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Coal Properties and Coalbed Methane Potential in the Southern Part of the Upper Silesian Coal Basin, Poland

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Abstract: The area studied covers unmined Pennsylvanian Ćwiklice and Dankowice coal deposits located in the southern part of the Upper Silesian Coal Basin, Poland. The geological structure of the area clearly affects the current distribution of methane. The content of methane is lower in coal seams lying within porous and permeable sandstones (Łaziska sandstones), whereas it is higher in seams that occur in sequences (Mudstone Series) where impermeable shales and mudstones occur. Due to the previous attempts to extract methane from boreholes, this area, characterized by a dense network of exploratory and prospecting drillings, is worth analyzing with regard to the conditions of methane occurrence in terms of extraction possibilities. Using contour maps, cross-sections and profiles, the variability of methane content and resources, as well as the moisture and ash content of coal seams, were analyzed. Methane content isolines are parallel to the boundary between the Cracow Sandstone Series and the Mudstone Series and to main faults. Coal moisture contents clearly reduce methane contents. A high methane content >8 m^3/t $coal^{daf}$ is typical for coal seams in which moisture contents do not exceed 5%. High- and medium-volatile bituminous coal in the area is characterized by low methane saturation, though saturation increases with depth. Coal permeability is variable (from 0.2 to more than 100 mD), but, below a depth of 1200 m, a clear trend of decreasing permeability with depth is evident. From the point of view of coalbed methane (CBM) recovery, relatively low coal permeabilities and methane saturation levels could make CBM output problematic in the studied area. Methane production will be more probable as a result of demethanation of the Dankowice 1 deposit, where coal mining is planned. This will result in the emission of methane into the atmosphere from ventilation shafts and methane drainage stations. Therefore, effective use of the gas captured by the methane drainage station is highly desirable for environmental and economic reasons.

Keywords: methane content; Moscovian Łaziska sandstones; tectonics; coal permeability; methane emissions; the Upper Silesian Coal Basin; Poland

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1. Introduction

Natural gas is considered the most ecological fuel among fossil fuels because it is characterized by clean combustion; it does not emit dust, soot and other harmful substances; and the emission of carbon dioxide is much lower than in the case of coal combustion. Methane accompanying coal deposits is a significant fire and explosion hazard during exploitation, but on the other hand, if properly managed, it can be a valuable energy resource. At the same time, the methane hazard is decreasing [1,2]. It is possible to exploit methane from both working and abandoned coal mines and from the so-called virgin fields, from which methane is extracted (as an unconventional gas) without or independently of coal, as in countries such as the USA, Australia and China.

In Poland, methane is extracted only in the Upper Silesian Coal Basin (USCB) from methane drainage of working and abandoned mines in the amount of approximately 200–300 million m^3 per year. Methane is also present in undeveloped coal deposits, where it may be a potential target for exploitation in the future. So far, the balance of resources of methane in areas outside the current hard coal mining in the USCB has been estimated at over 38 billion m^3 [3].

Two unmined Ćwiklice and Dankowice coal deposits in the southern part of the USCB (Figure 1), (Poland) were tested for coalbed methane (CBM) extraction in the 1990s by the companies Amoco and Metanel. In the neighboring area of Międzyrzecze, the Polish Oil and Gas Company (PGNiG) with the Polish Geological Institute tested CBM potential using a surface-to-inseam horizontal well that intersected a vertical production well. The results of the methane production test were satisfactory; however, this project was discontinued in 2019. During the current energy crisis and the uncertainty of energy supplies [4], studies on the possibilities of developing domestic energy resources (e.g., [5]) have become justified.

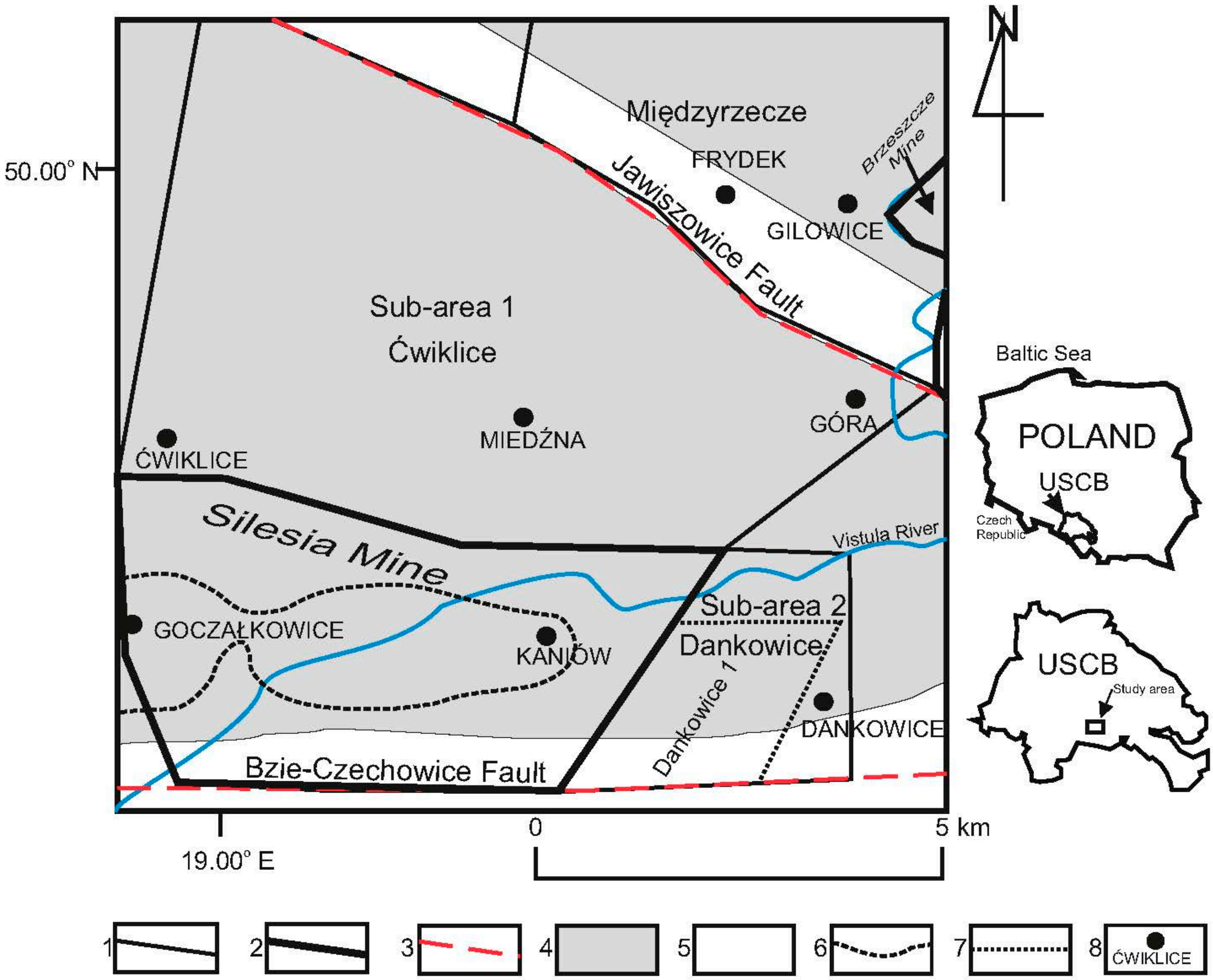


Figure 1. Location of the Ćwiklice and Dankowice sub-areas; 1—boundaries of coal fields, 2—boundaries of working mines, 3—important faults, 4—Cracow Sandstone Series, 5—Mudstone Series, 6—boundaries of free methane deposit "Silesia", 7—boundaries of Silesia 1 area with planned coal and methane exploitation, 8—important towns.

The Silesia coal mine, which exists nearby, is applying for a coal mining license in the Dankowice area and will face gas hazards if mining is initiated. The area of Ćwiklice, undeveloped for mining, is also an interesting area in terms of the possibility of methane development [6,7].

