Marek JASIONOWSKI, Dominika SIERADZ-BAŃKA

SUMMARY

The Brojce IG 1 borehole is located in north-western Poland. Rocks drilled in the borehole belong to three tectonic (structural) units: the Paleozoic platform (Variscan/sub-Permian), the northern part of the Pomeranian Segment of the Mid-Polish Anticlinorium (Permian–Mesozoic/sub-Cenozoic), and Cenozoic (only Quaternary glacial deposits). No Paleogene and Neogene deposits of the Polish Lowland Basin were found in the Brojce IG 1 borehole. The sediments drilled in the Brojce IG 1 borehole originated within the following sedimentary basins: the Pomeranian Basin (Devonian succesion), the central basin of the Upper Rotliegend, the Polish Zechstein Basin, and the Mesozoic basin of the Polish Lowlands (only Triassic and Lower and Middle Jurassic deposits have been documented).

The purpose of the drilling was to examine the geology of the sub-Permian formations in the place where seismic reflections seen in the brachyanticline base pinch out within levels Z1 and Z2. At this site, the sub-Zechstein formations occur at the shallowest depth within the entire Trzebiatów syncline. The drilling was also aimed at explaining the accumulation of natural gas in the Rotliegend and Carboniferous deposits in the area between Wrzosowo and Gorzysław gas fields. The drilling results showed:

- the absence of reservoir properities in the Main Dolomite and Rotliegend, as well as in the underlying Upper and Middle Devonian;
- no Carboniferous deposits in the southern part of the Trzebiatów syncline;
- the significant dip of the Upper and Middle Devonian deposits (approximately 51°), associated with the proximity of a fault.

Devonian formations belonging to the Givetian and Frasnian stages were found at depths ranging from 3674.5 to 4025.0 metres, according to well-log data. The Brojce IG 1 section is the only one in the West Pomerania in which Middle Devonian and Frasnian deposits have been identified relatively far to the southwest of previously recognized subcrops of this age in the region. The lithological characteristics of the lithostratigraphic units in this section are somewhat atypical compared to their proximal counterparts in the north-eastern and eastern parts of the Western Pomerania area. This is due to the Brojce IG 1 section's more distal position in the Pomeranian sedimentary basin, in the turn of the Givetian and Frasnian. The lithofacies composing the individual Givetian and Early Frasnian lithostratigraphic formations in the borehole are associated with the following environments: open sea, sub-tidal carbonate-marl shelf (Sianowo and Koczała Formations), sub-tidal clastic-carbonate shelf (Wyszebórz Formations), and the shelf basin in the middle Frasnian (Strzeżów Member, belonging to the Człuchów Formation). Petrographic studies of 60 thin sections revealed the presence of claystones and mudstones in places, as well as limestones, marls and, occasionally, sandstones.

According to well-log data, the Rotliegend deposits were drilled at a depth of 3609.5–3674.5 metres. According to the core sample, the top of the Rotliegend was reached at a depth of 3608.4 metres. Its section is bipartite. The lower part (37.5 metres) consists of volcanic rocks (primarily metamorphosed tuffs and extrusive rocks) belonging to the Greaterpoland volcanogenic formation (Odra group, lower Rotliegend), while the upper part (27.5 metres) consists of clastic rocks (sandstones, conglomerates, mudstones and claystones) belonging to the Noteć Formation. The section of volcanic rocks starts with pyroclastic rocks – dacite tuffs – which, towards the top of the Greaterpoland volcanogenic formation, are replaced by rhyolite tuffs, tuff lavas, and, at the very top, by effusive rocks composed of rhyolite. Sedimentological analysis of the upper part of the section showed that the sedimentary succession starts with coarse-grained conglomerates, which were deposited as a result of sheetfloods. Intercalations of sandstone and mudstone have been found among the conglomerates, along with evidence of bioturbation and cementation horizons associated with initial paleosols, as well as traces of flora. Up the section, the contribution of sandstone and mudstone increases, and the conglomerates become more fine-grained. The upper part of the Rotliegend sequence is dominated by sandstones with variable grain sizes, which are interbedded with laminated mudstones. These sandstones represent sheet floods and flash floods, as well as periods of stagnant water in shallow, periodic reservoirs.

Petrographic studies of Rotliegend clastic sediments (26 rock samples, totalling 45 thin sections) revealed a high proportion of conglomerates and mudstones, along with a smaller portion of claystones and mudstones. Studies of the volcanics (15 thin sections) showed the presence of two types of rocks . The first one consists of strongly silicified effusive rhyolites that pass into sintered tuffs down the section (at a depth of 3637.3–3642.0 metres). The second type

consists of rhyolite tuffs and their eluvium (at a depth of 3666.0–3671.0 metres).

