

Review

New Opportunities for Oil and Gas Exploration in Poland—A Review

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Abstract: Reserves totaling ~142 BCM (5 TCF) of natural gas trapped in 306 fields and ~22 MTOE (~157 MMBOE) of crude oil in 87 fields have been discovered. The prospection, exploration, and production of hydrocarbons are licensed: an entity interested in these kinds of activities needs to have concession, which is granted by the Polish Ministry of Climate and Environment for 10 to 30 years according to one of two independent ways—international tender or open door procedure. In this review, the most prospective areas for oil and gas exploration in Poland, selected by the Polish Geological Survey, and announced as dedicated for the next 6th tender round, planned in the second half of 2022, are described. These are: Block 413–414, Block 208, Cybinka–Torzym, Zielona Góra West, and Koło areas. The main exploration target of these tender areas is related to conventional and unconventional accumulations of gas and oil in the Carpathian basement, Carpathian Foredeep, and Outer Carpathians (Block 413–414), as well as in the Carboniferous, Permian Rotliegend, Zechstein Main Dolomite (Block 208, Cybinka–Torzym, Zielona Góra West), and in the Mesozoic of the Polish Lowlands (Koło). The second way of granting concession in Poland is the so-called open door procedure, in which an entity may apply for a concession for any other area selected on its own.

Keywords: oil and gas exploration opportunities; prospective areas; concession policy



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1. Introduction

Oil and gas exploration and production in Poland can be traced back to the nineteenth century. At that time, they were limited to the production of oil from the Outer Carpathian flysch belt in southern Poland. Since that time, plenty of oil and gas fields have been discovered in the Carpathian Foreland and Polish Lowland areas. Moreover, new perspectives appeared in the unconventional systems related to the shale-gas and tight-gas accumulations in various horizons. In this review, the current state of view concerning the most prospective geological horizons and their lateral extent for oil and gas exploration in Poland is presented.

According to the latest balance of mineral resources deposits in Poland, a report, which is published annually by the Polish Geological Survey [1,2], reserves totaling ~142 BCM (5 TCF) of natural gas trapped in 306 fields, and ~22 MTOE (~157 MMBOE) of crude oil in 87 fields have been discovered in Poland (Figure 1). In 2020, natural gas production exceeded 4.9 BCM (174 BCF), which constitutes approximately 22% of national demand ranging ~22 BCM (775 BCF). Crude oil production reached almost 1 MTOE (~6.5 MMBOE), covering ~3.7% of ~27 MTOE (192.9 MMBOE) demand. This illustrates a huge

gap between supply and demand in Poland, which may be balanced somewhat by new discoveries expected in different geological horizons. For comparison, proven natural gas resources in 2020 in Europe, excluding Russia and Belarus, were ~3.2 TCM (~111.9 TCF) with production ~218.6 BCM (~7.7 TCF); total World proved gas reserves were ~188.1 TCM (~6641.8 TCF) [3]. Gas resources in Poland accounted for only 4.5% of the resources of the whole of Europe. In the same way, total proved reserves of oil in Europe were ~1800 MTOE (~13,600 MMBOE) with production ~167,100 MTOE (~1,224,843 MMBOE); World reserves were ~244,400 MTOE [3]. Oil resources in Poland accounted for only 1.2% of the resources of Europe. Global energy consumption growth declined by 4% in 2020, in the context of the global pandemic, contrasting with an average of 2%/year over the 2000-2018 period [3]. Consumption in 2020 in Europe, excluding Russia and Belarus, was 14% of global energy consumption; oil and gas continue to hold the largest share of the energy mix (58%) [3].

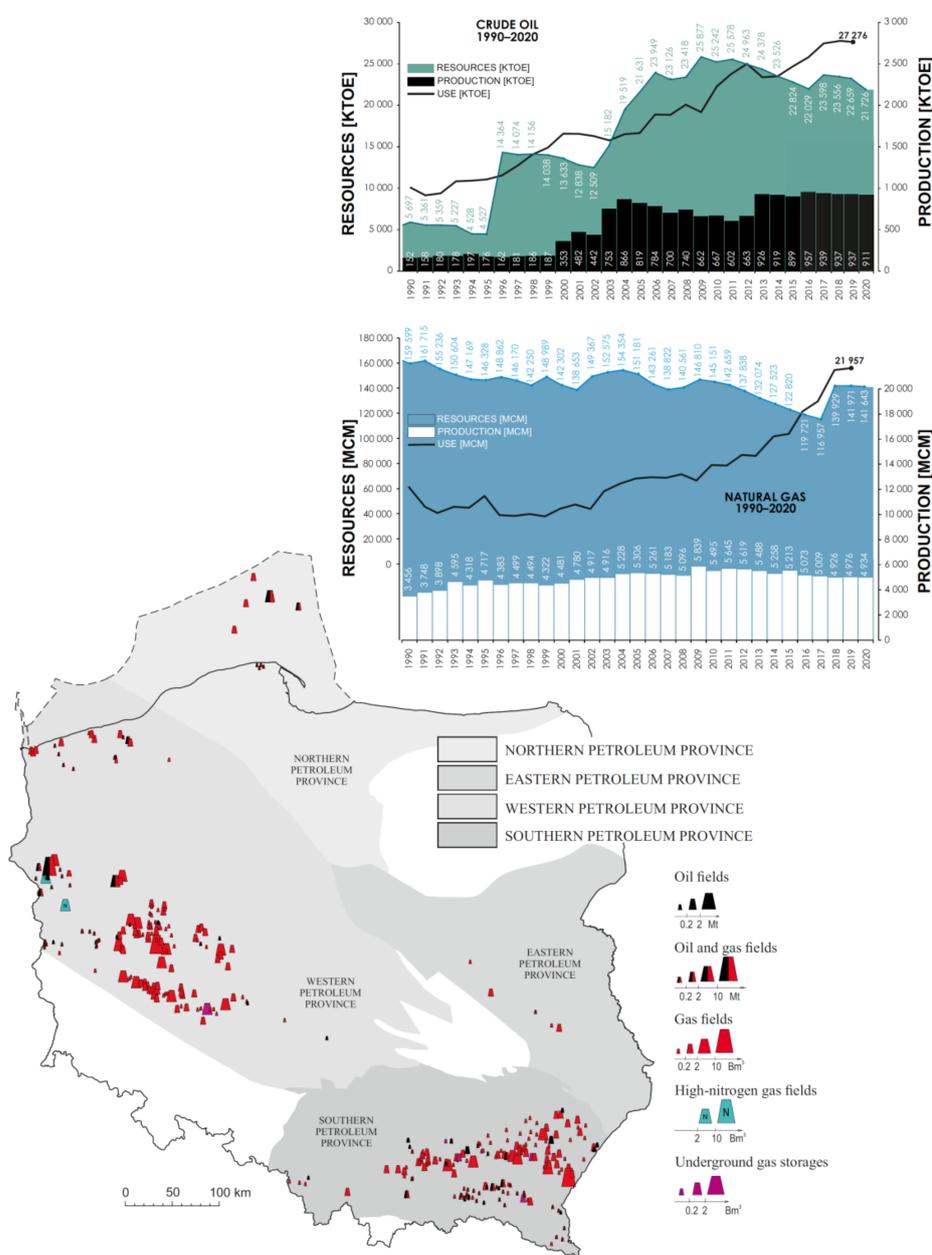


Figure 1. Crude oil and natural gas resources, production, and use in Poland 1990–2020 according to the Balances of mineral resources deposits in Poland [1,2]; location of oil and gas fields and underground gas storages in Poland in relation to petroleum provinces ([4]; compare to [5–7]).

The majority of European hydrocarbon reserves (excluding Russia) is located in the North Sea region within the Northern Permian basin, where reservoirs ranging from Carboniferous to Tertiary are present, e.g., [8], although the Adriatic region also has a long exploration history concerning hydrocarbon potential, e.g., [9,10], France, e.g., [11,12], Spain, e.g., [13], Italy, e.g., [14,15], Vienna Basin, e.g., [16], the Carpathians and their foreland in Czech, Poland, Ukraine, and Romania, e.g., [17–23], Transylvania, e.g., [20,24], Eastern Ukraine, e.g., [25] and the Black Sea, e.g., [26]. In Poland, new small- or medium-sized gas and oil fields continue to be discovered (e.g., Brzyska Wola, Czarna Wieś, Olchowiec, Pniewy, Rogoźnica, Wielichowo W, Gnojnica gas fields with total reserves of ~5.8 BCM/206 BCF, and Połęcko oil and gas field of total reserves of gas ~2.3 MCM/81 MCF and oil ~12.3 kTOE/87.6 MBOE; all of them documented by the Polish Oil and Gas Company in 2019–2020 in the Carpathian Foredeep and Polish Lowland) [1,2], which suggests the existence of still-unexplored regions. The primary targets of exploration are currently conventional reservoirs. Geologists have also identified a host of unconventional resources—including shale gas, tight gas, and coal bed methane ([27]; see also, e.g., [28–43] and citations therein). Oil (petroleum) provinces in Poland, in which exploration and production work can be conducted, have been defined by various authors [5–7]. In the PGS Report [4], the authors described four petroleum provinces (divided into sub-provinces of proved accumulations and regions of unconfirmed oil and gas occurrence), which included prospective areas for oil and gas conventional and unconventional accumulations in different geological regions (Figures 1–3): Northern and Eastern Petroleum Provinces for the East European Platform areas, Western Petroleum Province for the West European (Variscan) Platform, and Southern Petroleum Province for the Carpathian units and its basement. The main exploration targets, documented fields, as well as their documented and prospective resources are summarized in Table 1.