Successful exploitation of coalbed methane depends on a combination of various factors including, namely, the geological setting of methane accumulation, coal saturation with methane and coal properties such as porosity and especially permeability [8–15]. In addition to world leaders in CBM production, such as Australia and the USA, there has recently been a significant development of experimental methods of borehole methane output in China, with an emphasis on horizontal and multilateral boreholes, taking into account various geological, technical and depth conditions, etc. [16–19].

The area studied is characterized by methane-bearing coal seams with methane contents of ca. 1–17 m^3/t coal^{daf} and the occurrence of high- to medium-volatile bituminous coal [7,20]. In addition, a thick package of porous and permeable Moscovian Łaziska sandstones at the top of Pennsylvanian strata and regional dislocations, e.g., the Jawiszowice Fault, make the area interesting from a geological perspective. Due to methane exploitation tests carried out in the area and promising methane potential, the Ćwiklice and Dankowice coal deposits merit further testing for gas recovery. A dense network of drillings (on average 2 km by 2 km) makes it possible to create contour maps, cross-sections and profiles on the variability of the most important parameters (e.g., methane content and resources), which may be useful in assessing the possibility of further detailed research on CBM mining in the analyzed area.

Methane is a greenhouse gas, with a global warming potential (GWP) ranging from 20 to 36 times greater than that of carbon dioxide over a 100 year time period [21] [and references therein]. Coal mining is responsible for 6% of global methane emissions [2,22]. In 2021, USCB coal mines emitted approximately 600 million cubic meters of methane into the atmosphere. The USCB, as the most industrialized region in Poland, is responsible for a significant amount of methane released into the atmosphere—almost entirely from hard coal mining. Taking into account the ventilation emission and the exhaust of unused methane from the methane drainage station, it was determined that CH_4 from mines in the period 1994–2018 was responsible for 18–27% of the total emission of this gas in Poland and for only 3% when taking into account the emission of methane from the USCB to the emission of all greenhouse gases [23]. Therefore, the environmental impact of methane emissions related to the exploitation of coal and methane as an accompanying or main mineral cannot be ignored.

The aim of this study is to analyze the variability of methane contents in coal seams regarding the geological setting of the area, as well as coal rank and coal quality (moisture- and ash contents). For this purpose, maps of the variability of selected parameters characterizing the deposit, such as methane content, resources, moisture and ash, were constructed in order to determine the variability of these parameters. The saturation of the seams with methane and coal permeability were also analyzed. Based on the results, zones particularly enriched with methane have been selected, highlighting the advantages and disadvantages of the operating conditions. The possibility of methane emission into the atmosphere was also discussed, taking into account the current emission from the neighboring working mines.

2. The Area of Research

The area lies in the southern part of the USCB, within the Main Syncline in the faulted zone of the USCB. It covers unmined coal deposits in the Ćwiklice and Dankowice fields (Figure 1). Two nearby working coal mines, Silesia and Brzeszcze, are among the most gas-rich mines in the USCB.

2.1. Outline of Geology

Three lithostratigraphic complexes have been distinguished in the area. These are (a) carbonate and clastic Devonian and Lower Mississippian strata forming the basement of the Carboniferous coal-bearing beds, (b) Carboniferous (Upper Mississippian and Pennsylvanian) clastic rocks that constitute the coal-bearing sequence and (c) an overburden of Miocene strata and Quaternary deposits.

The Carboniferous coal-bearing sequence involves several lithostratigraphic series. The oldest Serpukhovian Paralic Series with marine horizons lies in the lowermost part of the sequence. The Lower Bashkirian Upper Silesian Sandstone Series, the Upper Bashkirian Mudstone Series and the youngest Moscovian Cracow Sandstone Series comprise continental sediments only [24]. All the Carboniferous series include clastic claystones, mudstones and sandstones with numerous coal seams (Figure 2). The boundary between the Carboniferous coal-bearing sequence and the Miocene strata is an erosive surface of varied morphology marked by a sandy breccia mixed with Miocene shales [6,7,24–26].

Stratigraphy			Lithostratigraphic division (after Kotas, 1995)		Series lithology	Coal seams identification numbers	Thickness of series
CARBONIFEROUS	PENSYLVANIAN	Moscovian	Libiąż Beds	Cracow Sandstone Series	Substantial portion of coarse grained and porous Łaziska sandstones that constitutes about 80% of the series profile. Claystones and mudstones with several meter thickness accompany the coal seams.	118	Several hundred to >1000 m
			Łaziska Beds			201-216	
		Bashkirian	Orzesze Beds	Mudstone Series	Claystones and mudstones predominate (60-80% of the profile) over sandstones occurring as thin beds. Tuffite horizons are present. Numerous thin coal seams occur.	301-327	300-1000 m on average
			Załęże Beds			328-364 401-406	
			Ruda Beds	Upper Silesian Sandstone Series	Fine-grained sandstones predominate over mudstones and claystones. Thick but less numerous coal seams occur in both Ruda and Saddle Beds (the thickest seam no 510 reaches 10 m of thickness)	407-420	0-200 m
			Saddle (Zabrze) Beds			501-510	
	MISSISSIPPIAN	Serpukhovian	Grodziec Beds	Paralic Series	Largely composed of sandstones with, in addition, claystones and mudstones with coal seams. Marine horizons occur.	601-620	400-600 m

Figure 2. Stratigraphy of the coal-bearing series after [7,26].

Miocene shales with sandstone intercalations of the Skawina Formation (90–700 m) provide a cover for the Carboniferous coal-bearing sequence over the entire area. This formation constitutes the molasse of the Carpathian Foredeep covering the southern part of the USCB. The Quaternary deposits also blanketing the entire area are glacial and fluvial sands and clays that are thickest in river valleys.

The area lies within the south-eastern part of the faulted zone on the southern flank of the Main Syncline trending in a NW–SE direction. This monoclinal structure is cut by numerous faults [7]. The major faults are some large NW–SE dislocations, e.g., the Bzie-Czechowice Fault and the Jawiszowice Fault (Figure 1). Both of these regional USCB structures have throws of several hundred meters to the south and are ca. 40 km long. They are Variscan faults rejuvenated during the Alpine orogeny [25]. Only close to the faults does the gentle N dip of the Carboniferous layers increase to ca. 30–40 degrees.

2.2. Coal Rank and Maceral Composition

Coal rank, expressed by the vitrinite reflectance (Ro), volatile matter (V^{daf}), as well as moisture (M^a) contents are low to moderate in the area. By reference to the ASTM Standard Classification of Coals by Rank, high- and medium-volatile bituminous coal dominates (power coal of types 31–34 in the Polish classification; [24]). Ro gradually increases in depth, from 0.60% at a depth of 300 m to 0.96% at 1350 m [27]. V^{daf} at a depth of 1000 m is 37–38% in the Ćwiklice area and decreases towards the south and north to 32–35% in the Dankowice area and to 31–35% in the Międzyrzecze area to the north of the Jawiszowice Fault. V^{daf} also decreases towards the large regional faults [24]. The coal rank conforms to the regional USCB pattern; it generally decreases towards the east. In contrast, the morphology of the coalification field of the USCB defines a gently undulating latitudinal pattern of eastward-plunging elevations and depressions [24].

Macerals of the vitrinite group prevail over liptinite and inertinite macerals. Vitrinite fluctuates between 40 and 70% and inertinite varies from 10 to 40%, whereas liptinite rarely exceeds 10% (average 5–8%, [27,28]).

3. Data Sources and Presentation

This work is based on archived data of methane content, defined as methane volume in a mass unit of dry and ash-free coal substance (m^3 CH_4/t $coal^{daf}$). The methane content was determined during deep exploration drillings for coal to predict the methane hazard in future mines and to prospect for methane as a fuel. In addition, other exploration wells for coalbed methane provide a complete set of methane measurements and data on coal quality. The data are archived in the National Geological Archive of the Polish Geological Institute and in the archive of Katowice Geological Enterprises. The data used in this study include methane contents in coal seams in a dry, ash-free state (G $coal^{daf}$), moisture contents in an analytical state (M^a), ash contents in an analytical state (A^a) and gas compositions. In total, 827 measurements of methane contents and 3276 measurements of gas composition from 39 boreholes were used. The boreholes, and all data used, are listed in Table 1. Information on coal properties (coal rank) and petrographic composition was obtained from the available literature data [24,27] and unpublished studies [28].

