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SUMMARY

The Grochowice M 9 borehole was drilled in the south-western part of the Fore-Sudetic Monocline, Kotla Commune, Głogów District, Lower Silesian Voivodeship. The main objective of the drilling was to prospect for copper ore in Permian sediments and to evaluate the potential for gas and oil accumulations. In addition to this generally defined task, the purpose of this borehole was also to provide details to the knowledge about the geological structure and mineral resource potential of the Fore-Sudetic Monocline, in particular to determine the industrial usefulness of ore mineralization in the Zechstein copper-bearing series and thus to check whether the Lubin-Sieroszowice copper ore deposit continues towards the NW, to determine the depth to the Zechstein ore series, and to evaluate the prospect for rock salt and potassium salt as well as lignite and uranium occurrences.

The Grochowice M 9 borehole was drilled within the framework of the project titled Projekt poszukiwań cechsztyńskich rud miedzi na obszarze zachodniej części monokliny przedsudeckiej, perykliny Żar i niecki północnosudeckiej (Prospection program for Zechstein copper ore deposits in the areas of western part of the Fore-Sudetic Monocline, Żary Pericline and North-Sudetic Trough) (Wyżykowski, 1974). The drilling was terminated in the Rotliegend at a depth of 1630 m, after piercing through the Quaternary, Neogene, Paleogene, Muschelkalk, Buntsandstein and Zechstein formations.

A range of borehole geophysical logs was performed in the well, but not all logs are currently available. The preserved well logs, spanning the depth interval from 1460 m to the well bottom, show a significant compliance of the profile interpreted from borehole geophysical techniques with the lithological section interpreted from drill cores. With the exception of a few sections with a total length of 75.5 m (mainly within the Paleogene, Neogene and Quaternary), the borehole was fully cored. The drill core material obtained from this well has provided geological data that became the basis for many substantive studies.

This volume contains the results of studies included in the report titled Poszukiwanie cechsztyńskich rud miedzi w rejonie monokliny przedsudeckiej. Dokumentacja wynikowa otworów: M-1 Lipowiec, M-5 Dryżyna, M-9 Grochowice, M-24 Dachów (Prospection for Zechstein copper ore deposits in the area of Fore-Sudetic Monocline. Documentation of the boreholes: M-1 Lipowiec, M-5 Dryżyna, M-9 Grochowice, M-24 Dachów) (Gospodarczyk et al., 1980), and their current interpretations, supplementary studies and new results of lithological, stratigraphical, palaeontological, petrological, sedimentological, mineralogical, geochemical, organic matter, natural gas reservoir, burial and thermal history, seismic, and borehole geophysics researches.

The bottom interval in the Grochowice M 9 borehole is represented by thin Rotliegend aeolian deposits (1626.13–1630.00 m; thickness 3.87 m). They are overlain by a relatively thick Zechstein series (432.13 m) in the 1194.0–1626.13 m depth interval. The Zechstein section consists of three carbonate-evaporite cyclothems: PZ1, PZ2 and PZ3, and the terrigenous-evaporite cyclothem PZ4, subdivided in this area into the PZ4a subcyclothem and the Top Terrigenous Series PZt. The cyclothems have variable thicknesses (PZ1 – 212.3 m, PZ2 – 86.4 m, PZ3 – 85.0 m, PZ4 – 47.0 m) and their sections are relatively complete. The only missing units are the older and younger potassium salts (K2, K3) and the Lower Pegmatite Anhydrite (A4a1). Full coring of the Zechstein succession enabled sedimentological logging and reconstructing sedimentary environments in the Zechstein basin of this area. The basal parts of the cyclothems are composed of Wiessliegend sandstones, shales (T1, T3) and carbonates (Ca1, Ca2). Upper in the cyclothem sections, evaporitic series are developed. These are: A1d, Na1 and A1g in PZ1, A2, Na2 and A2r in PZ2, A3 and Na3 in PZ3, and Na4a1, A4a2 and Na4a2 in PZ4.

