Teresa PODHALAŃSKA, Magdalena SIKORSKA-JAWOROWSKA

SUMMARY

The Lębork IG 1 borehole is located in northern Poland, West Pomeranian Voivodeship, in a geological unit known as the Łeba Elevation which is part of the Baltic Depression, a structural-tectonic unit of the East European Craton. The Baltic Depression is bounded from the west by faults of the Teisseyre-Törnquist Zone (TTZ), from the north by the Baltic Shield, and from the southeast by the Mazury-Podlasie Elevation.

Drilling operations started in 1959 and were completed in 1961. Because of the relatively high core recovery, the Lębork IG 1 borehole provided important new information on the Palaeozoic formations, in particular on the previously poorly explored Zechstein succession.

The drilling reached a depth of 3310.0 m. The sedimentary cover is represented by the following units: Ordovician, Silurian, Permian, Triassic, Cretaceous, Paleogene, Neogene and Quaternary. In the Lębork IG 1 borehole, like in other areas of the Baltic depression, the cover rests upon the crystalline basement drilled in several boreholes, e.g. Żarnowiec IG 1, Łeba 8, Kościerzyna IG 1 and Słupsk IG 1. The depth to the basement is variable and increases towards the southwest. In the Lębork IG 1 borehole, the basement has not been reached, but it is assumed that it can occur at a depth of approx. 3800–4000 m. The sedimentary cover is undeformed in this borehole and its thickness is 3310,0 m.

The sedimentary rocks covering the basement are Ediacaran through Quaternary in age and were deposited in two sedimentary basins. The first of them, the Baltic Basin, includes Ediacaran through Silurian deposits. No Devonian and Carboniferous deposits have been preserved: they were eroded away during uplifting movements at the Early/ Middle Devonian transition and in the Carboniferous. The thickness of the Lower Paleozoic succession is variable and increases to the south-west. The other sedimentary basin, the Polish Basin, includes Permian through Cretaceous deposits. The thickness of the Permian–Mesozoic sedimentary cover is smaller and does not exceed 900 m. Fragmentarily preserved Paleogene and Neogene deposits are overlain by Quaternary sediments of the last glaciations.

No borehole summary report is available for the Lębork IG 1 borehole, so the stratigraphic-lithologic column, technical drilling information, and the results of research carried out early after well completion are fragmentary.

The oldest system encountered in the Lębork IG 1 is the Ordovician. Its top occurs at a depth of 3273.0 m; the base has not been reached and the drilling was stopped at a depth of 3310.0 m within Darriwilian (Llanvirn) deposits. The small thickness of the Ordovician sediments indicates that subsidence was not compensated by sedimentation in this area. Ordovician deposits drilled in this borehole do not differ substantially from those observed in other borehole sections in the Polish Lowlands. They are represented by carbonate and marly facies. Only in the Sandbian and lower Katian (Caradoc), fine-grained siliciclastic rocks predominate: siltstones and claystones. Such lithology is characteristic of the Scanian confacies in the Baltic palaeobasin (Jaanusson, 1976). This confacies occupied a distal area of the East European Craton, which was subject to strong downward movements. These were the innermost parts of the basin which suffered a hindered supply of sediments.

Silurian rocks were drilled at a depth interval of 1027.6–3273.0 m, with a thickness of 2245.4 m. They are almost fully cored. The flat-lying Silurian deposits are composed mostly of fine-clastic rock: siltstones and claystones, and clayey and calcareous siltstones. In the upper Silurian, there are numerous siltstone interbeds. Throughout the entire section there are also carbonate interlayers and calcareous concretions, as well as intercalations of rocks of pyroclastic origin. The Silurian is represented by all its series: Llandovery, Wenlock, Ludlow and Pridoli, including most of its stages. The Silurian stratigraphy is based on graptolites which are frequent especially in the lower part of the section. They were the basis for the identification of a number of Silurian graptolite zones.

Verification is necessary as regards the Pridoli/Ludlow boundary, because its interpretations are different depending on the source material. Studies of Silurian deposits, recently carried out on the East European Platform, also confirm the necessity of verification of this boundary.

In the Lębork IG 1 borehole, a sedimentological analysis of the Upper Ordovician deposits (Sasino Claystone Formation and Prabuty Marl and Claystone Formation) and the lower Silurian deposits (Llandowery, Wenlock) (Pasłęk

Claystone Formation, Pelplin Claystone Formation, Kociewie Claystone and Siltstone Formation – lower section) has been performed. The study results show that these deposits accumulated in a very quiet environment of pelagic deposition from suspension within a hypoxic deep-marine basin. The first finding of sedimentary structures suggesting a periodic activity of sea bottom currents and distal turbidity currents was made in the Pasłęk Claystone Formation. A stronger periodic activity of sea currents – initially bottom currents and finally low-density turbidity currents, is inferred for the upper section of the Pelplin Claystone Formation. The greatest activity of the sea currents is recorded in the lower section of the Kociewie Claystone and Siltstone Formation. The whole section reveals a relationship between the amount of organic matter preserved in the sediment and the sediment colour (the darker colour the greater amount of TOC) and activity of sea bottom and turbidity currents in the sedimentary basin, causing periodic better oxygenation of bottom waters and, in consequence, resulting in a lower content of organic matter in the sediment.