Table 1. List of boreholes drilled in the Ćwiklice and Dankowice sub-areas with numbers of data. G—methane content, M^a—moisture content, A^a—ash content.

No.	Borehole	Number of Data				
		G	M^a	A^a	Gas Composition (CH_4, C+, N_2, CO_2, H_2)	Sub-Area
1	Ćwiklice 1	19	19	19	133	1
2	Ćwiklice 2	28	28	28	196	1
3	Ćwiklice 3	33	33	33	231	1
4	Ćwiklice 4	11	10	10	77	1
5	Ćwiklice 5	24	23	23	168	1
6	Ćwiklice 6	31	30	30	217	1
7	Ćwiklice 7	21	21	21	147	1
8	Ćwiklice 8	25	25	25	175	1
9	Ćwiklice 9	32	32	32	224	1

Table 1. *Cont.*

No.	Borehole	Number of Data				
		G	M[a]	A[a]	Gas Composition (CH_4, C+, N_2, CO_2, H_2)	Sub-Area
10	Pszczyna 32	10	5	5	70	1
11	Międzyrzecze-Bieruń 18	3	1	1	-	1
12	Międzyrzecze-Bieruń 78	10	10	10	-	1
13	Międzyrzecze-Bieruń 81	11	11	11	-	1
14	Międzyrzecze-Bieruń 82	11	9	9	-	1
15	Międzyrzecze-Bieruń 83	11	10	10	-	1
16	Międzyrzecze-Bieruń 84	8	8	8	56	1
17	Międzyrzecze-Bieruń 85	8	8	8	56	1
18	Międzyrzecze-Bieruń 86	6	6	6	-	1
19	Międzyrzecze-Bieruń 87	10	8	8	-	1
20	Międzyrzecze-Bieruń 88	14	13	13	98	1
21	Międzyrzecze-Bieruń 89	6	6	6	98	1
22	Międzyrzecze-Bieruń 90	8	8	8	56	1
23	Silesia 6	8	8	8	-	2
24	Silesia 8	18	17	17	-	2
25	Silesia 14	26	26	26	-	2
26	Silesia 16	42	41	41	-	2
27	Silesia 17	18	18	18	-	2
28	Silesia 18	25	25	25	-	1
29	Silesia 19	40	40	40	-	1
30	Silesia 20	47	47	47	-	1
31	Silesia 22	59	59	62	-	1
32	Silesia 24	41	41	41	189	2
33	Silesia 25	25	25	25	175	2
34	Silesia 26	35	35	35	203	2
35	Silesia 27	36	36	36	238	2
36	Silesia 28	11	11	11	77	2
37	Silesia 29	12	12	12	84	2
38	Silesia 30	22	22	22	154	2
39	G4 SDJ	22	22	22	154	2
	TOTAL	827	809	812	3276	

In the boreholes, methane contents were determined by the method of vacuum degasification of hermetic containers used by Katowice Geological Enterprises (KPG method) [6]. The method of degasification under atmospheric pressure used by the US Bureau of Mines was only applied in the boreholes made for coalbed methane exploitation (USBM method; [29]). Of the two methods, the latter is favored, as all the coal seam is sampled and lost gas is more precisely determined. In the KPG method, only a small sample of coal is analyzed, and gas lost during sampling is calculated using the coefficient 1.196, which can lead to error. The advantage of the KPG method is the short measurement time (2 days) compared with that of the USBM method (several weeks) [15]. In this study, to accommodate the methane content measurement errors, mean values of the methane content were calculated for every 200 m borehole interval.

The area was divided into two sub-areas related to geological setting and methane content (Figure 1). Sub-area 1 includes the Ćwiklice field to the south of the Jawiszowice Fault. Sub-area 2, Dankowice field, lies to the south, adjacent to the Bzie-Czechowice Fault.

To accommodate any methane content measurement errors and the variability of methane contents within the boreholes, trend lines of mean values of methane contents for each 200 m depth interval were plotted for each sub-area. These trend lines were compared with trend lines of moisture and ash contents as determined in the laboratory.

The horizontal distribution of methane contents, coal parameters such as moisture and ash contents, the topography of the top of Upper Bashkirian Mudstone Series and methane resources are presented on contour maps prepared using the Surfer 12 program applying the natural neighbor method.

The results were compared with one another and related to the geological setting. Finally, based on the methane content and sorption capacity of coal, coal saturation with methane was indicated and coal permeability was analyzed. Data on coal sorption capacity and permeability were obtained from previous studies [15,30].

Methane resources, defined as how much methane is possible to extract per each 1 m^2 of the ground surface, were calculated using the formula:

$$Gr = G * m * \gamma \quad (1)$$

where Gr is the methane resource (m^3/m^2), G is the gas content (m^3/t $coal^{daf}$), m is coal seam thickness (m) and γ is coal gravity (t/m^3). Gas content is assumed to be the mean content within the interval from 300 to 800 m depth in individual boreholes. Coal seam thickness is a total thickness of balanced (economic) coal seams (>0.6 m) and coal gravity is an average of the laboratory results (1.35 t/m^3).

Data on methane emissions from mines were obtained from the Annual Report on the State of Basic Natural and Technical Hazards in the Hard Coal Mining Industry [31], published annually. These data cover 2021 and relate to two mines, Brzeszcze and Silesia, adjacent to the study area. The total methane emission to the atmosphere was calculated from the formula:

$$E = E_t - M\ (m^3) \quad (2)$$

where E—emission of methane to the atmosphere (m^3), E_t—total emission of methane with ventilation air and captured by methane drainage stations (m^3) and M—methane used for economic purposes (m^3). The volume of methane emitted to the atmosphere and used was converted into CO_2 equivalent (in tons) assuming methane GWP was 30 times higher than that of CO_2.

4. Methane Occurrence and Origin

The USCB is a high gas-content coal basin with spatially variable methane concentrations in coal seams and enclosing rocks. Methane occupying the coal-bearing rock sequences is mainly sorbed gas or is physically and chemically linked to the coal substance. Quantities of methane in coal seams reflect a combination of many factors such as reservoir pressure, temperature, moisture content and coal rank [7,13,21,32,33]. Fluctuation in these factors due to geological processes can result, inter alia, in methane desorption from the coal seam matrix and migration into surrounding rocks or the atmosphere, adsorption by another coal seam or accumulation in permeable sandstones [6,13,34].

Long-lasting uplift of the Carboniferous coal-bearing rock mass between the Permian and the Oligocene and its contact with the atmosphere and erosion resulted in changes in rock temperature and reservoir (hydrostatic) pressure and methane migration. An outgassed zone reaching a depth of several hundred meters was then created [6,7,13,35]. Alpine tectonic processes, such as the Carpathian Foredeep forming in the Miocene and large rejuvenated faults, likely promoted and facilitated methane's upward migration from the deeper parts of the Carboniferous rock-mass and its accumulation in previously outgassed coal seams and permeable sandstones immediately below the thick impermeable Miocene cover [6,13–15].

Thus, two main patterns of methane contents and distribution with depth evolved in the USCB [6,7]. The pattern in the northern USCB region, lacking a continuous Miocene cover, includes an upper outgassed zone of coal-bearing rocks and a lower zone with high methane concentrations. The pattern in the southern USCB region, with a thick and continuous Miocene cover, involves two high-methane zones—a secondary, near-roof zone of high methane content and a primary, deep methane-bearing zone extending down to the prospected limit (ca 1500 m). A distinct interval of lower methane contents separates the two zones.

The predominant component in coalbed gas is methane (50–90 vol.% on average). Higher hydrocarbons (ethane, propane and butane) appear at depths >1000 m; their total share amounts to several percent. The remaining components are molecular nitrogen, carbon dioxide (<6 vol.%) and hydrogen (0.2 vol.% on average). The increase in the methane content with depth entails a decrease in the nitrogen content. (Figure 3).