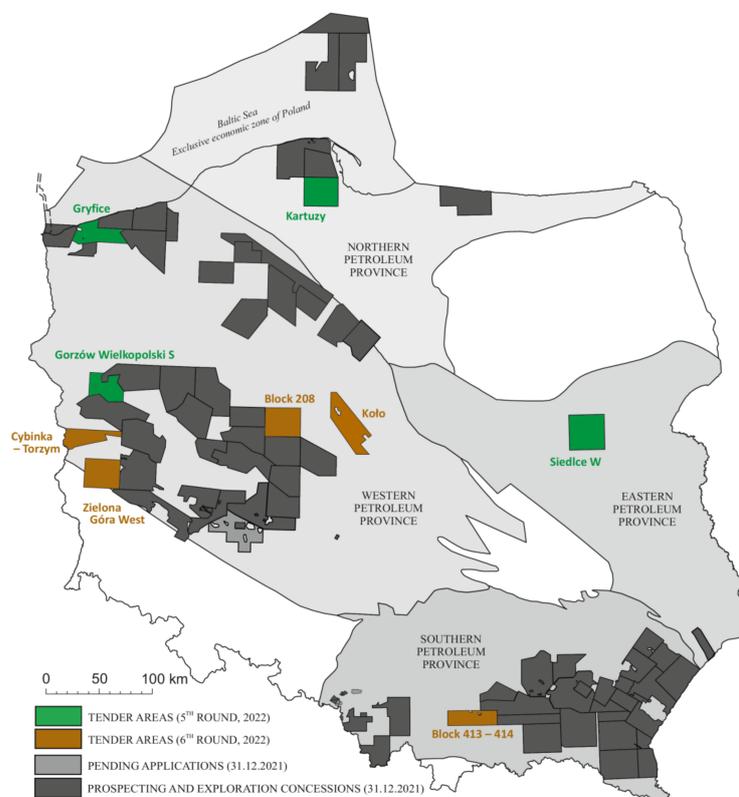


Figure 2. Cont.

ROUND V TENDER AREAS	TARGET
GORZÓW WIELKOPOLSKI S	Permian (Main Dolomite ^c)
GRYFICE	Permian (Main Dolomite ^c and Rotliegend ^d); Carboniferous ^c
KARTUZY	Lower Paleozoic ^{con} ; Cambrian ^{un}
SIEDLCE W	Lower Paleozoic ^{con} ; Cambrian ^c
ROUND VI TENDER AREAS	TARGET
BLOCK 413 – 414	Outer Carpathians ^c , Carpathian Foredeep ^c , Carpathian basement ^c
BLOCK 208	Carboniferous, Permian (Culm ^d , Rotliegend ^d , Main Dolomite ^c)
KOŁO	Mesozoic (Triassic ^c , Jurassic ^{con} , Cretaceous ^c)
CYBINKA – TORZYM	Permian (Rotliegend ^d and Main Dolomite ^c)
ZIELONA GÓRA WEST	Permian (Rotliegend ^d and Main Dolomite ^c)

^c – conventional, ^{un} – unconventional shale gas and shale oil, ^{lt} – unconventional light gas

Figure 2. Concessions for prospecting and exploration of hydrocarbon deposits together with concessions for prospecting and exploration of hydrocarbon deposits and production of hydrocarbons from deposit in relation to tender areas dedicated to 5th and 6th tender round and petroleum provinces of Poland.

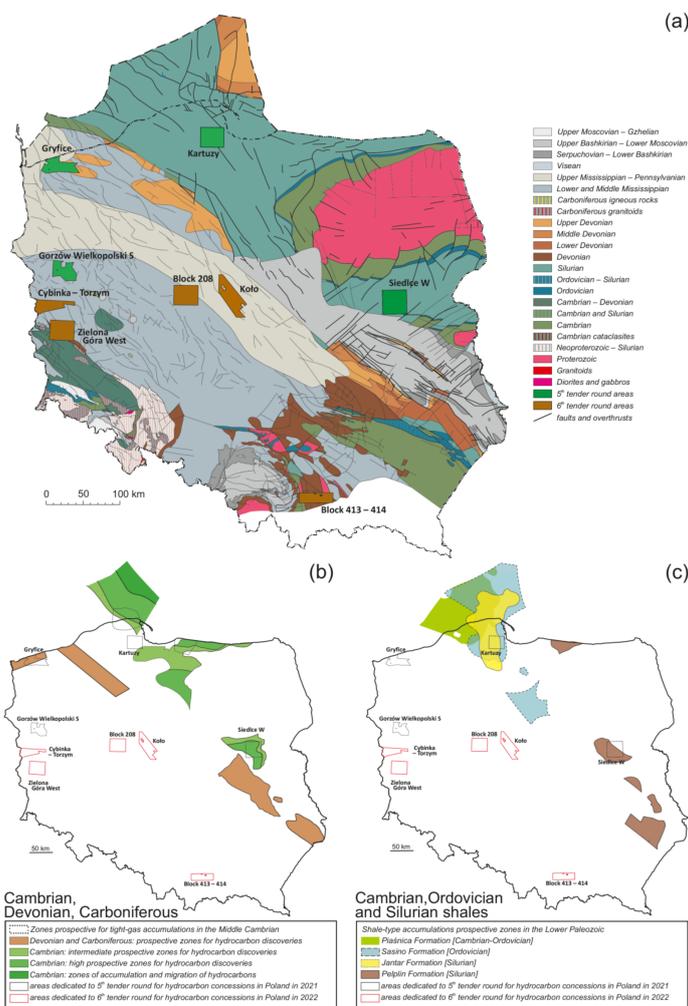


Figure 3. Location of the areas dedicated to the 5th and 6th tender rounds for hydrocarbon concessions: (a) on the Geological map of Poland without Permian and younger deposits ([44], simplified); (b) in relation to the prospective areas for conventional hydrocarbon accumulations in the Cambrian [45,46], Devonian, and Carboniferous ([47]; see also [48–50]) and prospective areas for tight-gas accumulations in the Middle Cambrian [27,37,39]; (c) in relation to the prospective areas for unconventional hydrocarbon accumulations in Lower Paleozoic shale formations [36].

In the Northern and Eastern Petroleum Provinces, conventional and unconventional (tight-type) accumulations in the Middle Cambrian sandstones [27,37,39,45,46,48,51–53], unconventional accumulations in the Lower Paleozoic shales [27–36], and Devonian and Carboniferous carbonate and clastic rocks [47–50] are expected (Figure 3). In total, 14 gas fields of resources of ~6.4 BCM (~226 BCF) and annual production of ~57 MCM (~2 BCF) of natural gas in 2020, and 8 oil fields of resources of ~6.3 MMTOE (~45 MMBOE) and annual production in 2020 of ~229 kTOE (~1.6 MMBOE) are documented in these provinces (Table 1; Figure 1). According to the balance of prospective resources deposits in Poland [27], unconventional (technically exploitable) resources of shale gas in the Lower Paleozoic strata are estimated at ~202.0–788.3 BCM (~7.1–27.8 TCF), while tight gas (technically exploitable) resources of the Cambrian Sandstones equal ~38.0 BCM (~1.3 TCF). In the Western Petroleum Province, oil and gas fields occur in the Carboniferous and three Permian horizons—Rotliegend, Zechstein Limestone, and Main Dolomite (Figure 4). Currently, 148 gas fields of resources of ~104 BCM (~3.7 TCF) and annual production of ~3.5 BCM (~124.3 BCF) of natural gas in 2020, and 38 oil fields of resources of ~14.4 MTOE (~102.7 MMBOE) and annual production of ~650 kTOE (~4.6 MMBOE) are documented in this province (Table 1; Figure 1). The unconventional tight gas (technically exploitable) resources of the Carboniferous and Permian/Rotliegend sandstones equal ~1.5–2.0 TCM (~53.0–70.6 TCF) [27]. In the Southern Petroleum Province, oil and gas fields occur in the Paleozoic-Mesozoic basement, autochthonous Miocene of the Carpathian Foredeep, and flysch belt of the Outer Carpathians. Currently, 144 gas fields of resources of ~33.1 BCM (~1.2 TCF) and annual production of ~1.4 BCM (~48.0 BCF) of natural gas in 2020 and 41 oil fields of resources of ~1.5 MTOE (~10.7 MMBOE) and annual production of ~32.9 kTOE (~235.2 MBOE) are documented in this province (Table 1; Figure 1).

