyrite, sphalerite and galena. Concentrations of key chemical elements (Cu, Ag, Zn and PB) are, therefore, relatively low. They do not have economic importance also because of a significant burial depth.

Uppermost Permian rocks assigned to the Rewal Formation occur at the 3127.5–3099.0 m depth interval and have a thickness of 28.5 m. They are poorly cored (2 m) and consist of terrigenous, inland deposits, which were formed after cessation of the evaporite accumulation (chapter p. 139, this volume). The Zechstein strata pass gradually into the Lower Triassic Baltic Formation.

The **Triassic** occurs at a depth of 1068.5–3099.0 m in the Piła 1/IG 1 borehole section. Triassic deposits are tripartite and divided into the clayey-sandstone Buntsandstein, the carbonate-clayey Röt and Muschelkalk Formations and the predominantly clayey Keuper. The Bunstsandstein group comprises the Baltic, Pomorze, Clayey and Röt Formations. The Permian–Triassic boundary is hardly distinguishable because of a lack of significant carbonate intercalations within mudstones and claystones of the Baltic Formation. Two remarkable sandstone-carbonate layers occur in the Pomorze Formation, which are assigned to the Drawsko Sandstone Member and the basal part of the Trzebiatów Member. A significant number of sandstone intercalations are observed in the Clayey “Formation”. Their occurrence is related to location of the Piła 1/IG 1 borehole in a transitional zone between deposition of the Połczyn Formation and the classical Clayey “Formation”. Likewise, some features of the Upper Buntsandstein Röt “Formation” in the Piła 1/IG 1 borehole make it similar to the Barwice Formation. Muschelkalk deposits are developed in a typical way for the study area and consist mostly of limestones, in the lower part, of the marly-dolomitic middle part and of the bipartite limestone-clayey upper Muschelkalk. All typical lithostratigraphica units of the Keuper, along with the grey claystone and topmost anhydrite layers occur in the Piła 1/IG 1 borehole section. It is important to note that chronostratigraphical documentation of the Triassic is sparse because of poor coring of the deposits of this unit. The presence of the miospore *Voltziaceaesporites heteromorpha* Zone has been documented in the Upper Buntsandstein. It is dated to the boundary of the Olenekian and the Anisian. At the top of the non-divided Zbąszynek and Jarkowo Beds of the Middle Keuper is, in turn, documented the miospore *Corollina meyeriana* Zone, dated to the Norian.

Chrono- and lithostratigraphical documentation of the non-cored **Lower Jurassic** interval of the Piła 1/IG 1 borehole section is based on geophysical curves and their comparison with the Kaszewy 1 borehole section, which is located ca. 200 km southward from the study site. Lower Jurassic deposits are 805 m thick and occur at a depth of 263.5–1068.5 m. The following lithostratigraphical units have been distinguished based on a gamma ray geophysical curve: the Zagaje and Skłoby Formations (the Hettangian), the Ostrowiec Formation (the Sinemurian), the Gielniów and Drzewica Formations (the Pliensbachian) as well as the Ciechocinek and Borucice Formations (the Toarcian). The same method has been applied for determination of hypothetical depositional sequences based on the cyclo- and chronostratigraphical frameworks.

Middle Jurassic strata of the Piła 1/IG 1 borehole sections were not cored. They comprise a 78.5 m thick interval at a depth of 185.0–263.5 m. Two Middle Jurassic rock complexes consist of lower sandstone (51 m thick) beds and upper clayey-mudstone beds (27.5 m). The lower rock complex has been assigned to the Lower Aalenian and the upper one to the Upper Aalenian on the basis of geological data derived from nearby borehole sections from the area of Western Pomerania.

Paleogene and **Neogene** rocks of the Piła 1/IG 1 borehole section (88.0–185.0 m, 97 m thick) have been documented based on crushed-rock samples and geophysical measurements as well as their comparison with data derived from nearby, cartographic borehole sections. The Czempin Formation (the Lower Oligocene) and the Upper Mosina Formation (the Lower and the Upper Oligocene) have been distinguished in the Paleogene. Neogene deposits are represented by the Gorzów Formation (the Lower Miocene) and the Krajenka Formation (the Middle Miocene).

The youngest rocks documented in the Piła 1/IG 1 borehole sections, which occur at a depth of 0 to 88.0 m are of **Quarternary** age. They are represented by glacial till and fluvioglacial deposits of the South Polish Glaciation (Sanian Glaciation), the Middle Polish Glaciation (Wartanian Glaciation) and the North Polish Glaciation (Vistulian Glaciation).