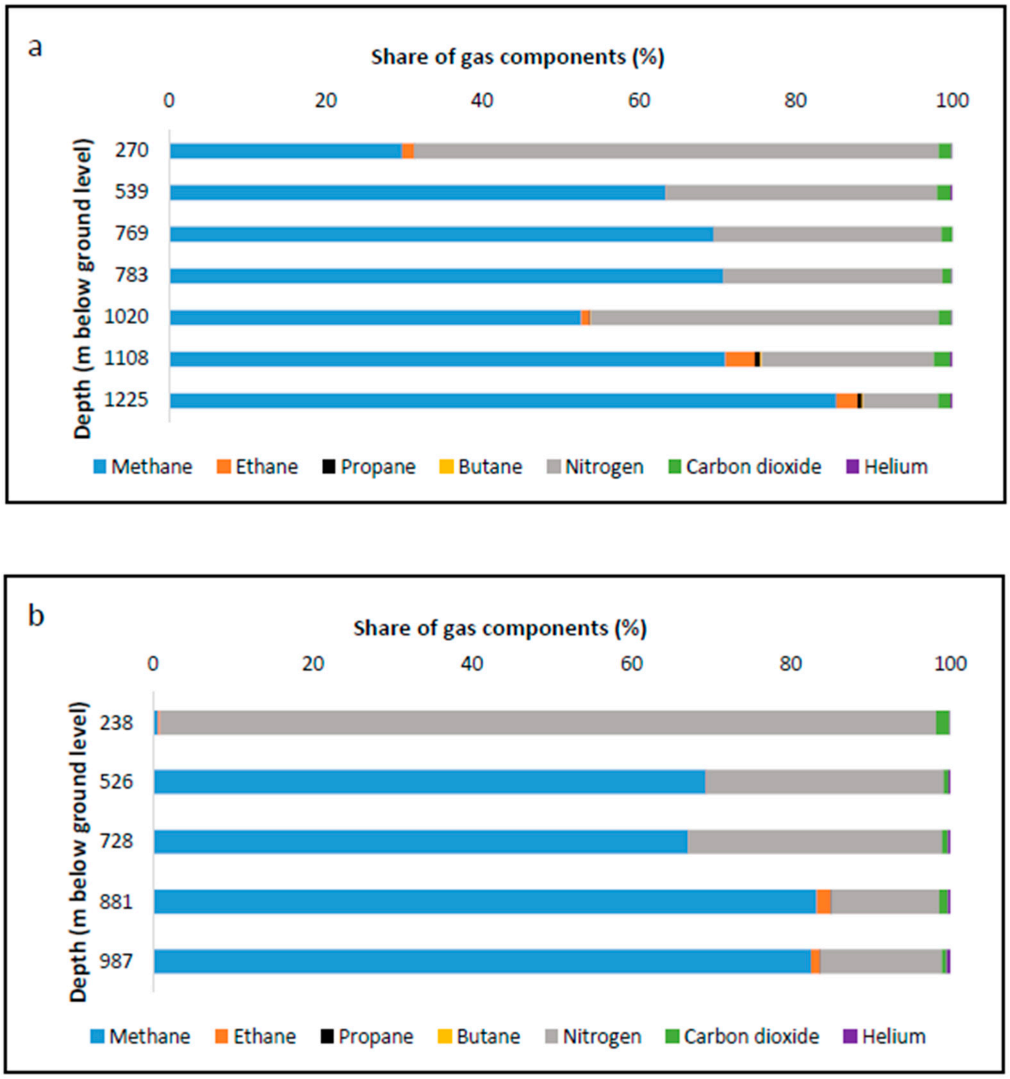


Figure 3. Gas composition versus depth in the study area, (**a**)—Ćwikice sub-area, (**b**)—Dankowice sub-area.

Isotopic research on the coalbed gases (methane, ethane and propane) has revealed that the hydrocarbons originated both during the thermogenic transformation of organic matter during coalification in the late Carboniferous and through microbial processes [7,35,36]. In the area, indigenous thermogenic methane ($\delta^{13}C$ (CH_4) >−50‰) occurs at depths >950 m below the top of the Carboniferous coal-bearing strata, migrated thermogenic methane ($\delta^{13}C$ (CH_4) = −65 to −50‰) between 950 and 400 m, a mixture of microbial and thermogenic methane ($\delta^{13}C$ (CH_4) ~−50‰) between 400 and 250 m and, in the uppermost 250 m below the top of coal-bearing sequence, only microbial methane from the microbial reduction in CO_2 ($\delta^{13}C$ (CH_4) between −71 and −65‰) [7]. Thus, the naturally outgassed zone, which previously reached a depth of 950 m below the Carboniferous top, began to be filled with migrating thermogenic methane in the Paleocene and/or early Miocene period and, at the same time, with isotopically light microbial methane generated by the invasion of meteoric waters with nutrients for archeobacteria and other producing micro-organisms [7,36]. The consequences of this today are the lack of outgassed zones, or their limited occurrence, in the area studied (Figure 4); methane occurs in coal in varying quantities throughout the entire Carboniferous profile.

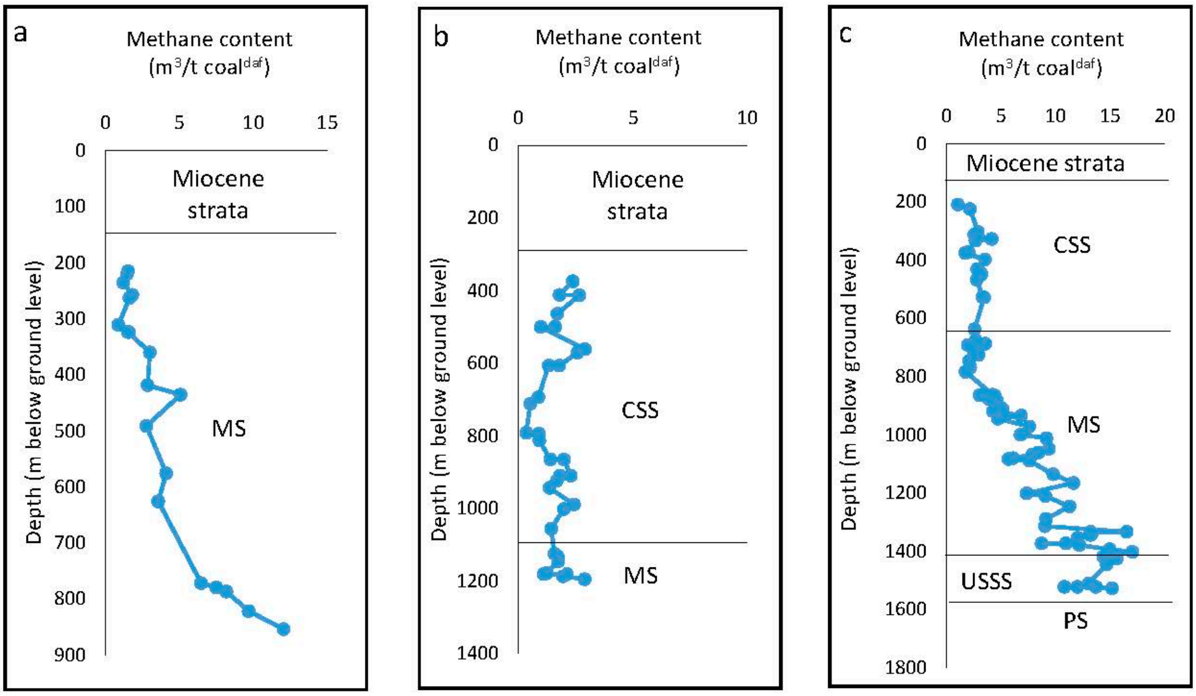


Figure 4. Depth distributions of methane contents in selected boreholes in sub-area 1 (**b**), sub-area 2 (**c**) and north of the study area (**a**). CSS—Cracow Sandstone Series, MS—Mudstone Series, USSS—Upper Silesian Sandstone Series, PS—Paralic Series.

5. Results and Discussion

5.1. Methane Trends

Vertical distribution of methane in the area is presented in Figure 4. In the Międzyrzecze field (Figure 4a) lying to the north of the study area, a rapid increase in methane content up to 15 m^3/t coal daf at a depth of 800–900 m is evident. In the Ćwiklice sub-area 1 (Figure 4b), such an increase with depth is not evident; contents do not exceed 5 m^3/t $coal^{daf}$. In the southern Dankowice sub-area 2 (Figure 4c), methane contents reach 17 m^3/t $coal^{daf}$ between 1400 and 1500 m. Beneath, methane contents tend to decrease with further depth.