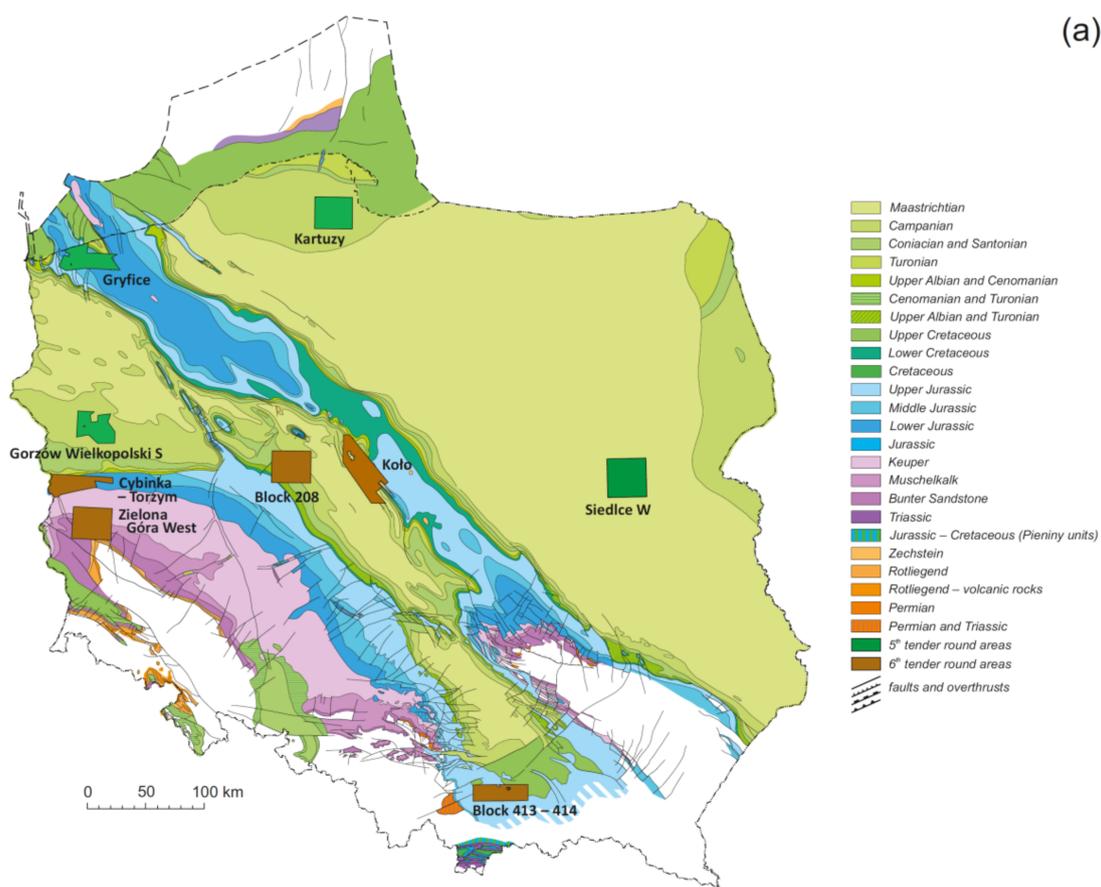


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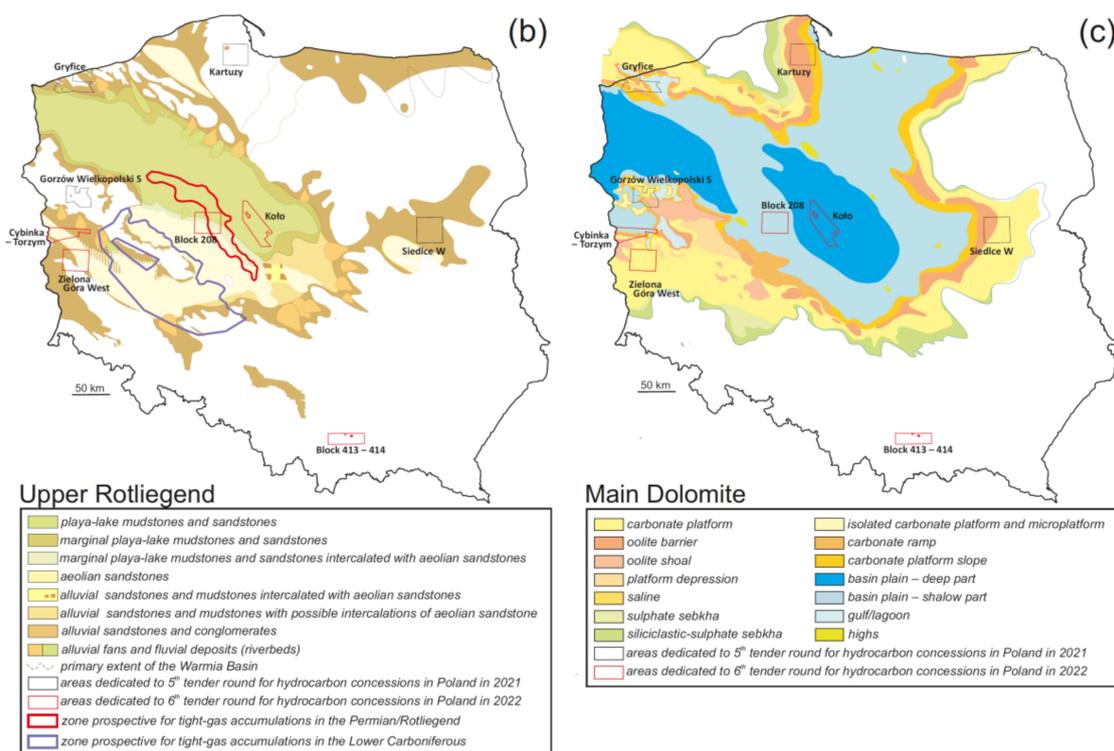


Figure 4. Location of the areas dedicated to the 5th and 6th tender rounds for hydrocarbon concessions: (a) on the Geological map of Poland without Cenozoic deposits ([54], simplified); (b) in relation to the Upper Rotliegend facies distribution [55] and prospective zones for tight-gas accumulations in the Permian/Rotliegend and Lower Carboniferous [27]; (c) in relation to the Permian/Zechstein Main Dolomite facies distribution [56].

The exploration activities can be conducted under the existing Polish licensing regime. Every entity interested in obtaining a hydrocarbon concession in Poland needs to go through the qualification procedure, being assessed in terms of state security. The application form and the requirements regarding the attachments are set out in the Regulation of the Council of Ministers [57]. According to the Polish Geological and Mining Law [58], current regulations allow two methods by which concessions can be granted. The first is the international tender procedure announced by the Polish Minister of Climate and Environment; the second is an open-door procedure, in which an entity may apply for a concession in any area that is not the subject of a tender or other concession and does not exceed an area of 1200 km² (see also [59–63]). At the end of October 2021, Poland operated 18 concessions for prospecting and exploration of hydrocarbon deposits, 53 concessions for prospecting and exploration of hydrocarbon deposits and production of hydrocarbons from the deposit, and 195 concessions for hydrocarbon production from the deposit. Moreover, 4 areas are dedicated to the 5th tender round for hydrocarbon concessions in Poland: Gorzów Wielkopolski S, Gryfice, Kartuzy, and Siedlce W tender areas (Figures 2–4) (see [63]). The tender round is planned to begin in the first half of 2022.

Table 1. Principal geological horizons of crude oil and natural gas occurrences in Poland with several fields, documented resources, production, and prospective conventional and unconventional reserves (see Figures 3 and 4) [1,2,27,48].

Petroleum Province	Geological Horizon	Type of Accumulation	Number of Documented Gas Fields	Documented Resources of Gas [MCM]	Production of Gas [MCM]	Prospective Reserves of Gas [BCM]	Number of Documented Oil Fields	Documented Resources of Oil [kTOE]	Production of Oil [kTOE]	Prospective Reserves of Oil [MTOE]
Northern and Eastern	Carboniferous	Conventional	2	50.08	0	~38.6	1	29.62	0	~19.36
	Devonian	Conventional	3	1154.99	29.54		1	6.36	0.26	
	Lower Paleozoic	Unconventional—shale-type	–	–	–	~202.0–788.3	–	–	–	~89.2–144.6
	Middle Cambrian	Unconventional—tight-type	–	–	–	~38.0	–	–	–	–
		Conventional	9	5189.44	27.03	~1.3	6	6215.27	228.3	~1.1
Western	Permian/Zechstein—Main Dolomite	Conventional	59	52,559.32	995.44	~219	38	14,381.59	649.94	~235
	Zechstein Limestone	Conventional	21	22,365.79	1474.89	–	–	–	–	–
	Permian Rotliegend	Conventional	61	26,763.87	992.75	~1410	–	–	–	–
	Permian Rotliegend	Unconventional—tight-type	–	–	–	~345–812	–	–	–	–
		Conventional	7	2762.01	56.35	~7.42	–	–	–	–
Carboniferous	Unconventional—tight-type	–	–	–	~1145	–	–	–	–	
Southern	Outer Carpathians	Conventional	34	1320.71	28.02	~30.6	29	676.7	20.29	~124.2
	Carpathian Foredeep	Conventional	99	29,985.34	1284.49	~57.1	12	815.17	12.64	~0.6
	Paleozoic-Mesozoic basement	Conventional	11	1768.96	45.47					

2. Materials and Methods

Every year, the geologists of the Polish Geological Institute-National Research Institute and the Department of Geology and Licensing of the Ministry of Climate and Environment indicate prospective areas—promising for discoveries of conventional and unconventional oil and gas deposits, based on the geological data resources stored in the National Geological Archive. From these propositions, the Polish Minister of Climate and Environment selects the areas dedicated to the international tender, which is organized to grant the concession for prospection and exploration of hydrocarbon deposits and production of hydrocarbons from the deposit.