According to well-log data, the Zechstein deposits in the Brojce IG 1 borehole were drilled at a depth of 2853.0–3609.5 metres. The Zechstein comprises three carbonate-evaporite cyclothems: PZ1, PZ2 and PZ3; and the terrigenous-evaporite cyclothem PZ4. Within PZ4, three subcyclothems can be distinguished: PZ4a, PZ4b and PZ4c. During the deposition of the carbonates, that initiated the first three cycles, three horizons of carbonates were formed, respectively: the Zechstein Limestone (Ca1), the Main Dolomite (Ca2), and the Platy Dolomite (Ca3) – all three were also drilled in the Brojce IG 1 borehole. The carbonate horizons are separated by evaporites, which are much thicker. These are mainly sulphates (anhydrite) and chlorides (rock salt – halite), with a small portion of potassium salts. Nearly half of the total thickness of the Zechstein in the borehole accounts for the first cyclothem, which measures 366 metres. The Brojce IG 1 Zechstein section lacks a fragment of the PZ2 cyclothem. More specifically, it lacks the A2 Basal Anhydrite. This is caused by tectonic discontinuity. This results in direct contact between the Main Dolomite and the Older Halite (Na2).

The Zechstein Limestone deposits (Ca1), which are approximately 8 metres thick, are pretty untypical compared to other Ca1 sections in the area, namely the micritic lowermost part of the sections is very thin (only 10 cm). The rest of the Ca2 sequence comprises a variety of grainy limestones. Microfacies studies show the dominance of oncoid packstones and the minor presence of grainstones. Few fossils have been found, mainly benthic foraminifers (including encrusting taxa), as well as bivalves, brachiopods and gastropods. Microbial deposits (stromatolites and biolaminites) were found at the top of Ca1. The diagenetic processes include: calcite cementation in some grainstones and in secondary pores (blocky cements), rare anhydrite cementation and anhydrite replacing carbonates.

The first studies of the Kupferschiefer type mineralization, carried out in the Brojce IG 1 borehole, showed that apart from the approximately 60 cm thick Kupferschiefer Shale, it includes the uppermost part of the Rotliegend at its base and the lower part of the Zechstein Limestone at the top. The borehole documentation originally did not describe the ore mineralisation. It was observed that pyrite mineralisation predominated over sphalerite and galena mineralisation (Py>Sph>Gn). A regional analysis of ore mineralisation throughout the Zechstein in Poland identified the Brojce IG 1 borehole as being located within a zone dominated by iron, where pyrite mineralisation predominates over sphalerite and lead mineralisation, with minor copper mineralisation. The results obtained confirm earlier assessments that recognised the Pomeranian zone as being unsuitable for exploring for economically significant Zechstein metal ores. This is due to the low concentrations of ore minerals and the considerable depth of the Zechstein copper-bearing rocks, which exceeds 4000 m in some places.

According to well-log data, the Triassic formations in the Brojce IG 1 borehole occur at a depth interval of 1156.5–2853.5 meters. They belong to the Upper, Middle and Lower Triassic and lithostratigraphically, to Buntsandstein (Baltic, Pomerania, Połczyn and Barwice formations), Muschelkalk and Keuper. They are dominated by various terrigenous facies, with significant contribution of carbonates, and, subordinate contribution of evaporites. 'Lower Rhaetian' and 'Upper Rhaetian' have been not distinguished and the relevant deposits were incorporated into 'Middle Keuper ' and 'Upper Keuper' respectively. This extended the range of the Keuper to the top of the Triassic. The Upper Keuper succession was classified as part of the Wielichowo Beds. The Drawno Beds were incorporated into the Jarkowo Beds. The Zbąszynek, Jarkowo and Drawno Beds were originally unseparated, however, due to the update, only the Zbąszynek and Jarkowo layers remain unseparated. Additionally, the Lower Keuper was designated as the parent unit of the Sulechów Beds. The top of these layers was considered to be the most accurate representation of the chronostratigraphic boundary between the Upper and Middle Triassic. The Lower Triassic boundary was correlated with the top of the Buntsandstein formation, as this provided the best approximation. Smaller units (members) were distinguished within the three formations of Upper and Middle Buntsandstein. They are clearly visible in well-log records and in the few cores taken from them.