Figures 5 and 6 show mean values of moisture, ash and methane contents at each 200 m level in the Carboniferous lithostratigraphic sequence. A gradual increase in methane content with depth is evident in sub-area 2 (Dankowice), whereas sub-area 1 is characterized by relatively low methane contents showing little variation (Figure 5). Moisture content decreases with depth in each area. Ash contents show no obvious trends.

Figures 7–9 show horizontal variations in methane—(Figure 7), moisture—(Figure 8) and ash (Figure 9) contents at −550 m above sea level (~800 m below ground) over the entire area. A visible increase in moisture content of <9 wt% towards the central part of sub-area 2 is evident (Figure 8). A general decrease in ash content (<8–12 wt%) towards the same sub-area is evident in Figure 9. Variations in methane contents are shown in Figure 7; the lowest values (<2.5 m^3/t $coal^{daf}$) are concentrated in sub-area 1, the highest (10–13.5 m^3/t $coal^{daf}$) close to the Jawiszowice Fault in the north-eastern part of sub-area 1.

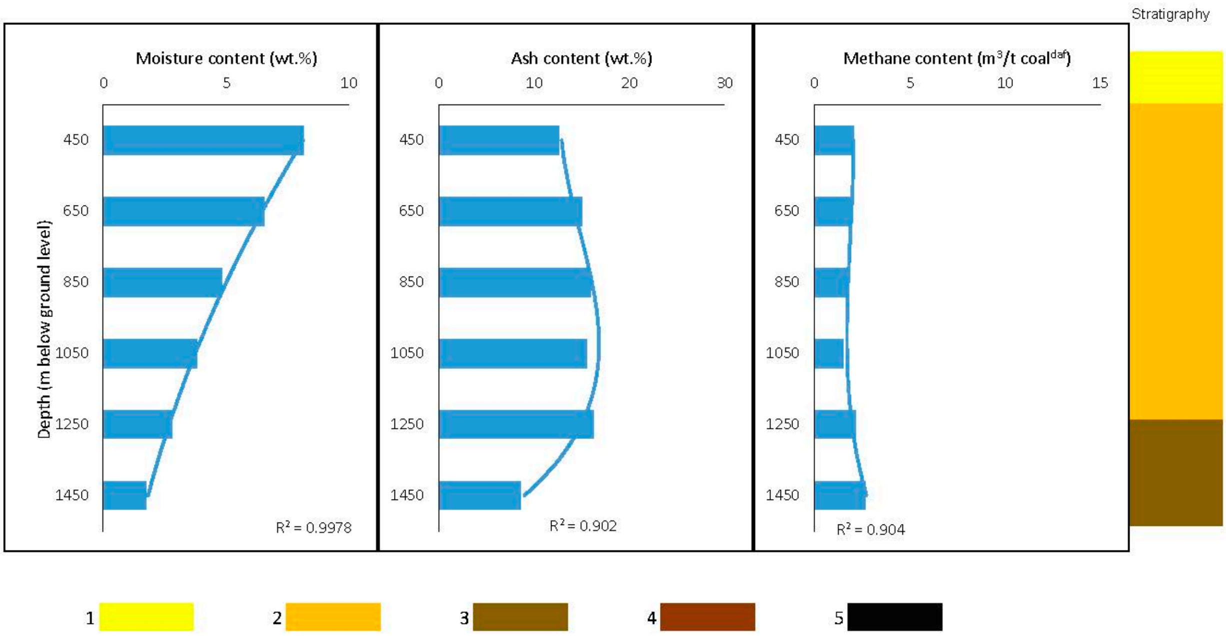


Figure 5. Depth trends of average moisture, ash and methane contents related to stratigraphy in sub-area 1 (Ćwiklice); 1—Miocene strata, 2—Moscovian Cracow Sandstone Series, 3—Upper Bashkirian Mudstone Series, 4—Lower Bashkirian Upper Silesian Sandstone Series, 5—Serpukhovian Paralic Series.

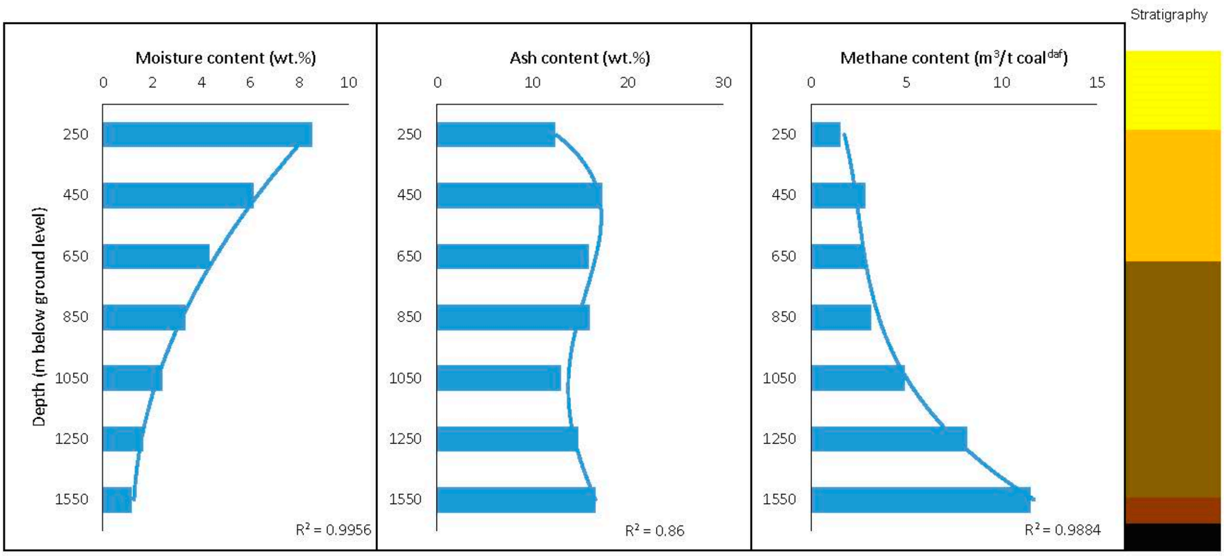


Figure 6. epth trends of average moisture, ash and methane contents related to stratigraphy in sub-area 2 (Dankowice). Explanations as in Figure 5.