Many prospects related to the shale-gas and shale-oil exploration during the so-called shale boom in Poland (2008–2015), as well as several research projects of the Polish Geological Survey, research institutions, and universities, dedicated to unconventional accumulations of hydrocarbons [27–43], brought new light into exploration opportunities in Poland, especially in the areas which were not previously considered as promising for new discoveries. This review refers to the results of the analysis of 127 final geological reports from the concessions, which operated during the shale boom in Poland and now are expired. Special attention was paid to why the concession expired, the scope of geological work performed, and the assessment of petroleum prospects from the entrepreneur’s point of view. As a result, five new prospective areas (free from other concessions and tender) have been selected and indicated for further exploration: Cybinka–Torzym, Zielona Góra West, Block 208, Koło, and Block 413–414 (Figures 2–5). These areas are announced by the Polish Ministry of Climate and Environments as dedicated to the 6th tender round for hydrocarbon concessions planned in the second half of 2022 [64].

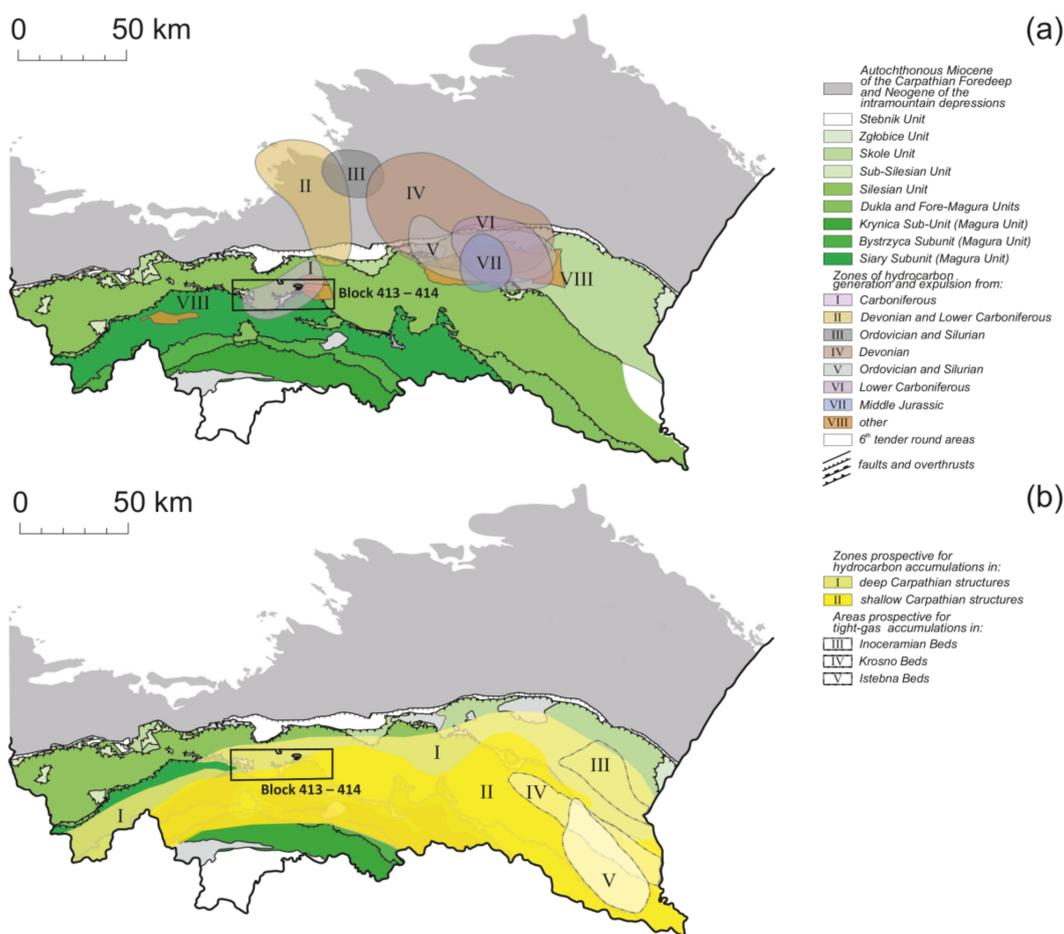


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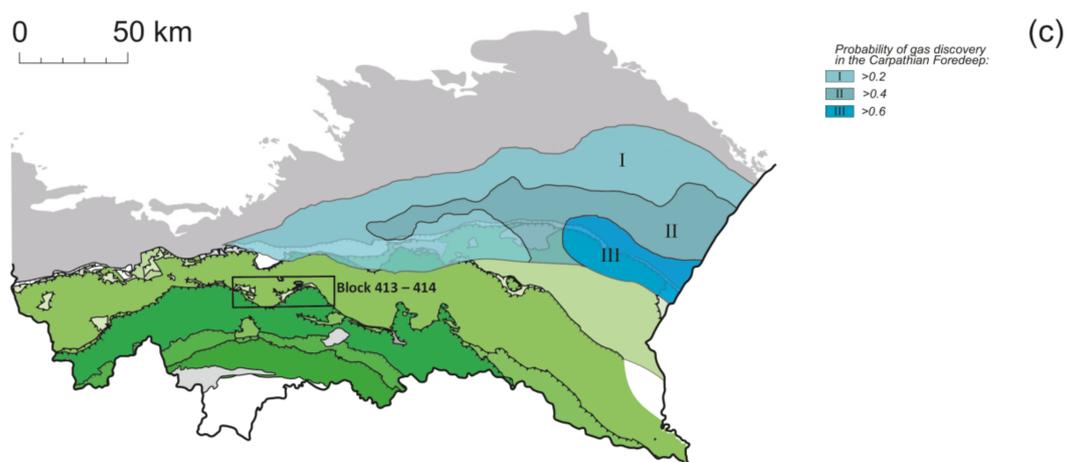


Figure 5. Hydrocarbon prospective areas in the Polish Outer Carpathians and Carpathian Foredeep: (a) zones of generation and expulsion of hydrocarbons from Paleozoic-Mesozoic basement of the Carpathian units [65]—possible petroleum exploration areas in the Southern Petroleum Province with the location of the Block 413–414 tender area; (b) zones prospective for conventional hydrocarbon occurrences in shallow and deep Carpathian structures ([66]; see also [27]) in the Southern Petroleum Province located in the Block 413–414 tender area; (c) zones with the highest discover the probability of gas-fields in the Miocene of the Carpathian Foredeep [67] in the Southern Petroleum Province located in the Block 413–414 tender area.

3. Results

3.1. Block 413–414

The Block 413–414 tender area of 666.20 km² (164,621 ac) is located in southern Poland, in the Southern Petroleum Province (Figures 2 and 5). The main exploration target is related here to conventional accumulations of gas and oil in the Silesian Nappe of the Outer Carpathians flysch belt, autochthonous Miocene of the Carpathian Foredeep, and Paleozoic-Mesozoic basement of the Carpathian units. These horizons were recognized by 118 lines of 2D seismic surveys, one 3D survey, as well as by 37 deep wells (Figure 6a). So far, four hydrocarbon fields have been discovered and documented in the close vicinity of the Block 413–414 tender area. These are the Łakta and Łapanów gas fields accumulated in Jurassic limestones, Raciborsko gas field in the autochthonous Miocene of the Carpathian Foredeep, and Słopnice oil and gas field in the Silesian Unit of the Outer Carpathians (Figure 6a). Previously, the Block 413–414 tender area was subjected to the hydrocarbon prospecting and exploration concessions no 33/99/p, 25/2001/p, and 43/2010/p, which resulted in the discovery of several prospective structures in the autochthonous Miocene of the Carpathian Foredeep and Paleozoic-Mesozoic basement.