Macroscopic observations and microlithofacies studies were carried out on the Zechstein copper-bearing series, comprising the Weissliegend, the Kupferschiefer and the Zechstein Limestone. The Weissliegend white sandstones (1622.34–1629.78 m) occur directly above the red-bed type sandstones (1629.78–1630.00 – unperceived thickness). The profile of Weissliegend is bipartite. Lower part (1626.13–1629.78 m) is developed as sub–horizontally and cross-bedded light-grey sandstones of aeolian origin, included in the Rotliegend. It is overlain by a Weissliegend marine succession (Bs1; 1622.34–1626.13 m) that is the equivalent of the basal conglomerate in sandy facies (Zp1). It is composed, from bottom to top, of horizontally laminated sandstones, structureless sandstones, and sandstones with minute sedimentary structures and bioturbation, deposited in the envi-

ronment of interdune shallow basins as a result of re-sedimentation of aeolian sands by calm waters of the Zechstein Sea. The total thickness of the Weissliegend is 7.44 m, including the marine unit (Bs1) with a thickness of 3.79 m. The sandstones are overlain by the characteristic Kupferschiefer (T1) with a small thickness of 0.25 m, composed of black laminated clay shales with an interbed of dolomitic mud shales. The Kupferschiefer represents a mature stage of the Zechstein Sea transgression, related to basin's deepening and deposition in an anoxic bottom waters. The overlying Zechstein Limestone (Ca1) is 2.94 m thick and is represented by grey calcareous dolomites – a micritic complex in the lower part and an oncolitic complex in the upper part at the contact with the Lower Anhydrite. The micritic complex was deposited in a sublittoral environment, while the oncolitic complex in a regressive shallow sublittoral environment. The Zechstein Limestone was deposited on a basinal plain between a nearshore carbonate platform and the Wolsztyn shoal.

In the Zechstein evaporite sections the striking features are the presence of an anhydrite ridge within the Lower Anhydrite, small thickness of the Oldest Halite (Na1), and an increased thickness of the Younger Halite (Na3). The evaporite horizons developed in shallow sedimentary basins due to increased seawater salinity. The salts of the first and second cyclothems were accumulated in shallow lagoons, while the salts of the third and fourth cyclothems are sediments of saline lagoons with a varying supply of clay material. Among the Zechstein salt layers in this borehole, only the Younger Halite has a sufficient thickness to estimate the mineral resource potential, because this borehole is included in the vast Gubin-Krotoszyn prospect area, predicted resources of which are estimated at more than 460 billion tonnes.

The Zechstein is overlain by Triassic deposits, 908.0 m in thickness (286.0–1194.0 m depth), represented by the Lower and Middle Triassic. The Triassic succession is subdivided into the Lower, Middle and Upper (Roetian) Buntsandstein, and the Lower and Middle Muschelkalk. The Buntsandstein attains a thickness of 709.5 m (484.5–1194.0 m depth), while the Muschelkalk – 198.5 m (286.0–484.5 m depth). The Middle Muschelkalk, identified based on lithological features of deposits lacking any faunal evidence, shows a strongly reduced section (14.5 m) due to erosion. The Lower Buntsandstein is composed of calcareous and dolomitic claystone-sandstone heteroliths, including oosparitic. The Middle Buntsandstein is represented by clayey sandstones with thin claystone interbeds. In the lower part, the sandstones contain calcareous ooids, commonly mineralized by iron oxides.

The Upper Buntsandstein is represented by alternating limestones, dolomites (with interbeds of organodetrital limestones), claystones and anhydrites. Small fibrous gypsum veins, and gypsum and anhydrite crystals and concretions occur throughout the section. The uppermost Upper Buntsandstein has yielded diverse macro- and microfossils, including the Roetian guide fossil bivalve Costatoria costata (Zenker) and numerous ostracods. The Buntsandstein sediments were accumulated in a very shallow basin having poor connections with an open sea, and remaining under the influence of a barrier or another shoal. The Middle Buntsandstein deposition took place partly in a fluvial environment. A wider connection with the Tethys Ocean occurred during deposition of the Upper Buntsandstein.

There is a continuous transition from the Roetian to Muschelkalk deposits within a complex of alternating carbonate and clay rocks. The lower boundary of the Muschelkalk is at a depth of 484.5 m, with a fauna typical of the Roetian below and with crinoids and diverse fossils characteristic of the Muschelkalk above. The Lower Muschelkalk is represented predominantly by limestones, with a small proportion of claystones and dolomites. The deposits were accumulated in a shallow, open epicontinental sea, initially in the lower tidal zone and then in the intertidal zone. The uppermost Lower-Middle Muschelkalk succession indicates a shallowing of the basin and a gradual regression of the Triassic sea. In the Grochowice M 9 section, the upper Middle Muschelkalk, Keuper, Jurassic and Cretaceous deposits are missing; they have been removed due to tectonic inversion at the Cretaceous/Paleogene transition.