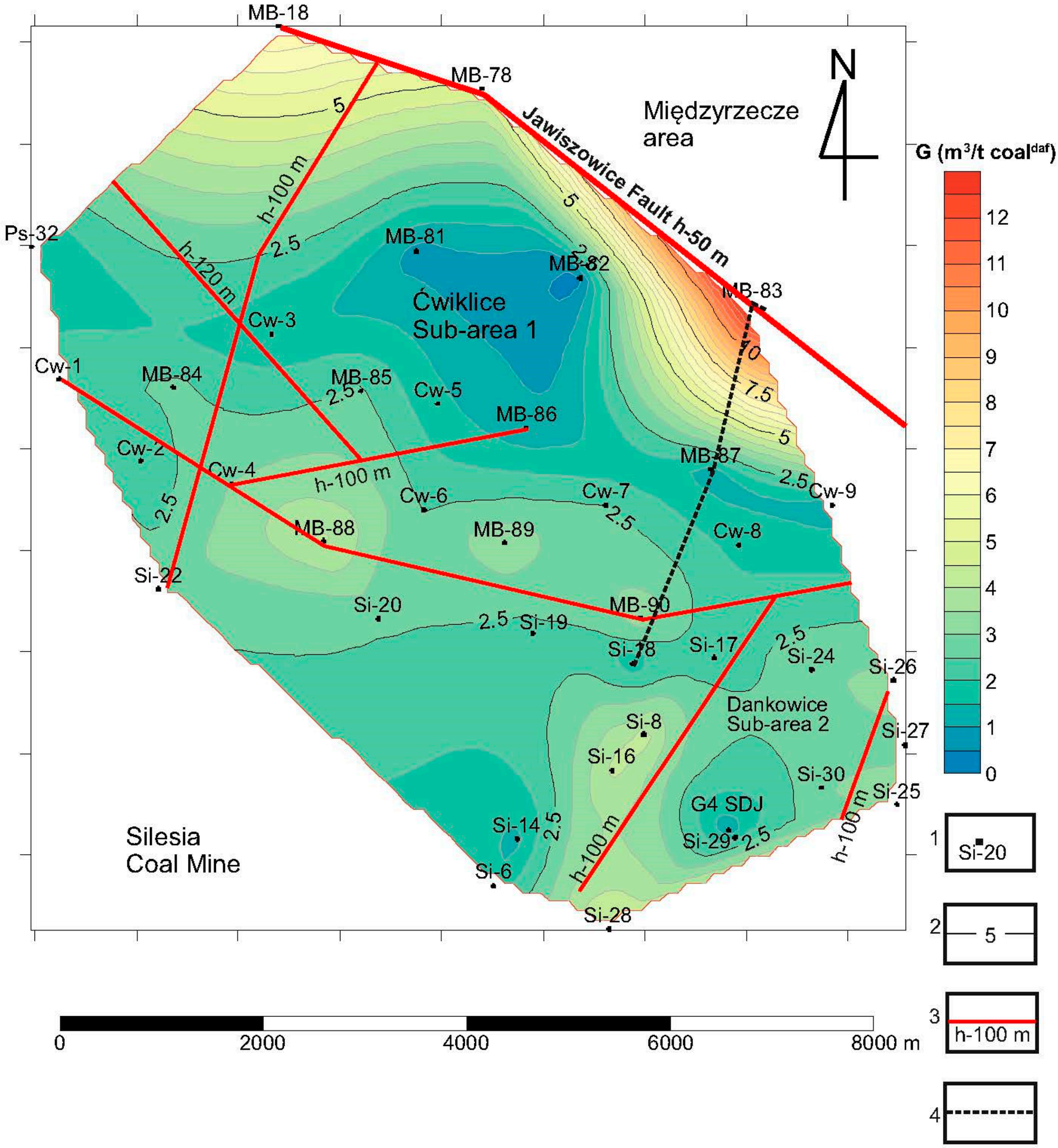


Figure 7. Methane content (G) distribution at the 800 m level below ground; 1—borehole, 2—line of methane content ($m^3/t\ coal^{daf}$), 3—important faults, 4—trace of cross-section in Figure 11.

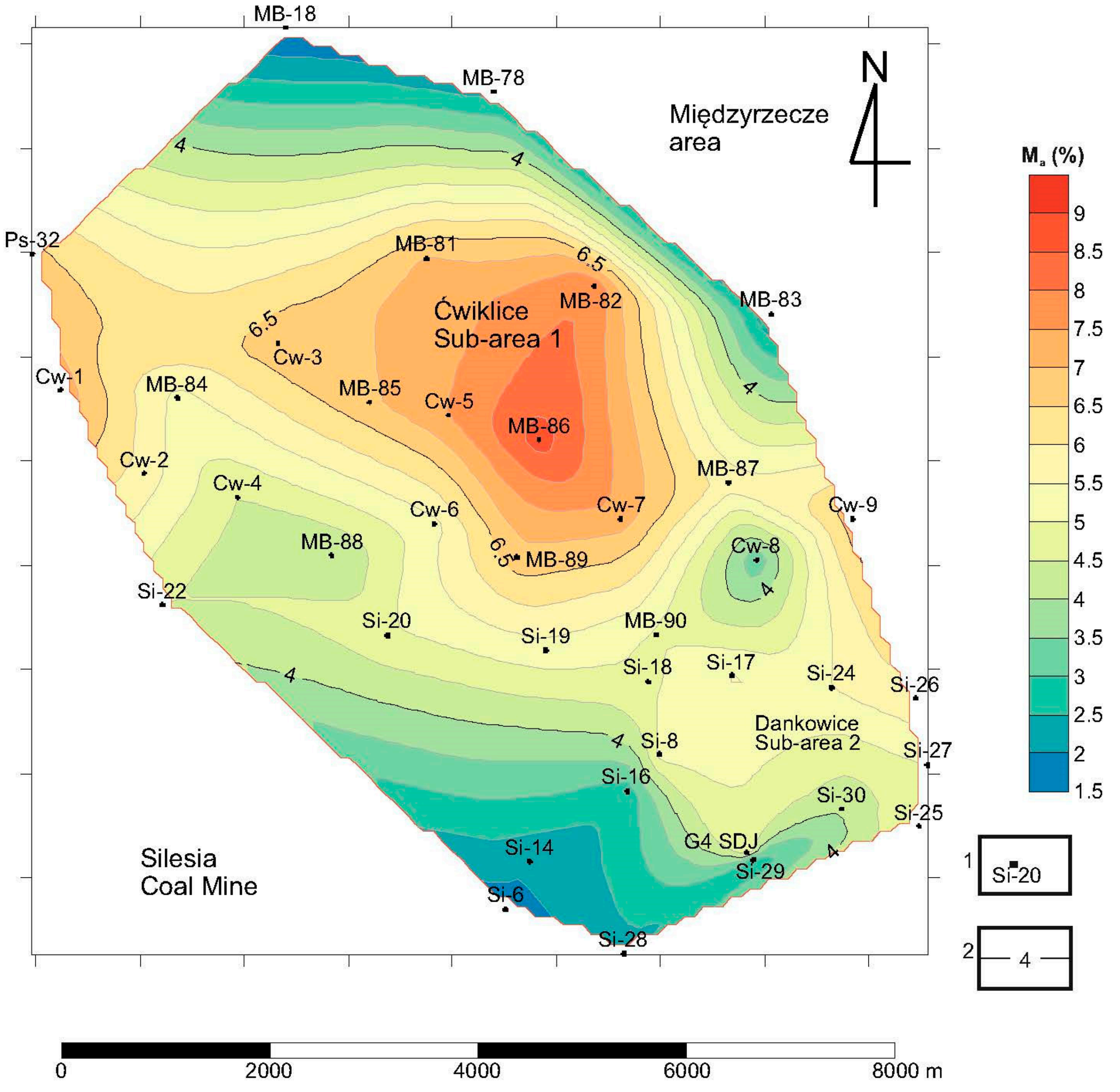


Figure 8. Moisture-content (M^a) distribution at the 800 m level below ground; 1—borehole, 2—important faults.