A palynological study performed for the Silurian section shows a clear quantitative and qualitative variability in the deposits. Based on the frequency and ranges of major genera and species, seven characteristic acritarch assemblages have been identified. They exhibit a mixed provenance; the genera and species are known from both Baltica and Gondwana. The nature of the acritarch assemblages does not give rise to unambiguous determination of their palaeogeographic provenance.

This Volume also presents the biostratigraphy of uppermost Silurian deposits and their correlation within the Baltic Basin, based on ostracods.

The Silurian succession is overlain by Permian deposits represented by the Rotliegend facies.

The Rotliegend was encountered in an interval of 994.0–1027.6 m. Its lower part is composed of conglomerates showing features of fluvial sediments, and the remaining section consists of poorly concise fine-grained sandstones.

The Zechstein succession was drilled at a depth of 756.4–994.0 m. The Lębork IG 1 borehole is located on the northern flank of the Zechstein basin, in the western part of the vast Baltic Embayment. To the north there extended a desert area of the South Baltic land. This part of the Zechstein Basin was located within the East European Craton; it was an area of lowest subsidence rate in the late Permian, completely compensated by sedimentation.

The Zechstein section of the Lębork IG 1 is not disturbed tectonically and is composed of two carbonate-evaporite cyclothems: PZ1 and PZ3, evaporite cyclothem PZ2, and the Top Terrigenous Series PZt corresponding to cyclothem PZ4.

Development of the Oldest Halite (cyclothem PZ1) was twofold. It results from a transformation of an open saline basin (stage I) into a more isolated salt lagoon whose marginal parts were probably dominated by saline conditions (stage II). A change in the sedimentary conditions within the continuous succession resulted in the replacement of deeper-water facies by shallow-water ones containing higher amounts of terrigenous material. A similar facies variability and two-stage development are also manifested by the Oldest Halite in the Gulf of Puck.

Detailed petrographic study of the Zechstein Limestone (Ca1) and Platy Dolomite (Ca3) show that the Ca1 deposits are represented by the dolomite facies, and the Ca3 sediments by the limestone, dolomite-limestone and carbonate-marly facies. Deposition of the Ca1 sediments in the Lębork IG 1 borehole took place in a shallow basinal zone. The microfacies succession of these sediments indicates an upward-increasing hydrodynamic regime. Local enrichment of microbial components may indicate small periodic changes in salinity, enabling the growth of algae and cyanobacteria. The Ca3 carbonate sediments represent a condensed section with a relatively complete sequence of sediments typical of the marginal zone of the basin. The granular-organodetrital and muddy-microbial microlithofacies represent sedimentation in a shallow-water zone, accompanied by small hydrodynamic changes, not completely isolated from the influence of an open basin.

Most of the Lower Anhydrite section is represented by massive anhydrite with common pseudomorphs after selenite crystals. The Upper Anhydrite unit starts with anhydrite breccia overlain by nodular anhydrites with interbeds of massive veined anhydrites. Above, there are massive anhydrites, usually recrystallized, in places – especially in the uppermost part of this facies – with remarkable pseudomorphs after selenite crystals. The characteristic feature is the absence of nodular anhydrites in this part of the section.

Triassic deposits in the Lębork IG 1 borehole were identified by Anna Szyperko-Śliwczyńska at a depth of 427.0–763.0 m (original description of the borehole section). In this volume, the base of the Triassic is drawn at a depth of 756.4 m. The Triassic deposits were cored continuously with a few breaks in the upper part of the section. Triassic age of these deposits was interpreted based mainly on lithological evidence and regional correlations, and determined as Lower Triassic. The Lębork IG 1 borehole is located in the northern edge of the Triassic sedimentary basin of Poland. The lack of Middle and Upper Triassic is due to erosion and non-deposition. Precise identification of the sedimentary gap is not possible at this stage of research. On account of lack of biostratigraphic data, the chronostratigraphic boundaries should be treated as conventional, drawn at the nearest lithostratigraphic boundaries based on Wagner (2008).

Cretaceous rocks were drilled at a depth of 143.0–429.5 m.