The Muschelkalk is overlain by Cenozoic sediments, 286 m in thickness. The Paleogene section is represented by Oligocene transgressive deposits of the Leszno Formation, 41.5 m thick, composed of glauconite-quartz sands with quartz gravel, and mudstones. The Neogene succession is represented by the Miocene formations: Rawicz, Ścinawa, Pawłowice and Poznań. Their overall thickness is 237.4 m. Ten Neogene deposits were accumulated in a terrestrial environment on an alluvial plain in nearshore peat-forming marsh and bog environments. Coal seams to occur within the Rawicz Formation (Dąbrowa coal seam IV), Ścinawa Formation (Ścinawa coal seam III and Lusatian coal seam II) and Poznań Formation (Mid-Polish coal seam I). The Quaternary deposits (tills and sands) are 7.1 m thick.

Reflected-light microscopic studies of polished sections of rocks from the Zechstein copper-bearing series show the presence of rich ore mineralization represented by bornite (Cu_5FeS_4), chalcopyrite ($CuFeS_2$), covellite (CuS), digenite (Cu_9S_5), chalcocite Cu_2S), sphalerite (ZnS), galena (PbS), and pyrite and marcasite (FeS_2). The richest ore mineralization is found in the Weissliegend (with dominant chalcocite, bornite and covellite), the Kupferschiefer (bornite and chalcocite), and in the lower part of the Zechstein Limestone (bornite, chalcopyrite, covellite, digenite, sphalerite and galena). The only mineral found in the Lower and Upper Anhydrite, as well as the Main Dolomite is pyrite.

Based on chemical studies of rock samples from the copper-bearing series it has been shown that the copper mineralization is concentrated in a 1.52-m-thick ore interval (1622.09–1623.61 m depth) comprising much of the Weissliegend and the Kupferschiefer. In this interval, the copper content varies in the range of 0.11–8.52 wt%, and the silver concentration is 1–100 ppm. A characteristic feature is the tripartition of the ore interval, which is expressed by the presence of two mineralization-rich intervals with the copper content of >0.5 wt%, interspersed with an interval of lower concentration. The lower ore interval (1623.15–1623.61 m) occurs in the lower part of the Weissliegend, while the upper interval (1622.09–1622.37 m) spans the topmost part of the Weissliegend and the Kupferschiefer. Total ore-bearing interval (1622.09–1623.61 m), at cut-off Cu grade in composite sample over 0.5%, averages 1.6 wt% Cu and 29 ppm Ag, and the Cu equivalent grade is 1.83 wt%, and the Cu_e productivity is 67.81 kg/m^2. The average content of accessory metals in this interval is low (0.02 wt% Pb, 0.08 wt% Zn, 51 ppm Co, 26 ppm Mo, 65 ppm Ni and 76 ppm V), and the gold concentration is negligible (up to 7 ppb). In this region, there are two prospective areas for copper ore occurrence: Grochowice I and Grochowice II (based on the Grochowice M 9 borehole). The Grochowice I area, 15.80 km2 in size, may contain 1.125 Mt Cu and 7,386 t Ag, and smaller the Grochowice II area – 0.143 Mt Cu and 205 t Ag. These data allows suggesting that the Grochowice M 9 borehole area belongs to a Cu-rich copper-bearing belt, which is the northwest-trending extension of the Lubin-Sieroszowice Cu-Ag deposit parallel to the eastern range of the Zielona Góra Rote Fäule area.

Due to the lack of gamma-spectrometric measurements in the Grochowice M 9 borehole, the analysis of uranium concentration in Lower Triassic deposits was based on the results of regional studies. They show that uranium mineralization can occur in two uranium-bearing horizons in the Middle Buntsandstein. The lower horizon, associated with carbonate rocks, mainly grey-beige oolite limestones, is characterized by uranium concentration below 350 ppm in the samples, and the average concentration in the mineralized layer (less than 1 m thick) is about 60 ppm. The upper horizon is associated with grey mudstones (containing coalified debris of organic matter), occurring in light grey sandstones. The maximum uranium concentration in the samples is up to 600 ppm, and the mean content in the mineralized interval (with a thickness below 0.5 m) do not exceed 100 ppm. Uranium is accompanied by vanadium, molybdenum, selenium, zinc and lead. Such uranium concentrations are not of economic significance.

