

SUMMARY

The Kętrzyn IG 1 and Kętrzyn IG 2 boreholes are located in northern Poland, within the Baltic Depression, which is part of the East European Platform. The boreholes were drilled in the area of wedging out of Paleozoic deposits at the boundary between the Baltic Depression and the Mazury-Suwałki Elevation.

The scope of studies, presented in the drilling project, was a continuation to explore the geological structure of the Mazury-Suwałki Elevation in terms of prospect for oil and gas. The main objective of the Kętrzyn IG 1 drilling and, located 24 km to the southeast, Kętrzyn IG 2 drilling was a further exploration of the lower Palaeozoic succession and facies changes in the northern margin of the Mazury-Suwałki Elevation on account of the possibility of discovery of hydrocarbon deposits in this area.

Another objective of the drilling operations was to obtain data on the lithology of younger deposits in northern Poland, particularly the extent of Zechstein deposits: saline facies, bituminous shales (formerly "Mansfeld shales"), as well as Lower Triassic deposits. The next important objective was to explore the crystalline basement in search of iron and non-ferrous metal ores in the eastern part of the Mazury-Suwałki Elevation.

The Kętrzyn IG 1 borehole was located on a regional seismic section line Wejsuny-Bartoszyce-state border, run by the Geophysical Exploration Company in 1961. The drilling operations commenced in July 1964 and were completed in February 1965, followed by formation tests. The borehole was abandoned in October 1966. Drilling operations of the Kętrzyn IG 2 borehole were launched in June 1963, and completed in January 1964. After formation tests, the borehole was abandoned in May 1964.

In the Kętrzyn IG 1, the top of the crystalline basement is at a depth of 1840 m. The crystalline rocks are overlain by Cambrian, Ordovician, Silurian, Permian, Triassic, Jurassic, Cretaceous, Palaeogene and Quaternary rocks. During drilling, distinct oil and gas shows were reported in the lowermost Silurian and Ordovician limestones. The lower Silurian limestones yielded non-economic oil flow during drilling.

In the Kętrzyn IG 2 borehole, the crystalline basement was drilled at a depth of 1532.9 m, and was overlain by Cambrian rocks followed by Permian, Triassic, Jurassic,

Cretaceous, Palaeogene and Neogene, and Quaternary formations. It should be emphasized that the stratigraphic column of the Kętrzyn IG 2 is incomplete due to the lack of Ordovician and Silurian deposits and the incomplete Lower Permian section.

The present study provides full information and research results from these two boreholes.

The research includes, among others, new palaeontological, stratigraphic, sedimentological and petrographic studies of some intervals, supported by organic matter investigations.

Formation tests and geophysical borehole measurements were the basis for extensive studies of deposition rate and modelling of thermal and burial history.

The boundaries of chronostratigraphic units in non-cored intervals or lacking biostratigraphic evidence are approximate. They have been drawn by the authors with a varying degree of accuracy, based on various criteria, including comparison with other boreholes and knowledge of the regional development and evolution of the sedimentary basin.

The crystalline basement was encountered in both boreholes. Its igneous rocks belong to the East European Precambrian Platform. Coarse-grained anorthosites, representing plagioclase cumulates and found in the Kętrzyn IG 1, are the major component of the Kętrzyn alkaline intrusion. Along with the coarse-grained porphyric monzonites from the Kętrzyn IG 2 borehole, they belong to the vast Mazury complex stretching from eastern Pomerania and Warmia to the Veisiejai complex in south-western Lithuania. Both types of rocks represent members of the plutonic anorthosite-mangerite-charnockite-granite (AMCG) series. Crystallization age of the Mazury complex rocks, covering the range from 1.55 to 1.49 Ba, corresponds to the early Mesoproterozoic. In terms of geochemical classification, the transition rocks represent the shoshonite series: a ferruginous and metalumina variety. High concentrations of alkalis, zirconium, yttrium and rare earth elements make them similar to intraplate A-type granites.

