Teresa PODHALAŃSKA, Magdalena SIKORSKA-JAWOROWSKA

SUMMARY

The Polik IG 1 borehole is located in the northern part of the Płock (Płock-Warsaw) Trough on the western slope of the East European Platform. The drilling was completed on February 23, 1987, at a depth of 4584.0 m after reaching the top Cambrian strata. The range of coring was variable. In total, 463.0 m of the borehole section was cored, which is 10.1% of the total borehole length.

The Polik IG 1 borehole section provides a record of successive structural levels, reflecting the geological history of the region. Its beginnings date back to the late Neoproterozoic. The borehole was drilled in the down dropped, marginal part of the East European Platform. The top of the crystalline basement (not reached by this borehole) occurs at a depth of 5000 m and descends southwestwards, like in the other regions of the marginal part of the platform.

The development of the Palaeozoic sedimentary cover in the western part of the East European Platform was preceded by a period of long-term erosion of the crystalline basement. In the Polik IG 1 borehole, the oldest rocks are ~Series 3 (Middle Cambrian) deposits. The prevalence of erosion over sedimentation in the Furongian (Late Cambrian) resulted in the lack of uppermost Middle and Upper Cambrian deposits in this part of the sedimentary basin.

The Polik IG 1 is among few boreholes in which Ordovician deposits have been encountered in the basement of the Warsaw Trough. In Silurian times, the moving front of the Caledonian collision was the main factor controlling deposition in the basin. The Lower Palaeozoic section is reduced in this borehole. Much of Ludlow and Pridoli deposits are missing due to post-Silurian erosion. The Devonian and Carboniferous are also absent. The Permian starts with thin Rotliegend deposits.

The development of Permian-Mesozoic sedimentary formations in the Polish Lowlands was associated with the evolution of the epicontinental sedimentary basin in this region. Terrigenous clastic sedimentation prevailed over most of Triassic times, in the Early and Middle Jurassic, and during the Early Cretaceous. The Permian-Mesozoic stage of the basin evolution was finally completed during the Danian sedimentation.

The oldest deposits drilled in the Polik IG 1 borehole are Middle Cambrian mudstones, sandstones and heteroliths occurring (driller's depth) in the interval between 4507.0 m (4505.0 m logger's depth) and 4584.0 m.

The Ordovician deposits were encountered at a depth of 4438.0–4505.0 m (from well logs) and their thickness is 67.0 m. The Ordovician section was partly cored. It is represented by the standard global stages: Darriwilian, Sandbian, Katian and Hirnantian. They correspond, according to the classic British division, to the sequence from the Llanwirn through the Upper Ashgill.

The Ordovician of the Polik IG 1 borehole is represented by three lithostratigraphic units (from the base upward): Polik Limestone Formation, Sasino Claystone Formation, and Prabuty Marl and Claystone Formation.

The Silurian deposits, predominantly claystones, mudstones and siltstones, lie horizontally or at a low angle of a few degrees; no significant tectonic deformation has been observed, except for infrequent slickensides. Silurian deposits of similar lithologies have been found in the nearby boreholes of Bodzanów IG 1, Kamionki IG 3, Bieżuń 1 and Szczawno 1. The Silurian deposits are overlain, with a large stratigraphic gap, by Permian deposits of the Rotliegend. Like the other Lower Palaeozoic rocks of this region, they were deposited in the distal part of the Baltic-Podlasie-Lublin Basin stretching along the western slope of Baltica from the late Proterozoic onward. The predominant lithologies are mudstones, claystones and siltstones, which are calcareous at many intervals. There are also intercalations and lenses of limestones and thin interbeds of pyroclastic deposits – tuffites. The Ludlow deposits contain abundant muscovite. The dominant rock type is mudstone, which is a mixture of clay and silt fractions in different proportions (the rock is called claystone in the final borehole report). The presence of siltstones and calcareous siltstones („mudstones" according to the final borehole report) is characteristic of the Kociewie Formation of the Upper Wenlock and Ludlow.

The total thickness of the lower Silurian, Llandovery and Wenlock is 258.0 m. It increases in the Ludlow, and, along with the Gorstian and lowermost Ludfordian, it reaches 414.0 m. The original thickness of the Silurian was much greater; erosional processes removed much of the Ludlow and the whole of the Pridoli.

In the Polik IG 1 and Kamionki IG 3 boreholes, evaporitic deposits of the PZ1 cyclothem are underlain by red clastic, coarse-grained (psammite fraction) rocks assigned to the Upper Rotliegend (Warta Group).

