

SUMMARY

The Malbork IG 1 borehole is situated in the central area of the Baltic Depression, in the western part of the East European Craton. The main goal of the drilling was “to study the prospectivity of the Mesozoic and Paleozoic rocks, and facies and reservoir conditions”, as well as to examine the geology of the Baltic Depression, to clarify the geological-structural characteristics, and to establish the stratigraphy and reconstruct the lithofacies development. Drilling work started in 1987. In addition to the tasks related to regional and petroleum geology, the borehole was also designed to penetrate the Lower Triassic to determine the contents of uranium in relation to the exploration operations for this strategic and energy raw material, carried out in the 1980s in the Krynica Morska region.

The Malbork IG 1 exploration borehole was completed in 1988, and it stopped at a depth of 3680.0 m in crystalline rocks of the East European Platform after the fulfillment of the full range of geological tasks. The total drill core yield was 640 m in 127 drill core intervals, which accounts for 17.4% of the total thickness of the pierced rocks.

The drill core material provided many geological data, which became the basis of numerous studies. This volume contains information and research results from the borehole's final report *Dokumentacja wyników otworu badawczego Malbork IG 1* (Areń *et al.*, 1990) and from new research results of lithofacies, lithological, stratigraphical, petrographical, sedimentological, structural and geochemical investigations. A full set of hydrogeological and geophysical measurements was performed. An analysis of subsidence and sediment deposition rates in the Paleozoic and Mesozoic was also carried out.

The boundaries of chronostratigraphic units in non-cored intervals are approximate and determined based on, *inter alia*, correlation of the well logs with the corresponding well logs from biostratigraphically dated sections of the nearest boreholes: Gdańsk IG 1, Pasłęk IG 1 and Prabuty IG 1.

Crystalline rocks from the Malbork IG 1 borehole belong to the SW part of the East European Craton and, in the regional division, to different tectonic units (Warmia Zone, Baltica Terrane, West-Lithuanian Terrane (Zone) and Polish-Lithuanian Terrane). In this borehole, at a depth of 3661.0 m, there are coarsely crystalline and porphyroblastic granitoids, which cannot be classified as typical rapakivi granites. They should be considered as hornblende-biotite granitogneisses included in the so-called Warmia granitoids. There is no justification for including the Warmia granitoids into the so-called Mazury Complex showing features of an AMCG-type magmatic complex (anorthosite-mangerite-charnockite-granite [rapakivi]),

which differ in geochemical characteristics, although they intruded at the same time, about 1.50–1.54 billion years ago, during the Danish-Polish orogeny. Geochemical data indicate that the Warmia granitoids originated in a volcanic arc environment. They are characterized by well-developed foliation (SO [magmatic] + SM [mylonitic]) dipping at 40–45°, with kinematic proxies documenting a thrust deformation regime during the Danish-Polish orogeny.

The sedimentary cover starts with Ediacaran and Lower Cambrian deposits. The Lower Cambrian deposits correspond approximately to the Terreneuvian and Stage 2. There is no sedimentary break between the underlying Żarnowiec Formation and the Cambrian deposits. The Żarnowiec Formation is represented by brownish and variously coloured, very coarse-grained sandstones and conglomerates. The Cambrian deposits were drilled at a depth of 3637.0–3234.0 m. The average drill-core yield for the Cambrian succession was 88%. Despite such a high yield, the paleontological material from the Cambrian is very poor and indeterminate. The Lower/Middle Cambrian boundary is conventionally drawn based on a correlation with the nearby boreholes of Gdańsk IG 1 and Prabuty IG 1.

The suit of lithological and sedimentological features indicates that initially during the Middle Cambrian the region was a shallow-marine sublittoral area, above wave base. As the sea retreated from the eastern area of the Baltic Depression, the basin became shallower and the sedimentation took place in shallow-marine but not yet coastal environments. Subsequent retreat of the sea, excepting periods of short incursions, had led to the emergence of large land areas on which a sustained period of denudation began.