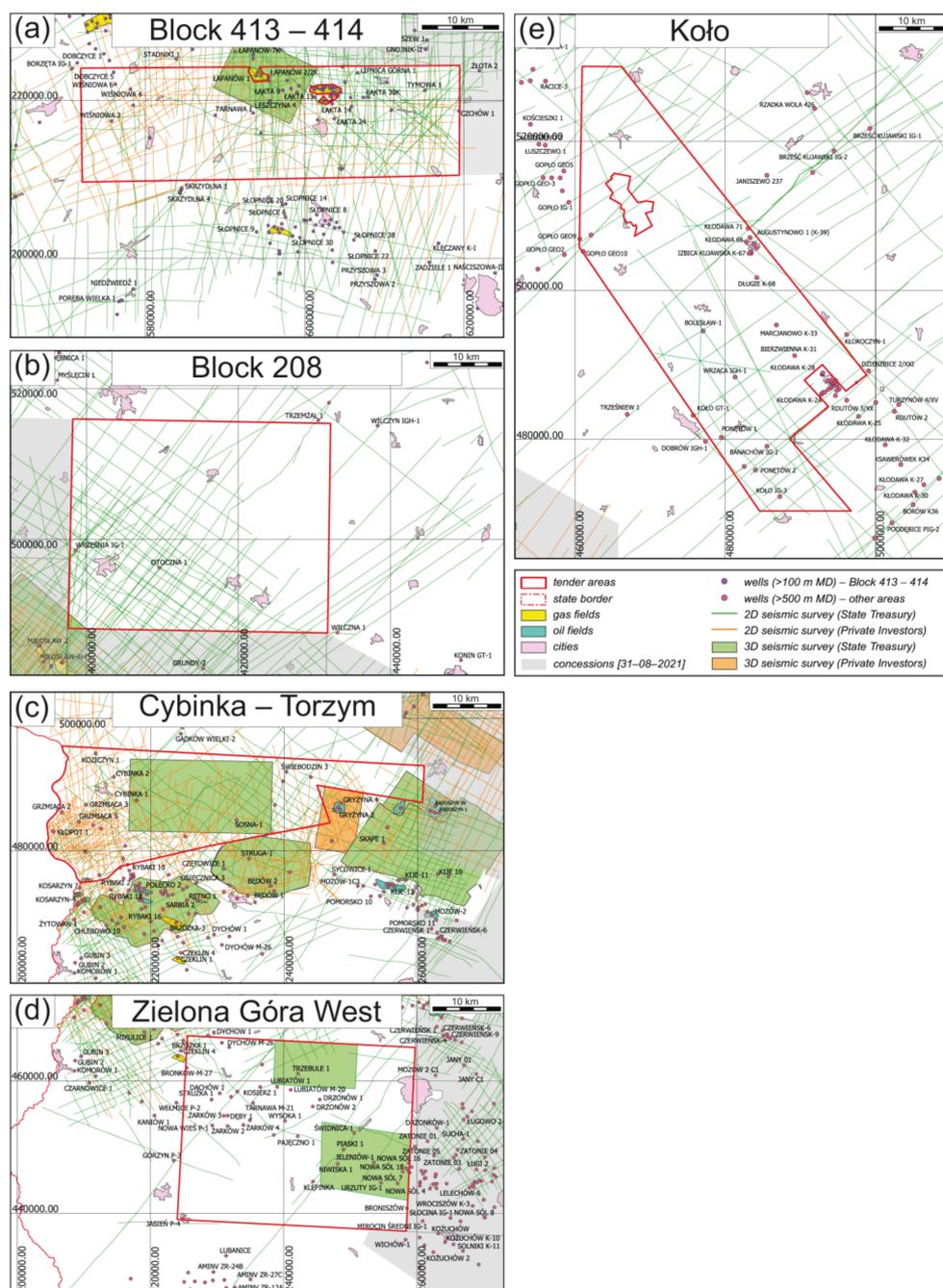


Figure 6. Location of the Block 413–414 (a), Block 208 (b), Cybinka–Torzym (c), Zielona Góra West (d), and Koło (e) tender areas in relation to the other prospecting and exploration concessions, seismic survey, deep wells, and oil and gas fields [68,69].

Block 413–414 is situated within the Outer Carpathians, at the border of the Magura, Fore-Magura, and Silesian Units (Figure 5). Below, the Sub-Silesian Unit and allochthonous Miocene of the Stebnik Units were identified in numerous wells. This folded and thrust succession covers the autochthonous Miocene of the Carpathian Foredeep. The deepest part is built of the Precambrian, Paleozoic and Mesozoic rocks of the Małopolska and Upper Silesian Blocks as the basement of the Carpathian units.

The following Magura, Fore-Magura, and Silesian units, composed of Cretaceous to Lower Miocene deposits attributed to different lithostratigraphic units of the Outer Carpathian flysch belt, occur as the uppermost structural elements in the Block 413–414 tender area. The Silesian Unit is the most important in terms of hydrocarbon exploration. It can be traced

at the surface in the northern part of Block 413–414 and dips southwardly below the Fore-Magura and Magura units to the depth above 2000 m b.g.l. (Figure 7). In the petroleum system developed in the Silesian Unit of the Outer Carpathians flysch belt, the Istebna and Krosno sandstones are assumed to be the principal reservoir rocks, in which gas and oil are accumulated in structural traps—fault-related synclines and anticlines, sealed by intercalations of fine-grained sediments, e.g., [70–73]. Hydrocarbons were generated from Menilite, Cieszyn, Verovice, and Lgota Beds (Figure 7), with TOC = 0.69–12.2%, locally exceeding 20%, and HI = 49–713 mg HC/g TOC in the former unit [74–84]. The process of generation of hydrocarbons has been continuous from the middle Miocene until the present in deep synclines and duplex zones in the Silesian Unit, e.g., [74].

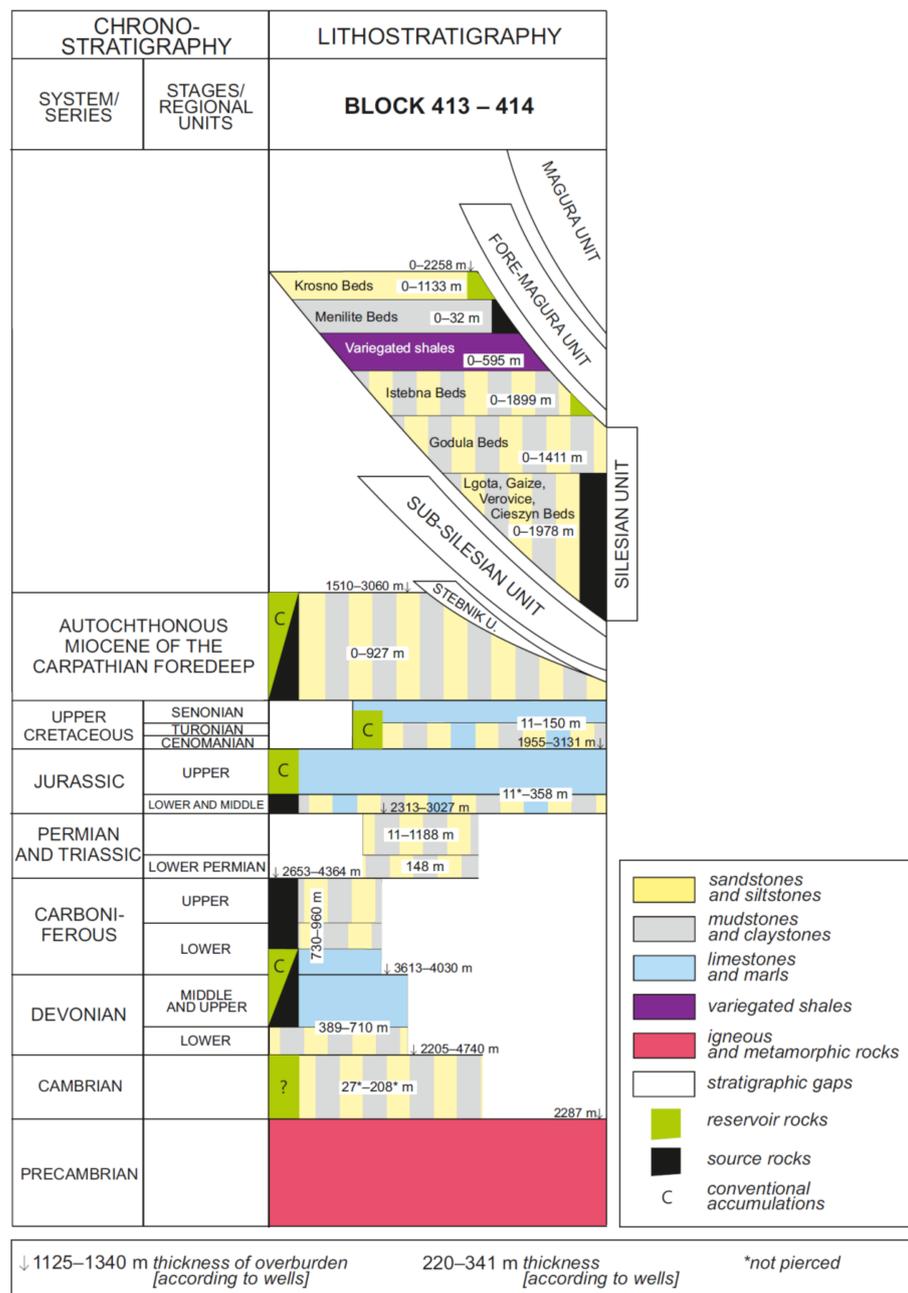


Figure 7. Stratigraphy, lithology, and petroleum system elements (horizons of source and reservoir rocks) in the Block 413–414 tender area dedicated to the 6th tender round for hydrocarbon concessions in Poland.

The autochthonous Miocene of the Carpathian Foredeep occurs below the Outer Carpathians flysch, being buried to the depths 1510–3060 m b.g.l. and reaching up to 927 m in thickness (Figure 7). This succession comprises Badenian and Sarmatian sandstones intercalated with claystones and mudstones. In its upper part, the Miocene sediments are detached, folded, and overthrust as allochthonous Stebnik Unit over the autochthonous succession. The second petroleum system is developed in the Carpathian Foredeep. It comprises stratigraphic and structural traps related to the sandstones and sands, sealed locally by numerous intercalations of claystones and mudstones. The gas was generated from type III kerogen with a small admixture of type II from organic matter dispersed in fine-grained clastic rocks. TOC = 0.02–1.48% in the Upper Badenian and 0.02–3.22% in the Lower Sarmatian rocks with HI < 200 mg HC/g TOC and T_{max} = 395 °C and immature organic matter predominate; biogenic processes were the main factor responsible for gas generation [85–91]. Only in the deeply buried autochthonous Miocene deposits, below the Carpathian overthrust, may a low-temperature thermogenic generation occur [85–91]. The regional seal of the system is formed by the Stebnik and Carpathians napes.