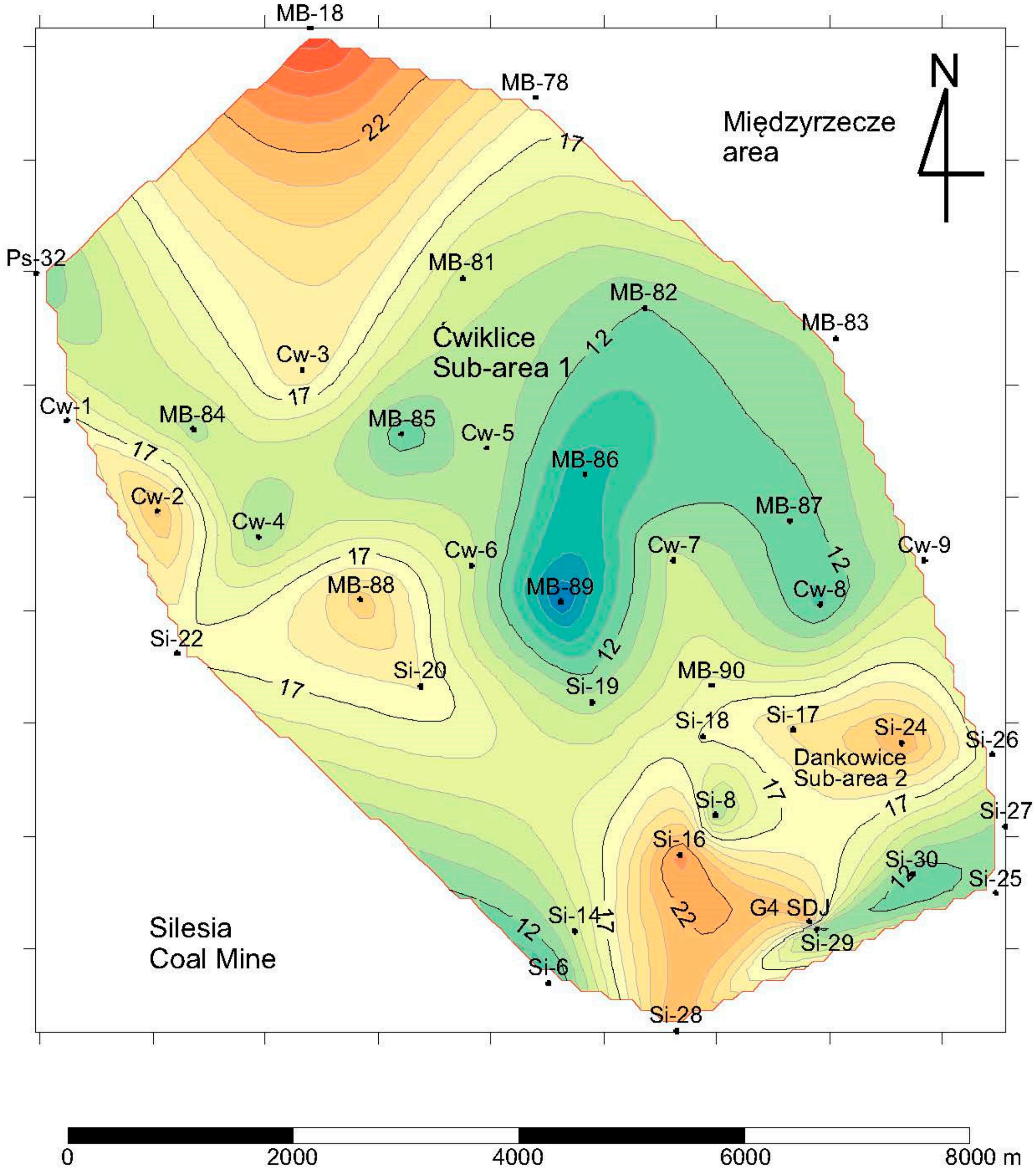


Figure 9. Ash content (A^a) distribution at the 800 m level below ground; 1—borehole, 2—important faults.

As outgassed zones (with methane contents <0.1 m^3/t coal^{daf}) occur to a very limited extent at most, methane-bearing zones are essentially present throughout the entire Carboniferous profile (Figures 4–6). In the uppermost part of the coal-bearing sequence within sub-areas 1 and 2, a weakly developed shallow, secondary methane zone is observed with methane contents of ca. 3 m^3/t coal^{daf} on average (maximum <5 m^3/t coal^{daf}). The highest methane contents (~15–17 m^3/t coal^{daf}) occur at depths of >1000 m in the area of Międzyrzecze adjacent to the study area from the north, and >1500 m in sub-area 2 (Dankowice).

5.2. Factors Influencing Methane Distribution

5.2.1. Lithology and Tectonics

The lithologies occurring in the area (Section 2) include coarse-grained, porous and permeable Moscovian Łaziska sandstones with an effective porosity of 15–20% that belong to the Cracow Sandstone Series; fine-grained, weakly permeable claystones and mudstones of the Upper Bashkirian Mudstone Series; and weakly permeable sandstone packages of the Lower Bashkirian Upper Silesian Sandstone Series. Methane-bearing coal seams are interbedded with all of these. Coal seams in the Łaziska sandstones are characterized by relatively low methane contents compared with seams hosted by mudstones and claystones (Figures 4–6). Methane contents clearly increase with depth between the Cracow Sandstone Series and Mudstone Series (Figure 4c); in the former, contents do not exceed 5 m^3/t $coal^{daf}$, whereas they reach 17 m^3/t $coal^{daf}$ at the boundary between the Mudstone Series and the Upper Silesian Sandstone Series (Figures 4c and 6). The Łaziska sandstones predominate in sub-area 1. The fact that the top of the Mudstone Series plunges deeply to below −800 m above sea level, i.e., ~1050 m below ground (Figure 10), implies a large thickness of the Cracow Sandstone Series that lies above. The area of lower methane contents coincides reasonably well with the area of enhanced thickness of Łaziska sandstones (Figures 7 and 10).

In Figure 11, a cross-section through the study area, the isolines of methane content are arranged mainly parallel to the boundary between the Cracow Sandstone Series and the Mudstone Series. Moreover, the isolines of higher methane contents (>4.5 m^3/t $coal^{daf}$) are located within the latter.

The main tectonic elements in the area are the Jawiszowice and Bzie-Czechowice faults, with throws of several dozen to hundreds of meters to the south (Section 2). As seen in Figure 11, methane contents are higher near the Jawiszowice Fault (borehole MB 83 located in the Jawiszowice fault zone). As shown in Figure 7, the lines of methane content are more or less parallel to the faults located in the studied area, and the zones with increased methane content are located near the faults. This may indicate the migration of methane along faults and accompanying fractures and/or the sealing of gas accumulation sites with a fault zone. In the study area, faults separate areas with a different distribution of methane content or move gas-bearing zones in the direction of their displacement. Similar observations have been made elsewhere in the USCB [13,37].

Lower methane contents within sub-area 1 to the south of the Jawiszowice Fault coincide with the occurrence of porous and permeable Łaziska sandstones that facilitate methane migration. A few kilometers to the west (Figure 1), in the free methane deposit "Silesia", the gas accumulated in Łaziska sandstones because of migration from coal seams due to coal exploitation and the underground system of methane drainage [7,38,39]. The occurrence of free methane in the Łaziska sandstones in sub-area 1 cannot be excluded. Partly outgassed coal seams lying among permeable sandstones also occur elsewhere [40].

The pathways of methane migration are both permeable sandstones and fracture zones associated with faults. Isotope studies (Section 4) have revealed that between depths of 400 and 900 m below the Carboniferous roof, migrating gases predominate [7].