Biostratigarphical dating of the studied rocks were mostly based on **palynological methods**. Spores typical of the Carboniferous have been found both in the Carboniferous and the Permian deposits (chapter p. 153, this volume). It seems that the Carboniferous spores were re-deposited during the sedimentation of the Rotliegend facies; worth noting is also a lack of typical Permian taxa. Microfloristic assemblages in the Triassic deposits of the Piła 1/IG 1 section were assigned to the Upper Olenekian–Lower Anisian and Norian (chapter p. 155, this volume). The Toarcian has been documented in the Lower Jurassic Ciechocinek Formation based on palynological data. Pollens distinctive of the Middle Oligocene have been found in the Czempin Formation, some of these taxa may, nevertheless, also occur in the Lower Miocene (chapter p. 155, this volume).

The **organic matter** analyses were based on samples derived from the Carboniferous, Permian and Triassic (chapter p. 157, this volume) and Lower Jurassic (chapter p. 161, this volume). The Triassic samples were derived from the Reed Sandstone, Lower Gypsum Beds, Sulechów Beds and the Muschelkalk. All these deposits contain macerals of the vitrinite group with an admixture of macerals of the inertinite group. In addition, in the Reed Sandstone samples has been observed an admixture of amorphous organic matter forming organic-mineral associations of the bituminous type. The maceral composition points to the predominance of the terrestrial organic matter. The Muschelkalk deposits contain, however, mixed, terrestrial-marine organic matter. TOC concentrations is relatively low in the Triassic deposits and range from 0.1 to 0.6 wt.% of the rocks. Bitumen concentrations oscillate between 0.001 and 0.029 wt.% of the rocks. The bitumen features are typical of heavy hydrocarbon fraction generated from marine source rocks.

Permian organic matter was analysed from selected, informal Zechstein lithostratigraphical units including the Main Dolomite, Upper Anhydrite, Lower Anhydrite and the Zechstein Limestone. The maceral composition is similar in all these deposits. The predominant component of these rocks is amorphous organic matter, which contains admixtures of macerals of the vitrinite and inertinite groups. The organic matter is mostly marine but contains a slight amount of terrestrial detritus. TOC concentrations, which were analysed in two samples only, amount to 0.4 and 0.5 wt.% of the rocks. Bitumens constitute 0.003 and 0.007 wt.% of the rocks. They were likely generated from the kerogen of the parent rocks but it is not possible to exclude the presence of some amount of migratory bitumens in the Zechstein deposits.

Only trace amount of organic matter was observed in the Carboniferous.

The thermal maturity of the rocks of the Piła 1/IG 1 section increases with their burial depth, starting from the early phase of the oil window in the Reed Sandstone (Keuper, 1473.0–1476.0 m, R_O = 0.77–0.78 %) to conditions corresponding to the wet gas phase in the Zechstein (4159.1–4379.1 m, R_O = 1.87–2.32 %). Because of the low bitumen content and their epigenetic character the studied rocks cannot be a possible source of hydrocarbons of economic significance.

Reservoir properties were studied on the basis of analyses of **physical and chemical parameters of the rocks** including: carbonate content, effective and total porosity, permeability, specific and volume density of the rocks as well as sulphur and bitumen concentrations (chapter p. 161, this volume). The analysis of the Carboniferous, Rotliegend, Zechstein and Lower Triassic deposits unambiguously indicates that all these deposits do not possess good reservoir properties. They show very weak permeability or its total lack in the most cases. The analyses of the sulphur and bitumen concentrations have been carried out for the Upper Triassic and Lower Jurassic samples only. Sulphur concentrations of these rocks are below detection limit, whereas their bitumen content does not exceed 0.035 wt.%

An area within a radius of 10 km from the Piła 1/IG 1 borehole was covered with a network of **seismic profiles**. They were mostly acquired in the early 1980s; two younger profiles were conducted in the year 1998 (chapter p. 176, this volume). Interpretation of the 2D seismic profiles has allowed identification of the top levels of the Middle Jurassic, Lower Jurassic, Upper Triassic, Middle Triassic, Lower Triassic, Permian and the Rotliegend. The Piła 1/IG 1 borehole section is located on the slope of an anticline formed on the Permian salt pillow.

A set of geophysical measurements of **well logging** have been acquired during the drilling of the Piła 1/IG 1 borehole section. They include various radiometric, acoustic and electrometric imaging (chapter p. 177, this volume). The calculated petrophysical parameters of the rocks prove their poor reservoir properties. The rock complexes consist of impermeable to weakly permeable deposits; in addition, sandy intervals contain a significant amount of clay. The significant clay content is responsible for low values of the permeability coefficient of the studied rocks even at their considerable total porosity. This was, for example, observed in the case of the Lower Jurassic deposits, whose total porosity amounts to 18 wt.%. Deeper sandstone strata underwent significant compaction, which has resulted in the disappointing values of their permeability coefficient, which oscillates, mostly in the range of a few percent, between 0.1 and 1 mD.