The specific geochemical nature of these intrusive rocks, the presence of the Svecofennian crust metamorphosed 250–300 million years ago, and primarily the lack of any signs of penetrative foliation indicate an anorogenic

origin of the Mesoproterozoic magmatism that correlates well with the intracratonic intrusions of Rapakivi granites and gabbroid cumulates widespread in central Fennoscandia.

The lowermost part of the sedimentary cover in the Kętrzyn IG 1 and Kętrzyn IG 2 boreholes is represented by Lower Cambrian strata corresponding approximately to the Terreneuvian and the Series 2. In the Kętrzyn IG 1 borehole, the Cambrian strata occur in the interval of 1613.0–1840.0 m (driller's depth), reaching a thickness of 227.0 m. The Lower and Middle Cambrian deposits, despite the long core interval, yielded very little core. The Cambrian section is composed of sandstones and subordinate mudstones with very poor faunal evidence. The packages of interbedded fine-grained sandstones and mudstones contain very numerous trace fossils of very monotonous ichnotaxonomic and ethological composition.

In the Kętrzyn IG 2 borehole, the Cambrian occurs at a depth of 1448.6–1532.9 m (driller's depth) and is represented only by the Lower Cambrian composed of sandstones, in its lower part, and by claystones and siltstones upper in the section. Clay-rich rocks contain small fossils of brachiopods. The Cambrian stratigraphy has been established based on correlations with the nearby boreholes. Petrological studies show the presence of different types of sandstones: arkose, arenite and quartz wacke, often synsedimentarily deformed, with abundant bioturbation, as well as claystones and silty claystones. These rocks have not undergone significant diagenetic processes.

The Ordovician was encountered only in the Kętrzyn IG 1 borehole. In the area of Kętrzyn IG 2, Ordovician deposits along with younger rocks were removed by erosion before the Permian. In the Kętrzyn IG 1 borehole, the Ordovician section is 66.5 m thick and occurs at a depth of 1540.5–1607.0 m (logger's depth; driller's depth: 1544.5–1613.0 m (68.5 m)). In the cored interval, the global standard Ordovician stratigraphic units have been distinguished, including the Floian through the Hirnantian, corresponding according to the British division to the Arenigian through the Ashgill.

Also the Silurian occurs only in the Kętrzyn IG 1 borehole. The stratigraphic section is highly reduced and represented only by the two Series: Llandovery and Wenlock. The Ludlow, Pridoli and younger Palaeozoic deposits were eroded before the Permian.

The Silurian section is well cored and occurs at a depth of 1480.0–1544.5 m (driller's depth) with the thickness of 64.5 m. The Llandovery–Wenlock section is typical of the central part of the Baltic Depression and represented by dominant fine-clastic sediments: claystones, silty claystones and siltstones, often marly with limestone lenses or intercalations. The lower part of the Silurian is composed of nodular limestones. The stratal dip is 0°. Fossils found in the Silurian clastic deposits of the Kętrzyn IG 1 borehole are represented mainly by graptolites.

In terms of petrographic-lithofacies studies, the Ordovician and Silurian rocks are represented by glauconitic, carbonate and clay lithofacies, and their petrographic compo-

sition (Kętrzyn IG 1) is typical of the central part of the Baltic Depression.

The Permian occurs upon Silurian (Wenlock) deposits (Kętrzyn IG 1) or directly upon Cambrian rocks (Kętrzyn IG 2) and is represented by the Rotliegend and Zechstein facies.

The East European Craton was a land area during the Early Permian. At the end of the Early Permian (end of Rotliegend sedimentation and beginning of Zechstein sedimentation), small local basins developed in this area, filled with fluvial sediments mainly of braided rivers and streams. These basins were partially or completely isolated from the central Rotliegend basin of the Polish Lowlands that covered the Palaeozoic platform area with its depocentral structure referred to as the Mid-Polish Trough. The typical Rotliegend section of the Baltic Depression consists primarily of conglomerates and sandstones of various types, including conglomeratic sandstones: arkose or greywacke, with subordinate fine-clastic sediments (mudstones and claystones). The Rotliegend sections of the Baltic Depression represent the upper Rotliegend: the Noteć Megacycle corresponding to the Pasłęka Formation.