Petrological analysis of organic matter dispersed in the Weissliegend, the Lower and the Upper Anhydrite, and the Main Dolomite shows that its content is low (>0.3 vol.%) and it is represented by structureless vitrinite, bitumen, zooclasts, and inertinite and liptinite macerals. The pore space of sandstones contains solid bitumens. The Kupferschiefer is conspicuous by a considerable concentration of organic matter (7–10 vol.%). Its main component is vitrinite-like bitumen of low reflectance in the range of 0.35–0.45% R_o. It co-occurs with liptinite macerals, structureless vitrinite and inertinite. The average reflectance values, ranging from 0.64% R_o in the Kupferschiefer to 0.58% R_o in the Upper Anhydrite, and 0.56% R_o in the Main Dolomite, indicate low thermal maturity of the organic matter, corresponding to the initial phase of liquid hydrocarbon generation. These data point to the maximum palaeotemperatures of 70–80°C during the diagenesis, indicating low temperatures of hydrothermal solutions forming the ore mineralization in copper-bearing series.

The use of 1D modelling techniques has enabled the reconstruction of burial history of the Permian, Mesozoic, Paleogene and Neogene deposits, and of thermal evolution of the basin. A phase of increased burial and rapid sediment deposition rate up to ca. 200 m/My took place in the late Permian (Zechstein), while a fast decrease in subsidence and sediment deposition rate occurred at the end of the Triassic (up to ca. 30 m/My). After the period of fast burial, from end-Triassic to Neogene times, there was a decrease in sediment deposition rate with dominant erosional processes. The maximum burial depth of the base of the sedimentary cover (1750 m) was reached at the end of Cretaceous times. The borehole is located near the southern limit of a positive thermal anomaly covering the central part of the Fore-Sudetic Monocline, where the temperature under steady-state thermal equilibrium at a depth of 2 km is 55–73°C, the heat flow value is ca. 90 mW/m^2, and the mean geothermal gradient is 2.99°C/100 m.

Rock-Eval pyrolysis of the Kupferschiefer, the Lower Anhydrite, the Upper Anhydrite and the Main Dolomite samples exhibit various levels of hydrocarbon potential. The Kupferschiefer contains abundant organic matter (TOC 9.85 wt%), being a source rock with the highest hydrocarbon potential. The organic matter is in the oil window (T_{max} 431°C, S2 31.58 mgHC/g of rock, HI 321 mgHC/gTOC). Anhydrites with interlayers of clay-dolomitic material in the Upper Anhydrite as well as the Main Dolomite also show features of source rocks, in contrast to anhydrites with calcareous clay interlayers in the Lower Anhydrite. The dominant kerogen in the samples is of oil-prone type II and III, thermal maturity of which is between the immature phase and the initial phase of hydrocarbon generation.

The Grochowice M 9 borehole yielded an economic inflow of natural gas from the Weissliegend and the Rotliegend, with the potential producing rate of 71 Nm^3/min and the calorific value of 3192–3537 kcal/Nm^3. The average porosity of the sandstones is 11.64%, and the permeability is 8.66 mD. The main gas components are: nitrogen (63.15 vol.%), methane (35.64 vol.%), propane (0.82 vol.%) and helium (0.26 vol.%). This borehole discovered the Grochowice natural gas deposit, initiating its further development and production. It is located within a brachyanticlinal trap. Following the discovery, numerous prospecting projects were implemented in the south-western part of the Fore-Sudetic Monocline, resulting in the documenting and development of numerous natural gas deposits in the Lower Permian gas-bearing formations. The gas discovery by the Grochowice M 9 well has also pointed to the gas hazard problem in copper mining.

To illustrate the geological structure of the region, a NNW–SSE-trending seismic profile from the Grochowice region is presented, depicting the monoclinal pattern, disturbed by a gentle brachyanticline near the Grochowice M 9 borehole. It occurs over a regional elevation of pre-Permian basement in the Bielawa-Trzebnica direction, with which the occurrence of natural gas deposits, including the Grochowice deposit, is associated.

The Grochowice M 9 borehole was one of the first exploratory wells in prospecting for copper and silver ores and natural gas on the foreground of the still documented Lubin-Sieroszowice deposit, drilled in poorly recognized SW part of the Fore-Sudetic Monocline. Thanks to the multidisciplanatory approach, this borehole achieved its main exploratory objectives and provided comprehensive material about the stratigraphy, lithology and sedimentation of the Permian, Triassic, Paleogene and Neogene deposits, and about the geochemistry and mineralization of the Zechstein copper-bearing series. The main result of drilling this well was the finding of rich ore mineralization in the Zechstein copper-bearing series. It was apparent from this study that the Grochowice M 9 borehole area belongs to a Cu-rich copperbelt, which is the northwest-trending extension of the Lubin–Sieroszowice Cu-Ag deposit parallel to the eastern range of the Zielona Góra Rote Fäule area. The second very important result was the discovery of the Grochowice natural gas deposit that initiated its further development and production. The gas discovery by the Grochowice M 9 well has also pointed to the gas hazard problem in copper mining.

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