Ordovician sediments occur at a depth of 3187.5–3234.0 m (logger's depth), i.e. their total thickness is 46.5 m. The stratigraphic section, however, is incomplete and not representative of the region because the borehole is located within a fault zone and the Ordovician deposits are highly tectonically disturbed. The succession contains numerous tectonic reductions, slickensides and foldings.

Paleontological evidence for the Ordovician sediments is very poor. Stratigraphical subdivision has been established based on correlation of lithostratigraphic units and well logs with the marker Ordovician sections of the Prabuty IG 1 and Gdańsk IG 1 boreholes. The Ordovician is represented here by (undivided) the Hirnantian – Katian, Darriwillian – Sandbian and Floian – Dapingian (Ashgill–Arenig in the British division).

The Silurian deposits occur at a depth of 3187.5–2004.5, reaching 1183.0 m in thickness. The Silurian section is typical

of the central part of the Precambrian Platform. Horizontally lying fine-grained clastics are predominant: claystones and siltstones, with a few interbeds of carbonates. A global standard stratigraphic scheme for the Silurian System was used in subdividing into Series and Stages. The informal and local chronostratigraphic units ("Stages": Siedlce, Mielnik and Bielsk), established by H. Tomczyk and presented in the borehole's final report (Areń *et al.*, 1990), have been abandoned. The section is represented by the Llandovery, Wenlock, Ludlow and probably Pridoli. The boundaries with the Ordovician and Permian (Buntsandstein) are erosional.

The Permian is represented by both Rotliegend and Zechstein deposits. In the western part of the Baltic Depression, the thickness of the Permian clastics underlying the copper shale is small: 4.0 m in the Malbork IG 1 borehole. The dominant lithofacies throughout the western part of the Baltic Depression are fine-grained sandstones and mudstones. In the early Permian, the area was located in the north-eastern part of the Rotliegend basin. The Rotliegend deposits, represented by conglomerate – sandstone cycles typical of riverbed sediments, are separated from the Ordovician, Silurian or Cambrian rocks by a considerable stratigraphic gap.

In the late Permian the area under consideration was located in the axial zone of the Peribaltic Embayment near its connection with an open-marine basin extending in the Mid-Polish Trough. The stratigraphic section is characteristic of this zone and shows a very high similarity to the Prabuty IG 1 section. Zechstein evaporites were deposited in three cycles of PZ1, PZ2 and PZ3. There are no PZ4 sediments, and its lithofacies counterpart is the Top Terrigenous Series (PZt).

The Main Dolomite is a carbonate series occurring at the base of the Zechstein cyclothem PZ2. In central Poland, this unit contains both source and reservoir rocks for hydrocarbons. Numerous deposits of oil, natural gas or mixed, discovered in the Main Dolomite, make this level one of the major targets of hydrocarbon exploration in the Polish Lowlands. It forms a closed hydrodynamic system sealed at the top and bottom by evaporites, and is an excellent example of the development of the evaporitic oil-bearing formation. Some attention is drawn to the commonly occurring rocks of microbial and algal origin in the Main Dolomite, which could be a source of organic matter. However, studies of source rocks in the Zechstein section of the Malbork IG 1 borehole revealed that the Main Dolomite contains small amounts of poor quality source rocks that have no significance for hydrocarbon potential.

The lower boundary of the Buntsandstein (Lower Triassic) was placed at the first occurrence of lenticular bedding formed due to wave action (wave heteroliths). The lithostratigraphical subdivision and its chronostratigraphic interpretation are based on palynological analysis of drill cores and the specific geological setting of the Triassic sedimentary basin in the Polish Lowlands. The boundaries of chronostratigraphic units are approximate.