Zechstein deposits of both boreholes accumulated in the SE part of the Baltic Basin. These are near-shore sediments typical of the Zechstein basin of the Precambrian platform. The Zechstein carbonate–evaporite cyclothems are reduced in this area in terms of both stratigraphy and thickness, and are characterized by a predominance of carbonate and sulphate deposits (without salt series) with a participation of terrigenous rocks in the Kętrzyn IG 2 borehole. The terrigenous–evaporite cyclothem PZ4 – is absent, in contrast to most parts of the Baltic Basin. It is replaced by its facies equivalent represented by the Top Terrigenous Series (PZt).

The Zechstein section of the Kętrzyn IG 1 borehole represents a more basinal facies than that from the Kętrzyn IG 2, and a deeper marine area. The Kętrzyn IG 1 borehole reveals a more complete stratigraphic section represented by three carbonate–evaporite cyclothems PZ1, PZ2, PZ3 and the Top Terrigenous Series (PZt). The Zechstein section from the Kętrzyn IG 2 borehole, situated in a near-shore part of the Zechstein Basin during the late Permian, shows even greater stratigraphic gaps and thickness reductions.

The study of microfacies, diagenetic processes and sedimentary environments of the Zechstein Limestone, Main Dolomite and Platy Dolomite prove a shallow-water nature of the deposition and a low degree of diagenetic processes.

The Triassic deposits from both boreholes represent the north-eastern marginal zone of the sedimentary basin. The stratigraphic gap in this area spans the Muschelkalk (?Middle Triassic) and the Lower and Middle Keuper (uppermost ?Middle Triassic–?Norian). The Triassic section of the Kętrzyn IG 2 borehole is more complete and includes the Muschelkalk and the Nidzica Beds of the Middle Keuper. Thus, the gap spans the Lower Keuper and major part of the Middle Keuper (?Ladinian–?Carnian). The gap in these sections developed partly due to subsequent erosion, and partly due to non-deposition.

The Triassic section begins with Buntsandstein Group deposits corresponding to the Lower Triassic. The basinwide problem is how to determine the Permian/Triassic and Lower/Upper Triassic boundaries. The Buntsandstein Group consists of three subgroups: Lower, Middle and Upper Buntsandstein, and a number of formations. In the Kętrzyn IG 1 borehole, there is a sedimentary and erosional gap above the Elbląg Formation, which is the uppermost lithostratigraphic unit of the Buntsandstein Group, spanning Muschelkalk, and Lower and Middle Keuper deposits.

The Triassic section in both boreholes is terminated by the Bartoszyce Beds of the Upper Keuper, 17.5 m (Kętrzyn IG 1) and 13 m (Kętrzyn IG 2) in thickness. Sedimentary environment of the Upper Keuper deposits was typically of clearly reducing conditions. Deposition occurred probably on a floodplain within a fluvial depositional system in a humid environment with rich vegetation. The sandstone member found in the Kętrzyn IG 2 borehole represents probably a fluvial channel.

The total thicknesses of the Lower, Middle and Upper Jurassic in the Kętrzyn IG 1 and Kętrzyn IG 2 boreholes are 388.0 m and 342.5 m, respectively. The Lower Jurassic is represented by the Olsztyn Formation (Pliensbachian), Ciechocinek Formation (Lower Toarcian) and Borucice Formation (Upper Toarcian). The Middle Jurassic comprises the Bathonian sandstones and claystones and the Callovian mudstones. The latter deposits build the lower part of the Łyna Formation, whose upper part is included in the Lower Oxfordian. Upper in the Oxfordian, there are limestones of different types, representing the following formations: Spongy Limestone, Coralliferous Limestone, Calcareous-Marly (Kętrzyn IG 1) and Oolitic. These are overlain by the Calcareous-Marly-Coquina Formation of the Lower Kimmeridgian (both boreholes), and the Pałuki Formation of the Upper Kimmeridgian (Kętrzyn IG 1), represented by marls with marly limestone interbeds.