The Upper Cretaceous succession in the Lębork IG 1 borehole is 286.5 m thick. Most of it is represented by siliciclastic deposits spanning the time range from the Cenomanian up through the Upper Campanian. These are predominantly sandstones and quartz-glauconitic sands typical of the Łeba Elevation area. In the Turonian–Lower Coniacian, claystones and mudstones predominate. Much of the Upper Campanian section is composed of gaizes.

From the Cretaceous rocks, 79 samples were collected for microfaunal examinations. A relatively numerous and

diversified foraminiferal microfauna has allowed documenting Cenomanian and Turonian stages.

Paleogene and Neogene sediments were drilled at a depth of 71.5–143.0 m. They are overlain by Quaternary deposits represented by variously grained sands and glacial tills.

Micropalaeontological investigations of samples from late Paleogene deposits shows that foraminifers are represented exclusively by benthic species and the associations are typical of the Lower Oligocene Lower Mosina Formation.

A wide range of organic matter research shows that the lower Paleozoic succession layers are enriched in organic matter. The highest concentrations (1.1–6.2%) are found in single clayey horizons of the Upper Ordovician and Silurian (Llandovery, Wenlock) sections. The main organic components are fragments of graptolites and less frequent solid bitumens.

Individual samples representing the Upper Permian and Lower Triassic deposits indicate a low content (0.3–0.4%) of organic matter (mainly humus) in the early stage of oil generation (0.5% R_O), and the maximum palaeotemperatures during the diagenesis of the order of 50–60°C.

In the Ordovician and Silurian section, four levels enriched in dispersed organic matter (TOC > 1 wt.%) were identified in the Caradoc, lower Ashgill, Llandovery and Wenlock deposits. Organic matter shows geochemical properties of kerogen type III and IV. The profile of thermal maturity of organic matter reflects the generation phases from the „oil-window" (Pridoli and Ludlow deposits) to the „gas window" (Ludlow, Wenlock and Llandovery deposits), and/or overmature phases (Llandovery, Ashgill, Caradoc and Llanvirn deposits). Rocks which are not enriched in organic matter cannot be considered effective source rocks because their hydrocarbon potential has been exhausted in the past.

The Upper Cretaceous mudstones and claystones can be considered „good" source rocks, but the remaining Permian–Mesozoic formations represent „poor" source rocks for hydrocarbon generation.

Thermal maturity of the lower Palaeozoic complex increases significantly from the main phase of oil generation at the top of the Ludlow to the overmature phase in the Llandovery and Ordovician formations, with the reflection coefficient ranging from 0.8% to 2.3%. These data indicate a maximum diagenetic palaeotemperature of these rocks varying from 80 (at the top) to over 200°C (at the base).

1D thermal history modelling was performed for the section, which shows that the hydrocarbon generation zone comprises the Lower Triassic through Silurian (Wenlock) deposits. The Ordovician and Llandovery deposits fall in the overmature zone. Gas generation from these deposits started likely during the Late Cretaceous. The Ludlow and Pridoli deposits are in the oil generation window. The onset of oil generation for these rocks is the end of the Silurian and the beginning of the Devonian.

Geophysical well-log data have been processed using the Techlog program. They were digitized and summarized. The effect of standardizing and combining individual gamma and neutron-gamma ray log runs, as well as improved and supplemented composite resistivity and caliper logs, is presented in a graphical form. The measurement quality is discussed; unfortunately, the quality is not satisfactory especially in the case of natural gamma ray log. nevertheless, an attempt was made to perform a simplified interpretation mainly in terms of clay content. Finally, a brief description of thermal conditions in the borehole and the mineralization of formation waters are provided. These analyses can be used for regional geothermal or hydrogeochemical studies, and the processed composite curves can serve for correlations with the nearby boreholes.

The average seismic velocity measurements in the Lębork IG 1 borehole suggest that the observed changes are related to stratigraphic-lithological complexes identified in the geological section. The prominent boundaries of velocity contrasts allow distinguishing five major complexes: 1 – Cenozoic, 2 – Cretaceous and upper part of the Triassic with the average velocity lower than within the overburden, followed by the complexes of systematically increasing velocities, i.e. 3 – Lower Triassic with the topmost Zechstein layers, 4 – Zechstein, 5 – Silurian, including the lower series of lower average velocities.

Five reservoir horizons were tested in the borehole: one Silurian horizon, one Lower Permian horizon (including the topmost Silurian), two Upper Permian horizons, and one Lower Triassic horizon. Two formation tests yielded water inflows, however three horizons were characterised by a complete lack of inflow. Reservoir properties of two horizons: (1) Lower Permian including topmost Silurian and (2) Lower Triassic are considered moderate. These deposits are reservoirs of chloride-sodium and iodide water. Water present in both studied horizons is highly metamorphosed. Some hydrochemical indices demonstrate a small inflow of infiltration water.

Translated by Krzysztof Leszczyński