These boreholes were drilled in the zone of contact of the pre-Vendian and Palaeozoic platforms. The zone also coincides with the general limit of Rotliegend deposits in the Polish Basin. The Rotliegend deposits were encountered in the Polik IG 1 borehole at a depth of 3766,0–3760,0 m. These are loose gravels with the most frequent diameter of 5–7 cm, and the maximum of 10 cm. Most of them are subrounded fragments of grey quartzite sandstones. Sporadic are fragments of dolomites, granitoids and lapilla tuffs.

The stratigraphy and lithology of the Zechstein section is based on both drill core and well log data. There is a shift between driller's and logger's depths along the section. Driller's depths are greater by 9.0 m relative to well logs. The shift is observed at the Basal Anhydrite (A2)/Main Dolomite (Ca2) boundary, but it is highly probable that it follows the entire Zechstein section. The Zechstein section of the Polik IG1 borehole is located palaeogeographicaly within the broadly defined eastern part of the Zechstein Basin, in the East European Craton. This zone was characterised by low subsidence rates compensated by deposition. The Zechstein section of the Polik IG1 borehole is not disturbed tectonically and is composed of three carbonate-evaporitic cyclothems: PZ1, PZ2 and PZ3, and the terrigenous-evaporitic cyclothem PZ4a, topped by the terrigenous series PZt corresponding to the upper stratigraphic units of the PZ4 cyclothem in the central part of the evaporite basin.

The Triassic deposits occur within the 2401.0–3220.5 m interval (logger's depth) and were poorly cored: 10% in the Lower Triassic, 9% in the Middle Triassic, and 6% in the Upper Triassic. The Buntsandstein is 486 m thick and is characterised by the presence of sandstones and claystones and the stratigraphical gap at the boundary of the Middle and Upper Buntsandstein. The lithology is similar to that observed in other boreholes of this region, *i.e.* the Sierpc–Żuromin area, and shows particular similarity to the succession from the Sierpc 2 borehole. All lithostratigraphic formations known from the Triassic of north-eastern Poland have been identified in Polik IG 1.

In the Polik IG 1 borehole, the thickness of the Muschelkalk is 77 m and the thickness of the Lower and Middle Keuper (excluding the Nidzica Beds) is 137 m. This indicates that the figures do not deviate from the general thickness pattern of these deposits in the northern part of the Płock-Warsaw Trough. Sedimentation of the Muschelkalk occurred in a relatively uniform bathymetric conditions on a stable basement. It allowed the formation of an equally thick sedimentary cover in the region. The Lower and Middle Muschelkalk are represented by a homogeneous calcareous-dolomitic facies. The Middle Muschelkalk deposits reveal the presence of sulphide intercalations. In the Upper Muschelkalk, the characteristic feature is a high proportion of clay-marly rocks. At the end of Muschelkalk deposition, the sedimentary basin transformed into an intracontinental Keuper basin with brackish deposition. The uppermost Triassic is subdivided into two lithological complexes: the Nidzica Beds and the so-called *Trileites* Beds (= Bartoszyce Beds), typical of the whole Płock-Warsaw Trough.

The Lower Jurassic is 387.0 m thick in the Polik IG 1 borehole. Its lower boundary is established based on well logs at a depth of 2401.0 m, and its top at 2014.0 m. It overlies directly the Rhaetian clay-muddy deposits, and is overlain by the upper Middle Jurassic (uppermost Upper Bajocian or Lower Bathonian). The stratigraphic gap at the top spans the Aalenian and almost the whole of Bajocian. The following formations have been distinguished in the section: Zagaje Formation (Hettangian –?Lower Sinemurian), Ostrowiec Formation (Sinemurian), Gielniów Formation (Lower Pliensbachian), Drzewica Formation (Upper Pliensbachian), Ciechocinek Formation (Lower Toarcian) and Borucice Formation (Upper Toarcian).

The Upper Jurassic section has a thickness of 493.0 m and occurs at a depth of 1397.5–1890.5 m. It continuously overlies the Callovian deposits (Middle Jurassic) and passes upward continuously into a thin (8.0 m) series of Lower Berriasian (Lower Cretaceous) deposits, which in turn are overlain by the Upper Valanginian claystones. The sharp boundary between these deposits marks a stratigraphical gap spanning the upper Berriasian.