The Upper Cretaceous succession in the Kętrzyn IG 1 and Kętrzyn IG 2 boreholes is relatively thin: 243.5 m and 372.0 m, respectively. It starts with the Turonian and ends with the Upper Maastrichtian. The lithologic section is highly diverse, including chalk, limestone and marly limestone, marl and sandy marl, different varieties of gaiszes, mudstone, claystone, and quartz-glaucinitic sandstone. In addition, there is a number of hardgrounds and phosphorite horizons. Microfaunal studies and analysis of well logs in numerous boreholes of this region enabled identification of an extensive stratigraphic gap. The gap spans likely the lower part of the Turonian, part or entire Coniacian, Santonian, lowest Campanian and, probably, part of the lower Maastrichtian. Moreover, no Cenomanian deposits have been found here. All of these facts provide a good basis for considerations on sedimentary rhythmicity in the Late Cretaceous. The Upper Cretaceous sequence is represented by carbonate, siliceous-carbonate and siliciclastic depositional systems that accumulated in an open-marine basin. At the base, there is a thin layer of sandy deposits. Above, the Turonian and Coniacian section is represented by carbonates

dominated by limestones and chalk. Supply of terrigenous material from the northward-extending Scandinavian land (Baltic Shield) was negligible. Stronger influx of clastic material took place in the early Campanian and Maastrichtian (siliciclastic and siliceous-carbonate sedimentation with a considerable contribution of clastic material). The influx of clastics diminished in the late Campanian, likely due to the relative sea-level rise from mid-Campanian time.

The Upper Cretaceous succession is overlain by Cenozoic deposits found at a depth of 0–221.0 m in the Kętrzyn IG 1 borehole, and 0–228.0 m in the Kętrzyn IG 2 borehole. Quaternary variously grained sands, ice-dammed lake clays and tills overlie the Palaeogene in the Kętrzyn IG 1 and the Neogene in the Kętrzyn IG 2 borehole.

Analysis of sedimentation rate and 1-D modelling (Schlumberger PetroMod1-D software) of thermal and burial history were performed for the Kętrzyn IG 1 borehole. The section is characterized by the presence of several phases of increased burial and fast deposition rate. Periods of increased sedimentation rate were followed by periods of erosion or stagnation. The results of thermal history and burial modelling have allowed determination of hydrocarbon generation phases over geological time. The main phase of hydrocarbon generation in the Palaeozoic deposits, determined for the Kętrzyn IG 1 boreholes, occurred not later than the Middle Devonian. This phase corresponds to the oil window only.

A petrologic study of organic matter dispersed in the lower Palaeozoic deposits from a depth interval of 1480.1–1824.7 m (Kętrzyn IG 1 – Lower Cambrian–Silurian (Wenlock)) representing Lower Cambrian–Silurian (Wenlock) deposits shows a variable, but generally not very high content of organic matter (0.1–2.1% of planimetric surface). Increased concentrations (1.1–2.1 %) occur locally in the Silurian (top of the Llandovery, bottom of the Wenlock) and in the Ordovician (uppermost Hirnantian).

The maceral composition of organic matter in the Ordovician and Silurian sediments is represented mainly by vitrinite-like components (graptolites, solid bitumens, organoclasts) and liptinite (algae and alginite). Locally, small bitumen impregnation is observed.

Thermal maturity of the deposits corresponds to the main phase of oil generation, and it increases with depth of burial from 0.56 % Ro in the Wenlock deposits at a depth of 1480.1 m to 0.92 % Ro in the Lower Cambrian sediments at a depth of 1824.7 m, indicating not very high maximum palaeotemperatures of diagenetic processes: 60–100°C.