The basement of the Block 413–414 is formed of Precambrian folded and slightly metamorphosed claystones and conglomerates. Only one well—Wisniowa 6—reached the Precambrian at a depth of 2287 m b.g.l. (Figure 7). Above, the Cambrian sandstones, mudstones and claystones occur, with thickness ranging from at least 27 m to 208 m. They are covered by similar deposits attributed to the Lower Devonian, and above by the Middle to Upper Devonian carbonate rocks (organodetrritic and organogenic limestones). The total thickness of the Devonian is up to 710 m, and its upper surface lies at depth 3613–4030 m b.g.l. (Figure 7). The lowermost Carboniferous carbonates, as well as younger Carboniferous clastic rocks, form a 730–960 m thick complex, which upper surface was drilled at depth 2653–4364 m b.g.l. The Permian and probably Lower Triassic succession (up to 1337 m in thickness) is composed of different kinds of variegated clastics, recognized in the Liplas–Tarnawa tectonic trough (central part of the tender area). The listed above strata do not form a continuous cover in Block 413–414. Only the Jurassic succession occurs at the basement in the whole area, composed of carbonate-clastic rocks at the Lower to Middle Jurassic base and carbonate rocks at the top. The total thickness of the Jurassic succession is 11–358 m, and the depth of the top surface lies on 1955–3131 m b.g.l. (Figure 7). In the eastern part of the Block 413–414 tender area, the Jurassic is covered by Cenomanian and Turonian carbonate and clastic rocks and Senonian carbonates 11–150 m in thickness. The petroleum systems related to this Paleozoic-Mesozoic succession comprise hydrocarbons accumulated in Cambrian sandstones and the Devonian and Lower Carboniferous carbonates. In the Jurassic carbonates, as well as in the Cretaceous sandstones, commercial accumulations of gas and oil occur in the vicinity of the tender area. In the neighborhood of the Block 413–414 Kotarba et al. [65,92] indicated three horizons of source rocks: Middle to Upper Devonian carbonates with TOC = 0.0–2.6%, T_{max} = 428–466 °C, S₂ = 0.0–7.4 mg HC/g, HI = 0–367 mg HC/g TOC, OI = 10–219 mg CO₂/g TOC and predominance of type II kerogen, Carboniferous sediments: carbonates of Mississippian with TOC = 0.01–5.0%, T_{max} = 416–468 °C, S₂ = 0.13–13.7 mg HC/g, HI = 37–361 mg HC/g TOC, OI = 14–130 mg CO₂/g TOC, R_o = 0.92–1.0% and predominance of type II/III kerogen, and Mississippian clastics (“Kulm facies”) with TOC = 0.00–2.8%, T_{max} = 432–451 °C, S₂ = 0.33–3.0 mg HC/g, HI = 47–116 mg HC/g, OI = 7–73 mg CO₂/g TOC and predominance of type II/III kerogen. Indicated also were Lower to Middle Jurassic shales with TOC = 0.0–15.7%, T_{max} = 407–432 °C, S₂ = 0.22–43.1 mg HC/g, HI = 62–467 mg HC/g TOC, OI = 3–121 mg CO₂/g TOC and predominance of type III/II kerogen, but as immature they cannot be treated as source rock horizon. At least two stages of thermogenic hydrocarbon generation occurred in the Paleozoic-Mesozoic basement in the western part of the basement of the Carpathian Foredeep: first at the turn of the late Jurassic and early Cretaceous and second in the Miocene during the Carpathian overthrusting [65]. The petroleum expulsion process proceeded only from the Devonian and Carboniferous source rocks. The migration moved the expelled hydrocarbons to the Upper Jurassic carbon-

ates and the Upper Cretaceous sandstones during overthrusts of the Carpathian nappes in the Miocene [65]. However, according to burial and thermal history modeling of the Paleozoic-Mesozoic basement in the central part of the Polish Outer Carpathians (between Cracow and Dębica) [93], the Devonian and Carboniferous rocks cannot be an effective and important source rock for many Mesozoic petroleum fields, as their hydrocarbon potential was exhausted in the late Triassic to early Jurassic interval—before trap formation. The origin of hydrocarbons accumulated in the Mesozoic reservoirs is therefore in question: they may be generated from, e.g., Carpathian Oligocene Menilite shales and migrate to the Carpathian basement ([93], see also [94]).

3.2. Block 208 Tender Area

The Block 208 tender area of 946.10 km² (233,786 ac) is located in the central-western part of Poland, in the Western Petroleum Province (Figures 2 and 4). The main exploration target here is related to unconventional accumulations of gas in the Permian Upper Rotliegend and Carboniferous horizons [27,38,95–97], secondary to conventional accumulations of oil and gas in the Zechstein Main Dolomite (Figures 2, 3 and 8). No hydrocarbon fields have been discovered within the Block 208 tender area (Figure 6b). However, in the south-west and south vicinity, 8 conventional gas fields have been discovered in the Upper Rotliegend sandstones: Kromolice S, Kromolice, Środa Wielkopolska, Winna Góra, Miłosław, Miłosław E, Lisewo, and Komorze. All these gas fields are documented, and some are developed, each of them being explored by 3D seismic surveys and at least a couple of wells. The Upper Rotliegend sandstones in these gas fields are of relatively low to medium permeability (0–19.88 mD); however, they can still be classified as conventional reservoir rocks. Tight gas accumulations have been discovered west of Block 208, on neighboring Siekierki-Trzek block 207, in several wells: Trzek 1, 2, and 3, and Krzesinki 1, in combined conventional structural and unconventional traps. These discoveries are still not being documented as gas fields. Tight gas accumulations have been discovered west on block 208, on neighboring Siekierki-Trzek block 207, in several wells (Trzek 1, 2, and 3, and Krzesinki 1), in combined conventional structural traps and unconventional traps. These discoveries are still being not documented as gas fields. The Block 208 tender area was previously included in the hydrocarbon prospecting and exploration concession no 5/03/p, which resulted in the discovery of several prospective structures in the Rotliegend, which remained undrilled. Results of the studies in the frames of concession no. 5/03/p also pointed out a possibility of the existence of prospective reef structures within the Main Dolomite. However, such structures cannot be mapped using available 2D seismic data. No 3D seismic survey has been carried out there except a very small area in the SW corner of the Block 208 area, which covered neighboring hydrocarbon prospecting and exploration concessions. Available 2D seismic data include results of several 2D reflection seismic surveys completed in the 1970s, 1980s, and 1990s, generally covering SW part of the Block 208 area, 2D seismic surveys of 2005–2010 covering the southernmost part of the area (in total 10 profiles), a 2D seismic survey carried out in 2010 in the frames of the concession no 5/03/p (9 profiles) and the newest 2D seismic survey of 2019 covering most of the area (19 profiles; Figure 6b). NE part of the Block 208 area is unexplored by seismic. Only 2 deep wells—Otoczna 1 and Września IG-1—reached the Permian deposits within the tender area (Figure 6b).

The Block 208 area is situated in the Mogilno–Łódź segment of the Szczecin–Miechów Synclinorium, at the border of the Fore-Sudetic Monocline (Figure 4) [98,99]. Below, the Carboniferous strata of the Variscan Foreland basin occur, which covers the older Variscan basement (Figure 3). The thickness of the Main Dolomite recorded at depth 3769 m b.g.l. in the only well drilling through Zechstein within the area is 3.5 m. However, in another well, a few kilometers south, the Main Dolomite is 31 m thick and, according to results of 2D seismic, might have achieved similar thickness in southern and south-western parts of Block 208. The tender area is located quite far from any documented hydrocarbon field in the Main Dolomite—the closest one is the Buk oil and gas field located about 70 km

westward (see [70]. This horizon can play the role of a closed petroleum system (sealed from base and top by Zechstein evaporites), in which source rocks are intercalated with carbonate reservoir rocks (Figure 8) [100].