In the Polik IG 1 borehole, the Upper Jurassic succession consists of all its stages: Oxfordian, Kimmeridgian and Tithonian. A number of informal lithostratigraphic units have been distinguished within the stages: Spongy Limestone Formation, Oolitic Formation, Calcareous-Marly-Coquina Formation, Pałuki Formation, and Kcynia Formation with Corbula Limestone Member.

Analysis of micropalaeontological associations, mainly foraminifera documenting the presence of variable foraminiferal assemblages, is presented for the Middle and Upper Jurassic.

The Cretaceous has a thickness of 1141.0 m and occurs at a depth of 256.5–1397.5 m. Both the Upper (951.0 m) and Lower (190.0 m) Cretaceous are present. The lowermost Lower Cretaceous is missing in this borehole. In this region, the main Early Cretaceous marine transgression took place during the Late Valanginian, expanding in the Hauterivian. Initially, fine-grained siliciclastic deposits were accumulated in a shallow epicontinental basin. Later on, from the Late Albian onward, marls, limestones and opokas (the last ones predominantly in the Santonian) were deposited as a result of the great Late Cretaceous marine transgression. At the Cretaceous/Paleogene transition, there was a restructuring of the entire Mesozoic basin. In the Lower Palaeocene (Danian) basin, gaizes and marls were deposited under shallow-marine conditions.

Results of foraminifera-based micropalaeontological and biostratigraphical studies are presented for the Cretaceous. The relatively diverse and abundant microfaunal evidence allows documenting the Cenomanian, Upper Maastrichtian and Danian deposits. The characteristics of the diverse and very well-preserved assemblage of Upper Cretaceous and Palaeocene bryozoans is also given.

Above, there are the Oligocene clays and muds; the presence of the Eocene is not certain. It cannot be precluded that the Eocene is represented by the lowermost deposits

described in the Polik IG 1 borehole as belonging to the Lower Oligocene, and occurring in the interval of 181.0–212.5 m b.g.l. The Quaternary deposits are represented by sands, gravels and glacial tills.

The present volume also provides results of petrographic studies of Cambrian, Permian (Rotliegend and Zechstein), Triassic, Jurassic and Cretaceous deposits.

Detailed organic matter investigations were carried out to determine the hydrocarbon potential of deposits.

Microscopic studies show that the Lower Palaeozoic deposits are not prospective for hydrocarbon generation despite high contents of organic matter in the Caradocian and basal Wenlock strata. Thermal maturity of the Cambrian, Ordovician and Silurian rocks corresponds to the overmature phase during which destruction of hydrocarbons took place. Dry gas may have been generated only in the top Ludlow strata. The upper Permian and Middle Triassic carbonates are in the main phase of oil generation, however they are too poor in organic matter to be considered even poor source rocks for oil generation. The Lower and Middle Jurassic clastics can be determined good source rocks for liquid hydrocarbon generation.

Geochemical studies of organic matter show that the Ordovician (Katian–Sandbian, Hirnantian–upper Katian) deposits are good source rocks for hydrocarbon generation; however they have a small thickness. An increased amount of organic carbon is also observed in the Lower Cretaceous sandstone-claystone series, allowing including these deposits into „good" source rocks. Along the entire borehole section, the rocks contain low or trace amounts of labile components. The bitumens typically contain high proportions of resins and asphaltenes. Only a small percentage of the bitumens show a high proportion of hydrocarbons.

Geochemical analyses of organic matter in the lower Palaeozoic deposits, carried out using the Rock-Eval, SRA and LECO methods, have confirmed considerable variability of the individual stratigraphic intervals in terms of its maturity. The Middle Cambrian rocks do not show any maturity. The Sasino Formation claystones (Caradocian, Lower Katian–Sandbian) are source rocks of depleted hydrocarbon potential. Gamma ray logging and the CARBOLOG method suggest the occurrence of a few-metre thick bed (equivalent of the ?Jantar (mudstone) formation) with moderate TOC values near the base of the Llandovery. Results of the geochemical studies of Wenlock rocks allow discriminating between the basal part, which is rich in organic matter, and the top part, which is poor. The basal strata of the Wenlock are source rocks revealing depleted hydrocarbon potential, while its top strata cannot be considered source rocks. The Ludlow rocks, which are the continuation of upper Wenlock sedimentation, are not source rocks, either. The high variability and scatter of the T_{max} parameter throughout the whole Palaeozoic section do not allow for reliable determination of the degree of thermal alteration of organic matter. The values of HI and OI parameters also do not allow for the correct identification of kerogen type. Both these limitations result from the very high thermal maturity of organic matter.