The Malbork IG 1 borehole (along with two other boreholes) provided new data on the lithology of the Triassic uranium-bearing deposits, especially of the Elbląg Formation, dated to the uppermost unit of the Lower Triassic. The observations and the results of detailed analysis helped to determine sedimentary environments of the Elbląg Formation in the

section, its evolution and relationships of individual facies and cycles with similar units in coeval deposits from the Malbork region. Lithological analysis allowed identification of six lithofacies in the Elbląg Formation, related mainly to a continental sedimentary environment. Most of the deposits of the formation were accumulated in a marginal zone of a saline basin and represent a coastal plain facies association.

Previous studies of uranium mineralization in the Lower Triassic of the eastern part of the Baltic Depression showed the presence of several mineralized levels, mainly in sandy interbeds, predominantly in the lower part of the Elbląg Formation.

Sedimentological analysis of the upper part of the Lower Triassic in the Malbork region proves that any correlation of individual sandy-conglomerate lithosomes is doubtful, based on sedimentological criteria. It is possible and appropriate to correlate facies associations. It allows minimizing the spectrum of the analyzed sediments to the most prospective units.

Petrographic and mineralogical studies for the presence of ore mineralization were performed in the Zechstein copper-bearing series, including the Zechstein Limestone Ca1, copper shale T1 and Weissliegend Bs. Investigations proved the presence of rich pyrite mineralization, accompanied by subordinate disseminated chalcopyrite, sphalerite, galena and markasite.

In the central zone of the Baltic Depression, the Lower and Middle Jurassic shows a very reduced section, and only the Upper Jurassic is characterized by the presence of almost complete stratigraphic section. The total thickness of Jurassic deposits in the Malbork IG 1 borehole is 370.5 m. They overlie Upper Triassic claystones and siltstones, and there is a sedimentary gap between these deposits, spanning the lowermost Lower Jurassic. The Jurassic succession is overlain by upper Albian–Cenomanian quartz-glaucconitic sands. The stratigraphic gap spans almost the entire Lower Cretaceous. No drill core has been acquired from the Cretaceous rocks. Correlation between other boreholes from this region (e.g. Prabuty IG 1, Pasłęk IG 1 and Gdańsk IG 1) indicates that the Malbork IG 1 borehole section shows a transitional character between the western part of the Baltic Depression (with a more complete development of the Cretaceous succession) and its eastern part (where significant stratigraphic gaps are observed, spanning the upper Turonian, Coniacian, Santonian, Campanian and lower Maastrichtian). The Cretaceous succession is 498.0 m thick in the Malbork IG 1 borehole and is probably represented by the following chronostratigraphic units: upper Albian, Cenomanian, Turonian, Santonian, Campanian and Maastrichtian. A stratigraphic gap probably spans the Coniacian and possibly the upper Turonian. The Cretaceous is overlain by 105-m thick Cenozoic deposits. They are represented by a Paleogene–Neogene series (depth 35.0–105.0 m) composed of clays, sands and sandy muds, and by 35.0-m thick Quaternary deposits represented by variously grained sands, peats, silts, ice-dammed lake clays and glacial tills.

The Malbork IG 1 borehole is located in the central part of the land sector of the Baltic Basin, where deposits of two sedimentary basins are superimposed. The basins differ in the geometric frames and subsidence mechanisms. These are early Paleozoic Baltic Basin and the Permian–Mesozoic Polish Basin. There is evidence that deposits of the Devonian–Early Carboni-

ferous Basin had also been accumulated in this area, and later became eroded before the Early Permian. Tectonic subsidence analysis was performed with regard to each of these basins. Deposition rate analysis was also carried out to reconstruct the activity of source areas for detrital material.

Geochemical study of organic matter was carried out for the Lower and Middle Cambrian, Ordovician, Silurian, Upper Permian (Zechstein), Triassic and Lower–Middle Jurassic deposits. Only the Lower Silurian and uppermost Upper Jurassic deposits contain sufficiently large amounts of organic carbon to be considered “good” source rocks for hydrocarbon generation. Generally, the rocks from the Malbork IG 1 borehole contain small quantities of organic carbon. The lower Paleozoic rocks contain large amounts of labile components, which are generally of epigenetic origin. There is a considerable similarity in the composition of Middle Cambrian bitumens and oil found in deposits of this age.