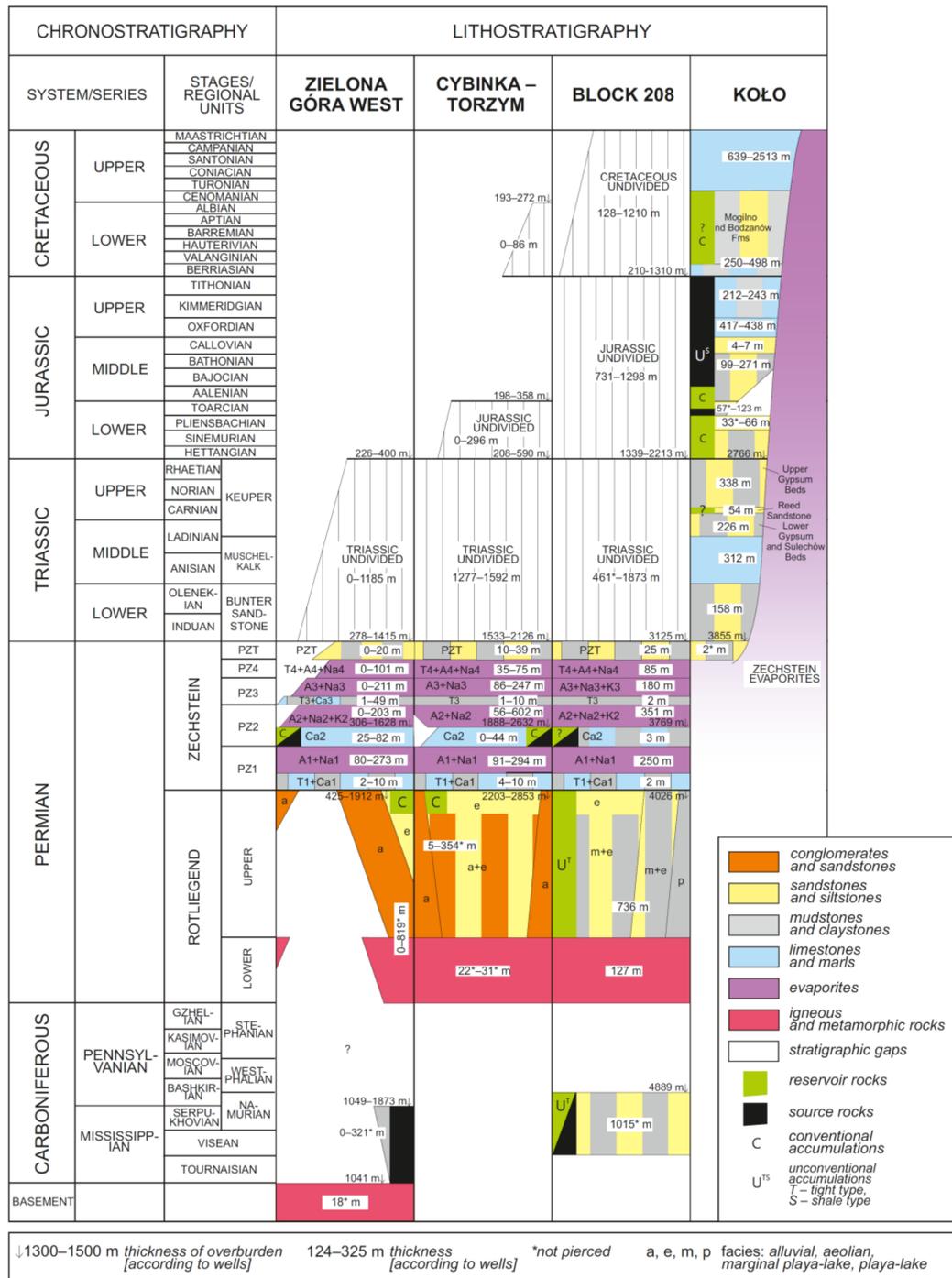


Figure 8. Stratigraphy, lithology, and petroleum system elements (horizons of source and reservoir rocks) in Block 208, Cybinka-Torzym, Zielona Góra West, and Koło tender area dedicated to the 6th tender round for hydrocarbon concessions in Poland.

The Upper Rotliegend horizon, which was drilled at depth 4026 m b.g.l. in the same well (Figure 8), generally includes 736 m fine-grained quartz sandstones with clayey-calcareous-ferruginous cement. Their petrophysical properties are varied [101,102]. The

porosity of Rotliegend sandstones within the tender area and its immediate vicinity is estimated as of 9–16% at best and average permeability up to 1 mD, possibly within the range of tight reservoirs in some areas [101,102]. The sediments of the Upper Rotliegend are mainly eolian (in SW and S part) and marginal playa-lake facies (Figures 4 and 7). The gas was generated from deeply buried Carboniferous flysch sediments deposited in the Variscan Foreland basin [103].

The Lower Carboniferous horizon was drilled only at depth 4889 m b.g.l. (Figure 8). A diverse lithology (sandstones, mudstones, and claystones) of 1015 m thick (not pierced) are characterized by relatively poor reservoir properties (mostly 1–2% of total porosity, 0–3 mD of permeability)—permeability and porosity of sandstones might be unsuitable for either conventional or tight reservoirs [97]. Any prospects for tight reservoirs in Lower Carboniferous sediments in the Block 208 area should be considered in its southern and south-western parts.

3.3. *Cybinka–Torzym and Zielona Góra West Tender Areas*

The Cybinka–Torzym tender area of 668.50 km² (165.189 ac) and Zielona Góra West tender area of 954.57 km² (235.879 ac) are located in western Poland in the Western Petroleum Province (Figures 2 and 4). The main exploration target is related here to conventional accumulations of gas and oil in the Permian Zechstein Main Dolomite and, less important, in the Upper Rotliegend horizons (Figures 2, 4 and 8) [96,102–112]. Numerous hydrocarbon fields have been discovered and documented in the southern and eastern part of the Cybinka–Torzym area in the Main Dolomite horizon (Brzózka, Czeklin, Gryżyna, Kije, Kije NE, Kosarzyn N, Kosarzyn S, Kosarzyn E, Ołobok; Figure 6c). These traps are visibly related to the palaeogeographic distribution of the carbonate platform edge zone facies, as well as their subsequent structural remodeling (Figure 4). So far, seismic surveys, including 219 profiles 2D and 3 surveys 3D, as well as 23 deep wells reaching or piercing the Main Dolomite, have been performed in the Cybinka–Torzym tender area (Figure 6c). Previously, the region was subjected to the hydrocarbon prospecting and exploration concessions no 6/2008/p and 8/2008/p, which resulted in the discovery of several prospective structures in the Main Dolomite, which remained undrilled [7].

In the vicinity of the Zielona Góra West, the Mozów S, Czeklin, and Nowa Sól hydrocarbon fields have been discovered in the Main Dolomite (Figure 6d). So far, seismic surveys, including 35 lines 2D and 2 surveys 3D, as well as 37 deep wells reaching or piercing the Main Dolomite, have been in the Zielona Góra West tender area (Figure 6d). Previously, the region was subjected to the hydrocarbon prospecting and exploration concessions no 14/2007/p, which resulted in discovering the Niwisko structure in the Main Dolomite, assuming that oil and type of trap are analogous to the Nowa Sól field. Based on available data, the investor estimated the chance of geological success at 28% due to the possible absence of an effective seal.

The Cybinka–Torzym and Zielona Góra West areas are situated in the Fore-Sudetic Monocline—one of the main structural units of the Permian-Mesozoic (Laramide) succession (Figure 4) (see [98,99]). Below, the Carboniferous strata of the Variscan Foreland basin occur, which covers the older Variscan basement (Figure 3). The Main Dolomite is up to 44 m in thickness and buried up to 1888–2632 m b.g.l. in the Cybinka–Torzym tender area, and is up to 82 m in thickness and buried up to 306–1628 m b.g.l. in the Zielona Góra West tender area (Figure 8). In both cases, this horizon plays a role in the closed petroleum system, sealed from top and bottom by Zechstein evaporites (Figure 8), e.g., [104]. In this system, source rocks are intercalated with carbonate reservoir rocks. The Main Dolomite basin was highly variable in western Poland: platform lagoons were separated from the slope by carbonate sand bars, and the platform margin was dissected by large-scale deep embayments and intervening salients (Figure 4). Microbialites originated in the carbonate platform and slope environments, as well as basin fine-grained organic-rich sediments, are supposed to be the source rocks [105]. They were deposited close to reservoir facies within the same basin. Crude oils accumulated in the Main Dolomite rocks of the Fore-Sudetic Monocline were

generated from type II kerogen. The natural gas usually contains considerable amounts of H₂S. The main generation phase of liquid hydrocarbons from the Main Dolomite deposits span from the late Triassic, the early and the Middle Jurassic times up to the beginning of Late Jurassic [104].

The Rotliegend horizon, which is buried 2203–2853 m b.g.l. in the Cybinka–Torzym tender area and 425–1912 m b.g.l. in the Zielona Góra West tender area is an additional target for gas exploration in western Poland (Figures 4 and 8). The Rotliegend lithology includes fine-grained quartz sandstones with clayey-calcareous-ferruginous cement. Their petrophysical properties are varied. The porosity of Rotliegend sandstones is 15–20% on average, and permeability varies from 2.5 to 60 mD, e.g., [70]. The sediments of the Upper Rotliegend are mainly eolian and less commonly fluvial facies (Figures 3 and 7) [55,95,113–117]. The gas accumulated within the Rotliegend is almost free of higher gaseous hydrocarbons and hydrogen sulfide but has admixtures of helium of up to 0.3–0.45%. The gas quality decreases westwards, where 5–10% (Cybinka–Torzym) and 10–20% (Zielona Góra West) of methane, and 95–80% of nitrogen occur in hydrocarbon fields. The gas was generated from deeply buried Carboniferous flysch sediments deposited in the Variscan Foreland basin [103]. Carboniferous source rocks are mainly shales with dispersed organic matter HI values ranging from 60 to 360 mg/g TOC, T_{max} = 440–520 °C [118]. Organic-carbon content is generally low (up to 4%). The organic material consists mainly of vitrinite group macerals, gas-prone type III kerogen [103]. Transformation ratios of Carboniferous deposits correlate to the thermogenic dry-gas phase, due to Early Permian magmatism, deep burial, and hydrothermal activity. The major trap formation and migration in Rotliegend probably took place during Triassic and Jurassic times [103]. The second migration phase in the Late Cretaceous was less intense during Laramide orogeny. The traps are mostly stratigraphic and may be stratigraphic/structural (fault-related) [119].