Geochemical studies of organic matter performed in the Lower and Middle Cambrian, Ordovician and Silurian deposits show the presence of “good” source rocks for hydrocarbon generation at some Silurian (Llandovery and Wenlock) intervals of the Kętrzyn IG 1 section. Other deposits are referred to as “weak” or “poor” source rocks, and higher organic carbon contents were recorded only at some point sites. Bacteria and marine algae are the source of primary organic matter in the Lower Palaeozoic deposits of this borehole.

The degree of organic matter alteration is low. Generally, it corresponds to the early stage of “oil-window”; the Ordovician deposits are slightly more altered than Silurian.

Analysis of the occurrence of high contents of labile components in the Silurian and Lower Ordovician deposits clearly shows that these bitumens are epigenetic.

Pyrolytic analysis of samples from the Silurian (Llandovery) and Ordovician (Katian–upper Caradoc in the British division) fine-clastic rocks (grey, dark grey and black claystones) of the Kętrzyn IG borehole was carried out to study their ability for hydrocarbon generation and to simulate the process in other locations under conditions of greater burial. Some of the claystones are more or less calcareous or sideritic and accompanied by numerous limestone and marl interbeds. The Llandovery and Caradoc samples can be divided into two groups differing in hydrocarbon potential values (HI) and showing very high similarity in terms of the organic matter type and the degree of thermal alteration.

The examinations indicate that the first group represents rocks dominated by degraded Type III kerogen, which show no potential for hydrocarbon generation.

The results of pyrolytic analysis of the second group point to very good potential source rocks dominated by oil-generative Type II kerogen.

A wide range of borehole geophysical measurements performed in the Kętrzyn IG 1 and Kętrzyn IG 2 boreholes has provided, particularly in the Kętrzyn IG 1, information on the lithological section, petrophysical parameters and thermal parameters of rocks. Particularly valuable are the results of thermal field observations. They point to abnormally low heat flow values within the Kętrzyn Anorthosite Massif, as well as to high probability of deep permafrost occurrence, especially in the central part of the area, which may have even survived to present times. These preliminary results can be used in prospects for geothermal energy

sources, hydrogeological studies, and in modelling of surface geophysical surveys, including seismic and gravimetric.

Measurements of average seismic velocities have revealed the presence of clear acoustic boundaries: positive in the Cretaceous and top of the Oxfordian, negative at the top of the Middle Jurassic, positive in the Buntsandstein and top of the Lower Cambrian. Their presence is confirmed by seismic records of reflections from these boundaries.

During formation tests, a minor non-economic amount of crude oil inflow accompanied by brine was observed in the Silurian limestones from a depth of 1520.2–1530.0 m in the Kętrzyn IG 1 borehole. In the course of about 9-month research, when special treatments were carried out to enhance the inflow, only 2 tons of crude oil were extracted. Due to non-economic oil amounts, the hole was sealed with a cement plug and abandoned.

Physicochemical studies of groundwater in the Kętrzyn IG 1 and Kętrzyn IG 2 boreholes show its clear zonation. The uppermost Cretaceous and Cenozoic formations contain slightly mineralized ($<4 \text{ g/dm}^3$) sodium-bicarbonate or bicarbonate-chloride-sodium waters, located in the zone of intense infiltration from the ground surface. The deeper aquifers contain chloride–sodium–calcium or chloride–sodium waters, and their mineralization increases with depth from about 10 to more than 130 g/dm^3 .

Results of laboratory analysis of water samples collected during drilling of the Kętrzyn IG 1 borehole show a depth-related decrease in the proportion of sodium ions in favour of calcium ions. Similarly, in the sub-Cretaceous formations, bicarbonate ions are replaced by chloride ions.

The deeper aquifers are isolated from meteoric waters. They occur in a prospective zone for hydrocarbon accumulation. In the Kętrzyn IG 2 borehole, sub-Jurassic formations have not been tested for technical reasons.

Translated by Krzysztof Leszczyński