According to the well-log data, the Jurassic deposits in the Brojce IG 1 borehole are located at a depth of 88.5–1156.0 m and comprise the Lower and Middle Jurassic only. The upper Middle Jurassic and Upper Jurassic, as well as the Cretaceous, were eroded during the inversion of the Mid-Polish Trough at the turn of the Cretaceous and Paleogene periods. The chronostratigraphic and lithostratigraphic divisions of the Lower Jurassic have been revised in comparison with the original borehole documentation. The Lower Jurassic deposits predominantly consist of sandstones, as well as some claystones and mudstones. They formed in terrestrial (river), deltaic, barrier-lagoon and shallow marine environments. Several formations can be distinguished: Zagaje, Skłoby, Ostrowiec, Łobez, Komorowo, Ciechocinek and Borucice. The Upper Jurassic deposits consist mainly of clayey-silty facies with sandstone intercalations. They often contain marine fauna and were formed primarily in marine environments. The boundary between the Jurassic and the Quaternary deposits in the borehole was moved downwards from a depth of 31.5 metres to 88.5 metres, compared to the original documentation. This was based on the analysis of the lithology, a comparison with nearby shallow cartographic boreholes, and the information on the numerous presence of the freshwater alga Botryococcus in the sample at the depth of 65.0–70.0 m, which contradicts the marine origin of the Callovian.

The uppermost part of the section drilled in the Brojce IG 1 borehole comprises Quaternary glacial deposits, reaching a thickness of 88.5 metres at a depth of between 0.0 and 88.5 metres. As previously stated, after the revision was carried out, it was decided to include in the Quaternary, deposits lying at a depth of 31.0–88.5 m, comprising various grained sands with light grey gravel and plant detritus, which had previously been classified as Jurassic. The Quaternary in the discussed borehole includes sands with gravel in the lower part, probably associated with the Middle Polish Glaciation. Up the section, there are glaciolacustrine silt and sand covered by glacial tills, whose origin is associated with the North Polish Glaciation (Vistula).

Palaeontological studies in the Brojce IG 1 borehole was conducted on a very limited scale. They involved Devonian coral fauna, where fragments of corals from the Tabulata and Rugosa groups were found. A total of 22 samples from Jurassic formations were analysed in palynological studies (megaspores). Of these, only four contained megaspores, which belonged to three groups indicating Sinemurian/Pliensbachian and Toarcian. Micropalaeontological studies of three samples showed a complete absence of microfauna.

Studies of organic matter were performed in Jurassic, Permian and Devonian formations. The organic material found in these rocks is extremely rare. Devonian rocks are characterised by the presence of vitrinite and inertinite due to their relatively high degree of maturity. The Jurassic rocks contained fragments of lignite, which were mainly made up of huminite. The degree of thermal maturity, as determined by measuring the reflectivity of organic matter, varies. Devonian rocks (4236.26–3726.50 m) are characterised by vitrinite reflectance values ranging from 1.22% to 1.86%. The lowest values (1.22% and 1.25%) were obtained only for two of the 26 samples tested; the remaining 24 samples had VRo values ranging from 1.31% to 1.86%. The measured values of vitrinite reflectance generally correspond to the gas window. The results of humic reflectance measurements in Jurassic deposits are in the range of 0.25–0.65% and indicate an immature stage. Analysis of 10 out of 13 samples from the Zechstein (11) and Devonian (2) formations using the Rock-Eval showed that the total organic carbon (TOC) content is very low, ranging from 0.06% to 0.27%. Elevated values were found in only three of the Zechstein samples: 1.10%, 0.77% and 0.72%. While most Zechstein samples are within the oil window, however, taking into account the TOC content and S1 and S2 values, it should be concluded that they do not have the potential to generate hydrocarbons.

Analysis of the bitumens and hydrocarbons found in the Brojce IG 1 borehole was based on core samples taken from stratigraphic units ranging from the Devonian to the Lower Jurassic. In the Jurassic interval (three samples), a generally low organic matter content of up to 0.2% was found. However, one black sandstone sample (from a depth of 409.0 metres) had an organic carbon content of 1.8% and an elevated bitumen content. Due to low thermal maturity (0.2–0.3% Ro), these features are interpreted as the result of hydrocarbon migration. In the Triassic, 11 samples were analysed, revealing a C-org content range of 0.1 to 0.2% and a bitumen content range of 0.003 to 0.013%. Saturated hydrocarbons dominate in shallower samples, while aromatic hydrocarbons dominate in deeper samples. These rocks show no potential for generating hydrocarbons. Local enrichment in organic matter and bitumens was observed in the Zechstein interval (12 samples), for example 1.4% organic carbon and 0.247% bituminous matter in the sample taken at a depth of 3247.0 metres. This may indicate the presence of source rock. Thermal maturity corresponds to the upper oil window. The content of organic carbon and bitumen in Rotliegend (two samples) does not exceed 0.1%, indicating negligible generation and migration potential. The Devonian samples (17 in total) are characterised by low content of organic matter (an average of 0.2%) and bitumen. Despite reaching maturity within the wet gas window, conditions for hydrocarbon generation and migration in the Devonian were unfavourable.