The velocity survey of the Piła 1/ IG 1 borehole section, based the analysis of the calculated smooth, interval and complex velocities (chapter p. 184, this volume), has allowed the identification of four rock complexes, connected with lithological variations occurring in the Paleogene–Rotliegend interval. The highest complex velocities were observed in carbonate sandstone beds of the Muschelkalk, the Middle Buntsandstein and the Lower Anhydrite (A1d). The most pronounced velocity contrasts were, on the other hand, observed at the boundaries of: (1) the Upper Mosina and the Czempin Formations of the Paleogene, (2) the Keuper and the Muschelkalk, (3) the Pomorze and the "Clayey" Formations of the Middle Buntsandstein, (4) the Zechstein and the Trassic Baltic Formation, (5) the PZ1 and PZ2 cyclothems of the Zechstein, as well as (6) in the top of the Drawa Formation of the Rotliegend. The identified complex boundaries allow correlation of the main reflexive horizons of the seismic profiles with corresponding lithostratigraphical units of the Piła 1/IG 1 borehole section and determination of its seismic framework.

The surrounding area of the Piła 1/IG 1 well was covered with **gravimetric and magnetic profiles** (chapter p. 194, this volume). The well is located, within an area of the gravimetric, Pomeranian high, whose south-western boundary coincides with boundary between Mid-Polish Anticlinorium and Szczecin–Miechów Synclinorium. Local, insignificant disturbances of the gravimetric data can be explained by the accumulation of glacial deposits. The Piła 1/IG 1 well is located within the south-western magnetic province, whose existence is related to the deep basement of the continental crust.

Magnetostratigraphic studies have been conducted in the Piła 1/IG 1 and Czaplinek IG 1 borehole sections in order to correlate with the global polarity time scale (chapter p. 198, this volume). In spite of the strong, diagenetic remagnetization of the majority of the studied samples, the primary Permian magnetic components and polarities of the ancient magnetic fields have been reconstructed. The boundary between the Kiaman and the Illawarra megachrons, correlated with the boundary of the Roadian and the Wordian, is situated in the lower part of the Drawa Formation.

Modelling of the palaeoburial depth and hydrocarbon generation (chapter p. 202, this volume) suggests that during the Mesozoic–Cenozoic transition a part of deposits from the study area, of ca. 1700 m thickness, was removed by the erosion. This is recorded in the porosity changes of the rocks related to their compaction. Enhanced subsidence and an elevated sedimentation rate took place in the Early Triassic

(600 m/Ma), with the peak of the sedimentation rate falling on the deposition of the Clayey "Formation" of the Middle Buntsandstein. A high sedimentation rate also occurred during the deposition of Rotliegend deposits (300 m/Ma for the Drawa Formation and 450 m/Ma for the Noteć Formation). According the modelling of the burial depth, the rocks of the Drawa Formation of the Rotliegend were buried at the maximal depth of 6500 m in the Late Cretaceous.

The principal objectives of **sampling of reservoir horizons** (chapter p. 214, this volume) was to investigate Paleozoic and Triassic strata for the presence of oil and gas fields. The studies comprised: one Rotliegend horizon, three Buntsandstein horizons, one Reed Sandstone (Keuper) horizon and one Lower Jurassic horizon. The studied rocks are characterized by an almost total lack of the reservoir properties as it has been determined by sampling. The inflow of brine with natural gas was observed in the volcanic rocks of the Rotliegend only. The lack of the inflow occurred in the Buntsandstein deposits, which confirms their low reservoir properties. Highly saturated brines, similar to salt lye, occur in the Reed Sandstone, but already 400 m above, in the Lower Jurassic horizon, low-mineralized waters with total mineralization of 6.7 g/dm^3 were observed. The observed hydrochemical threshold may show potentially favourable conditions for the hydrocarbon accumulations in the Reed Sandstone but the possibility of such accumulations in the neighbourhood of the Piła 1/IG 1 well has been negatively assessed based on analysis of hydrodynamical and hydrochemical properties of the sampling horizons.

Hydrogeological studies have shown the presence of **mineralized waters** of therapeutic properties (chapter p. 225, this volume). It is worth noting that the Lower Jurassic water-bearing horizon is a regional aquifer and a main source of healing waters in the Kujawy and Pomeranian regions of Poland. It is a horizon of the porous to porous-crack type with a tight water mirror. Waters of deeper aquifers are highly-mineralized, which has affected significantly their composition. The isotope composition of the waters points to the mixing of Quaternary infiltration waters with older waters, which have infiltrated the aquifer earlier. The healing waters of the Piła 1/ IG 1 borehole are not exploited because of the lack of the technical infrastructure for water extracting and transportation. The physico-chemical properties of the waters indicate that they may be used for the recreation-healing purposes and for farming of thermophilic fish.