3.4. Koło Tender Area

The Koło tender area of 1035.32 km² (255.883 ac) is located in central Poland, in the Western Petroleum Province (Figure 2). The main exploration target is related to possible conventional and unconventional accumulations of gas and oil expected in the Triassic, Jurassic, and Cretaceous rocks (Figure 8). Oil and gas fields within Mesozoic formations in the Koło tender area and its vicinity have not yet been discovered. Poor seismic (57 profiles 2D) and drilling (22 deep wells > 500 m MD) investigations, limited mostly to the exploration of brown coal and salts deposits, have been performed in the Koło tender area (Figure 6e). Previously, the area was subjected to hydrocarbon prospecting and exploration concession no 53/2011/p, which resulted in the discovery of one prospective structure related to the Kłodawa salt diapir. This structure has not been drilled out.

The Koło area is situated at the borderland of the Mid-Polish Anticlinorium (Kujawy segment) and Szczecin–Łódź–Miechów Synclinorium (Mogilno–Łódź segment), which form the main structural units of the Permian-Mesozoic (Laramide) succession (Figure 4) [98,99]. This succession originated as one of the numerous Mesozoic epicontinental basins of the Central European Basin System [120,121]. The occurrence of NW-SE-oriented salt pillows and diapirs, with the Kłodawa, Ponętów-Wartkowice, and the Gopło diapirs as the largest ones, is typical for the area (Figures 4 and 8) [54]. These structures, formed of Zechstein evaporites, partly pierce the Mesozoic sediments, and the stratigraphic gaps may occur in the Mesozoic and Cenozoic deposits lying above and in the neighborhood. Since the oldest rocks drilled in the area are of the Upper Permian age, the pre-Permian basement is poorly recognized in the Koło tender area. It is presumed that Devonian and Carboniferous rocks of the Variscan Foredeep occur here (Figure 3) [98,99]. This is especially important since the Carboniferous rocks are considered the fundamental source rock not only for the Polish Lowlands but also for plenty of gas fields in Western Europe ([120–122], and citations therein). The most promising reservoirs are porous Lower and Middle Jurassic sandstones forming structural and combined structural-stratigraphic traps [123–125]. It is also possible that stratigraphic traps exist in the form of bioherms within the Oxfordian limestones,

Lower Cretaceous sandstones, and channel fillings facies of fluvial Reed Sandstone (Upper Triassic), where gas shows have already been observed in wells from the Koło area and its vicinity. Potential traps are most likely closely related to intensive salt tectonics and may have various forms: from anticlinal structures above salt pillows, through structures induced by inversion, and above sub-Zechstein uplifts, to combined structural-stratigraphic traps next to the salt diapirs [126,127]. The hydrocarbon traps formation occurred during the Late Cretaceous inversion and deformations within the Permian-Mesozoic and older sediments, including rock faulting and plastic movements of Zechstein salts. Hypothetically, hydrocarbons were able to migrate from Carboniferous source rocks located in the Zechstein basement to the younger reservoirs of Permian and Mesozoic age sealed by the shales (Mesozoic) and evaporites (Permian, Triassic, Cretaceous). Moreover, some potential for unconventional hydrocarbon exploration in the Koło tender area is also postulated: TOC = 5.5–7.5% for Middle to Upper Jurassic rocks, which reached the initial main phase of the oil window in the Cretaceous time, was investigated; nevertheless, these rocks show no hydrocarbon expulsion ([128]; compare to [129]).

4. Discussion

So far, 56 areas prospective for new oil and gas discoveries were defined in Poland by PGS (see summary in PGS Report, 2021). A total of 32 of them became subjects of four tender rounds, which were organized by the Polish Ministry of Climate and Environment for granting the concessions for prospection and exploration of hydrocarbon deposits and exploitation of hydrocarbons from the deposit. As a result of performed tenders, 11 concessions have been granted. Another four areas: Gorzów Wielkopolski S, Gryfice, Kartuzy, and Siedlce W are subjected to the 5th tender round for hydrocarbon concessions in Poland, planned in the first half of 2022 (Figures 2–4). These areas are dedicated to prospection and exploration of conventional oil and gas fields in the Middle Cambrian, Carboniferous, Permian–Rotliegend, and Permian–Zechstein/Main Dolomite, as well as unconventional gas accumulations in the Lower Paleozoic shales.

The areas described in this review are subjected to the 6th tender round for granting the concessions for prospection and exploration of hydrocarbon deposits and exploitation of hydrocarbons from the deposit, which is planned for 2022. Conventional accumulations of gas are highly expected in one Carpathian area—Block 413–414, in which Jurassic of the Carpathian basement, as well as Miocene of the Carpathian Foredeep and flysch succession of the Silesian Unit, are prospective. The Block 208 tender area brings possibilities of unconventional tight-gas exploration in the Permian–Rotliegend deposits and probably in the Carboniferous; moreover, some prospects are in question also in the Main Dolomite. In two cases, in the Cybinka–Torzym and Zielona Góra West areas, the main exploration target is related to conventional accumulations of gas and oil in the Permian–Zechstein/Main Dolomite, while the Upper Rotliegend is an additional horizon of exploration, bringing another opportunity for discoveries. In the Koło area, an exploration should focus on conventional gas accumulations in the Mesozoic succession in traps related to salt diapirs, and unconventional accumulations of shale gas are also possible in the Jurassic shales.

The detailed geological data of the tender areas (location, environmental restrictions, geology, petroleum plays, hydrocarbon deposits, wells, seismic surveys, gravimetry, magnetic and magnetotelluric surveys, as well as petroleum prospectives) are collected in the individual reports (so-called geological data packages), which will be published on the following websites when the tender begins: <https://www.pgi.gov.pl/en/tender-blocks.html> (accessed on 13 December 2021); <https://bip.mos.gov.pl/koncesje-geologiczne/przetargi-na-koncesje-na-poszukiwanie-rozpoznawanie-i-wydobywanie-weglowodorow/> (accessed on 13 December 2021).

These data will also be available in the data room organized in the National Geological Archive (Polish Geological Institute–National Research Institute, 4 Rakowiecka Street, Warsaw, Poland) during the tender.

An entity may also apply for a concession for any area that is not a subject of a tender or other concession (so-called open door procedure). However, the area cannot exceed 1200 km². In both cases, the concession is granted for a period from 10 to 30 years and is divided into (I) the exploration phase and (II) the production phase (starts after obtaining an investment decision). If a deposit is documented or partly documented, it is also provided that the hydrocarbon production from the deposit can be started even as the exploration phase is still underway.

According to the recent proposals to change the geological and mining law in Poland, the extraction of hydrocarbons may be combined with the storage of carbon dioxide, which makes it possible to return to the many depleted oil and gas fields in Poland. This may be the industry's greatest growth impulse since the shale boom in Poland. Especially the Permian fields seem to be the best target because of their proven complete tightness. In the Cybinka–Torzym area, such a field is the Kosarzyn N oil field, in which 34.5 kTOE (258 MBOE) of oil and 5.61 MCM (0.2 BCF) of gas from the recoverable resources were extracted until 2014 [69], while the initial geological resources were estimated at 109 kTOE (816 MBOE) of oil. A recovery factor amounted to 31%. The production was discontinued in 2014 due to the water cut of the Kosarzyn-8 well. Tests carried out on hydrocarbon deposits in the United States have proven that CO₂ injection may increase the recovery factor from 5 to 25% [130], or, when selecting the most effective method, can be enhanced by 30–40% [131].

5. Conclusions

- The 6th international tender round for granting the concessions for prospecting and exploration of hydrocarbon deposits and exploitation hydrocarbons from the deposit is planned for the second half of 2022.
- Five areas have been announced by the Polish Minister of Climate and Environment as the subject of the 6th tender round. These are Block 413–414, located within the Outer Carpathians, Block 208, Cybinka–Torzym, Zielona Góra West, and Koło, located in the Polish Lowland.
- Conventional accumulations of hydrocarbons are expected in the Paleozoic-Mesozoic strata of the Carpathian basement, as well as in the autochthonous Miocene of the Carpathian Foredeep and the Outer Carpathians in the Block 413–414 area.
- Unconventional accumulations of tight-gas in the Lower Permian–Rotliegend and Carboniferous strata are expected in Block 208, while conventional accumulations of oil and gas in the Upper Permian–Zechstein/Main Dolomite rocks are less probable, although not completely excluded.
- The main exploration target of the Cybinka–Torzym and Zielona Góra West areas is related to the conventional accumulations of gas and oil in the Upper Permian–Zechstein/Main Dolomite and conventional accumulations of gas in the Lower Permian–Rotliegend.
- Conventional (salt-diapirs related traps) and unconventional (shale-type) gas accumulations are supposed to occur in the Mesozoic succession of the Koło area.
- The entities can also apply for a concession by submitting an application to the
- Ministry according to the open door policy.
- Concession is granted for 10 to 30 years and is divided into the prospecting and exploration phase and the production phase.
- The Polish Minister of Climate and Environment is the concession authority on the territory of Poland.

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