The burial history of the sedimentary cover and the crystalline substrate in the Brojce IG 1 borehole was reconstructed based on a one-dimensional numerical model. The model took into account the main phases of subsidence, uplift, and variations of thermal conditions against the geological history of the region. The model was calibrated using contemporary temperature data and vitrinite reflectance measurements. Heat flux values of 45–55 mW/m² were adopted and the thermal conductivity of the rocks was determined based on their lithological characteristics. Two large stratigraphic gaps were identified in the profile: The Famennian– Gzhelian gap, with erosion of 1200–2500 metres, and the Oxfordian–Pliocene gap, with erosion of 1300–1800 metres. The burial history ranges from the Middle Devonian (Givetian) to the Quaternary, and comprises six phases: three rapid and two slower phases of burial, as well as two phases of uplift – one intense and one moderate. The maximum burial depths of the Devonian, Permian and Lower Triassic strata were 4700, 4100 and 3300 metres, respectively, with temperatures reaching 180°C. As a result, these units reached thermal maturity for hydrocarbon generation. From the youngest Callovian to the Pliocene, moderate tectonic movements continued, leading to the formation of a second large erosion gap.

Analysis of the well-log data revealed an absence of reservoir properties in both the Rotliegend and the Main Dolomite. However, the Lower Jurassic clastic formations reveal good collector properties. These results were confirmed by drill stem tests (see below). No hydrocarbon-saturated formations were found in the borehole.

Analysis of seismic velocity curves made it possible to identify major changes in values associated with lithological variability in stratigraphic sections ranging from the Quaternary to the Middle Devonian. The highest velocity contrast was recorded at a depth of 3,260 metres, at the boundary between Older Halite (Na2), Main Dolomite (Ca2) and Upper Anhydrite (A1g). Significant, but less pronounced, speed contrasts were also observed at the boundaries between the Hettangian (Lower Jurassic), the Keuper (Upper Triassic) and the Muschelkalk (Middle Triassic), the Buntsandstein (Lower Triassic) and the Triassic (Lower Buntsandstein), and the Permian (the uppermost cyclothem of the Zechstein). The identified boundaries of the complexes enabled the most distinct reflections in the seismic profiles to be linked to their corresponding lithostratigraphic units.

The interpretation of 2D seismic section T0870580, located in the Brojce IG 1 borehole area, involved correlating seismic horizons with the tops of the following formations: The Upper, Middle and Lower Jurassic; the Upper, Middle and Lower Triassic; the Upper and Lower Permian; the Upper and Lower Carboniferous; and the Upper and Middle Devonian. Faults were also identified. The seismic data was linked to the Brojce IG 1 borehole before the reflection boundaries were interpreted. When analysing the area's geological structure, it was noted that the T0870580 section contains Cretaceous, Upper Jurassic and Upper and Lower Carboniferous formations, which were not present in the Brojce IG 1 borehole. The horizons associated with these formations (the lower Cretaceous/upper Jurassic boundary and the upper and lower Carboniferous boundaries) were identified and interpreted on a fragment of section T0070582. This was achieved by linking the profile to the Sadlno 1 borehole and then correlating it with section T0870580. Numerous faults in the Permian and older formations were identified in the interpreted section. The geological structure of the Brojce IG 1 borehole area was imaged using 2D seismic data interpretation.

Magnetostratigraphic studies of sediments from Zechstein's Rewal Formation and the Lower Buntsandstein of the Baltic Formation enabled the identification of three magnetozones. This made it possible to correlate them chronostratigraphically with analogous formations from other places in the Polish Lowlands, as well as to link them to the global scale of changes in magnetic polarity. This correlation suggests that the section of the Brojce IG 1 borehole examined was formed during the late Changhsingian to early Olenekian period. The average sedimentation rate for the formations studied was 2.4 cm per 100 years.

Drill stem tests revealed that there were no hydrocarbons present in the Permian in either the Main Dolomite horizon or the Rotliegend horizon. Like the Upper and Middle Devonian formations beneath them, these formations do not exhibit reservoir properties – they are impermeable. On the other hand, Mesozoic formations are characterised by good reservoir properties. This is particularly evident in the case of the Lower Jurassic, from which an average flow rate of 23.6 m^3/h was obtained. All of the Mesozoic horizons that have been tested are characterised by good permeability. In the case of the Upper Buntsandstein (Röt Formation) and the Lower Jurassic formations, they are characterised by high permeability. However, no clear signs of bitumen were found in any of the tested intervals. The hydrochemical profile revealed an obvious increase in mineralisation with depth, as well as an overall rise in chloride concentration at the expense of sulphates and bicarbonates. The low mineralisation of the waters in the Lower Jurassic horizon suggests that this horizon is located in a zone of the intense exchange.