Organic matter in the lower Paleozoic rocks is of sapropelic type and is highly altered. The organic matter is sourced from bacteria and marine algae. Its maturity varies with depth: the most highly altered organic matter was found in the Cambrian rocks, the lowest alteration is observed in the Silurian (Ludlow and Pridoli). Generally, the degree of alteration of organic matter corresponds to the stage of “oil-window”. Organic matter in the Permian and Mesozoic is of sapropelic type, but there is a remarkable proportion of humic material. Organic matter found in the Permian, Triassic and Jurassic deposits is poorly altered.

Petrographic characteristics of dispersed organic matter in the Permian–Mesozoic and lower Paleozoic section indicate that the Cambrian–Jurassic deposits are characterized by variable, often poor and very poor content of organic matter. Elevated concentrations occur locally in the Jurassic, Permian, topmost Silurian, Wenlock and Llandovery deposits.

The maceral composition of organic matter in the Permian–Mesozoic is represented mainly by humus: colotelinite-type vitrinite and inertinite, with a small percentage of liptinite macerals. The lower Paleozoic organic matter is also of low diversity in terms of genetic type, petrographic composition and form of occurrence. Its main ingredient is vitrinite-like material: solid bitumens and zooclasts (mainly the remains of graptolites). Bitumen impregnation is locally observed. Thermal maturity of the deposits varies with depth within a wide range from the immature phase and early phase of

oil generation in the Permian and Mesozoic through the main and late phase of oil generation in the Silurian and Ordovician to the main phase of gas generation in the Cambrian deposits. These data indicate that individual Llandovery and Wenlock clay horizons are potential source rocks for hydrocarbon generation (crude oil, condensates, wet gases).

Geophysical well logging was performed to a depth of 3680.0 m. In addition to the standard set of research methods, very important measurements were made for uranium mineralization in the Lower Triassic section at a depth of 1000.0–1300.0 m.

To illustrate the geology of the region, the WO060189 seismic profile is presented. No tectonic deformation has been identified within the Permian–Mesozoic succession.

Silurian, Ordovician and Cambrian deposits were encountered beneath the Zechstein, and the Precambrian basement was finally reached. No tectonic deformation or thickness deviations have been found in the sub-Zechstein, either. Average velocity analysis was performed for the interval of 50–3660 m. Velocity boundaries were detected at the Cretaceous/Jurassic contact, within the Lower Triassic, and at the Triassic/Permian and Permian/Silurian contacts. Particularly good physical conditions for recording seismic boundaries are at the top and base of the Zechstein. This is confirmed by seismic surveys, which recorded reflections associated with the topmost and lowermost layers of the Zechstein. Velocity changes can also be observed in the Silurian, at the Silurian/Ordovician boundary and in the Cambrian. Therefore, there are conditions to obtain reflection horizons from the entire depth range of the sedimentary succession in this area.

Formation tests performed for hydrocarbon occurrence included several tests in the Cambrian and 2 tests in the Mesozoic.

The Middle Cambrian sandstone show very poor reservoir properties. They occur in a zone of anomalously low reservoir pressure. Dying flows of oil at the final stage of testing prove the existence of a small lens-like body, isolated from the Cambrian oil reservoir. The test results allow, however, to extending the Cambrian oil-bearing zone. The brines from Mesozoic levels occur in a zone of difficult exchange with less mineralized waters found at higher stratigraphic levels. Infiltration rate is low. The brines are metamorphosed and subsequently partly freshened. The Mesozoic horizons are not prospective for hydrocarbons. The chemical composition of the brine from the Jurassic deposits suggests its potential use in balneotherapy.