To determine the basic physical and chemical parameters of rocks, core samples were analysed for specific and bulk density, effective and total porosity, carbonate content, and permeability. The analyses were performed on 146 core samples acquired from sedimentary rocks of various stratigraphic units, including Cambrian, Ordovician, Silurian, Permian, Triassic, Jurassic and Cretaceous.

One-dimensional modelling of thermal history and burial conditions was performed to characterise the stages of basin subsidence, thermal events and subsidence phases. The bipartition of the thermal maturity profile between the Permo-Mesozoic and lower Palaeozoic deposits, as well as the lack of Devonian and Carboniferous deposits due to erosion, resulted in difficulties in the determination of thermal history along the borehole section. The stage of erosion was of key importance in the formation of present-day maturity of the lower Palaeozoic deposits. The suggested most reliable variant is erosion of Ludlow (in part), Pridoli, Devonian and Carboniferous deposits at the level of 2120 m and increased heat flow in the Carboniferous up to 130 Mw/m^2. This model is not unambiguous and there are alternative variants.

Results of geophysical studies in the Polik IG 1 borehole are an essential element in the exploration of the sedimentary cover in the study area. Interpretational work has provided data on the entire borehole section in terms of basic petrophysical parameters, *i.e.* porosity, density, thermal conductivity, and acoustic wave velocity. The thermal field has been fully examined, determining not only the value of subsurface heat flow and stabilized temperature, but also calculating the amount of palaeoclimatic effect that is well visible in the borehole. The level of detail of the interpretation work, as well as the research goal of acquiring the basic knowledge on the simplified lithological-petrophysical model of rocks occurring in the borehole section, allows for treating the results as a preliminary author's variant of interpretational results.

Seismometric measurements, performed in the borehole in 1987, covered average seismic velocities and acoustic profiling. The graphs of smoothed, interval and complex velocities, compiled based on these measurements, reflect the complex geological profile of the borehole. The Upper Cretaceous deposits are characterised by a few gradually increasing values of complex velocity from 2150 to 3550 m/s. The first drop in velocity is observed at the Upper Cretaceous and Lower Cretaceous boundary. The greatest velocity contrast, observed in the whole section, resulted in the distinguishing of the Oxfordian series in the Upper Jurassic deposits, with the velocity of 4250 m/s. Below the Upper Jurassic a uniform velocity packet of 3550–3675 m/s is observed, corresponding to the Middle and Lower Jurassic and Upper Triassic deposits. Beneath, another velocity gradient change discriminates the Middle Triassic and Middle Buntsandstein deposits with the average value of 4150 m/s. A lower average complex velocity of 3900 m/s defines the Lower Buntsandstein strata. The range of changes in the gradual increase of the velocity parameter from 3900 to 5300 m/s characterises the Zechstein deposits. The last

complex is associated with the interval of Silurian, Ordovician and ~Series 3 (Middle Cambrian) deposits and is featured by the values of 4800–5050 m/s.

The acquired results down to a depth of 4530 m underline the differences in the lithologies of the individual strata. Taken into account for the velocity distributions, they facilitate correlating and assigning the reflection seismic horizons on cross-sections to the individual Permo-Mesozoic and Upper Palaeozoic units.

Interpretation of seismic surveys in the surroundings of the Polik IG 1 borehole was carried out. In the immediate vicinity of the borehole, there are only two 2D seismic lines run in the 1980s and reinterpreted in 2013. The Polik IG 1 borehole has allowed stratigraphic identification of the following seismic horizons: top Cambrian, Ordovician, base and top Zechstein, Triassic, Middle Jurassic, Upper Jurassic and Lower Cretaceous.

Hydrogeological tests of the lower Palaeozoic deposits showed lack of significant brine inflow, but only its slight seepage. No flow and no hydrocarbon shows were observed in the Rotliegend deposits. The Triassic deposits exhibit moderate reservoir properties, while the Cretaceous deposits – good properties. The tests revealed no natural gas shows. Hydrochemical and hydrodynamic indices demonstrate that the Mesozoic deposits are located in a zone of relatively unfavourable conditions for hydrocarbon accumulation. The Palaeozoic deposits are characterised by very poor reservoir properties.

Translated by Krzysztof Leszczyński