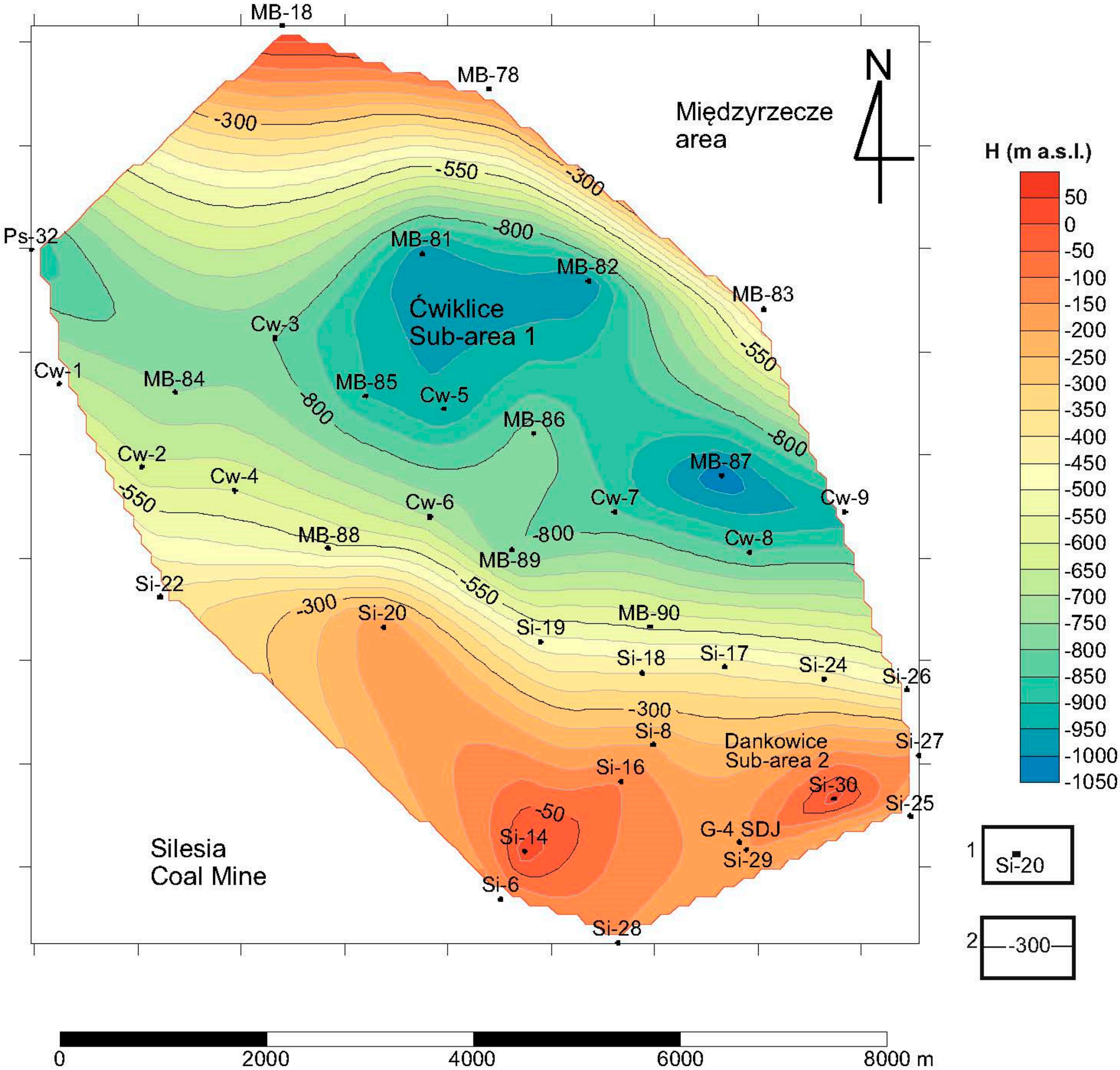


Figure 10. The topography of the top of the Mudstone Series; 1—isoline of the top (H) of the Mudstone Series (m above sea level). Other explanations as on Figures 10–12.

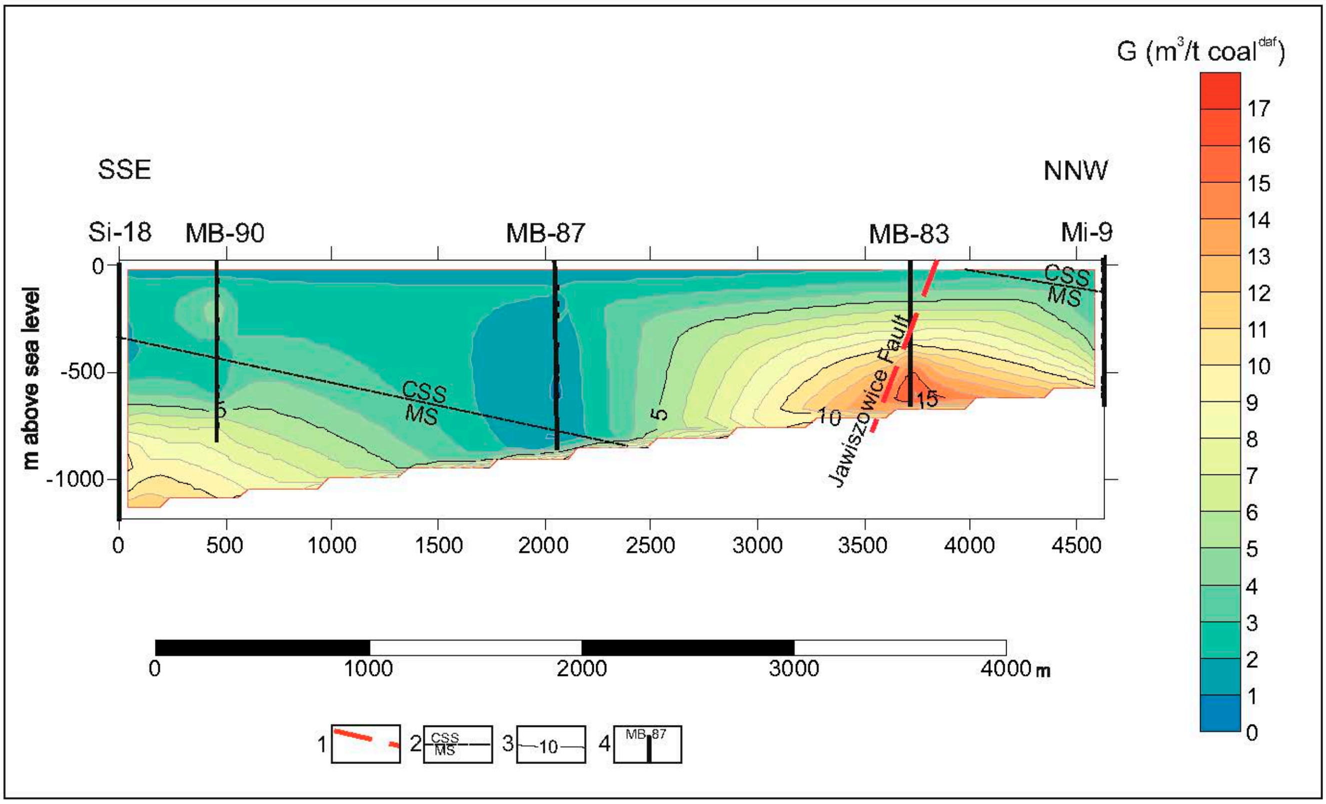
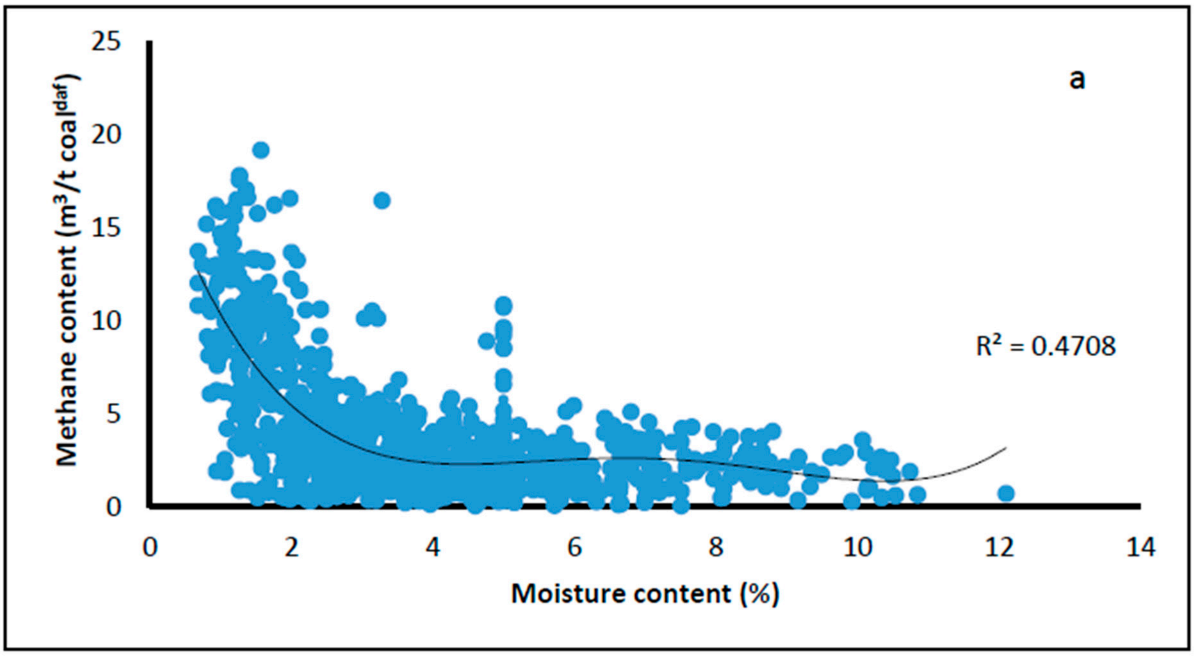


Figure 11. Cross-section across the Ćwiklice and Dankowice sub-areas; 1—Jawiszowice Fault, 2—boundary between the Cracow Sandstone Series (CSS) and the Mudstone Series (MS), 3—isoline of methane content G (m^3/t $coal^{daf}$), 4—borehole.



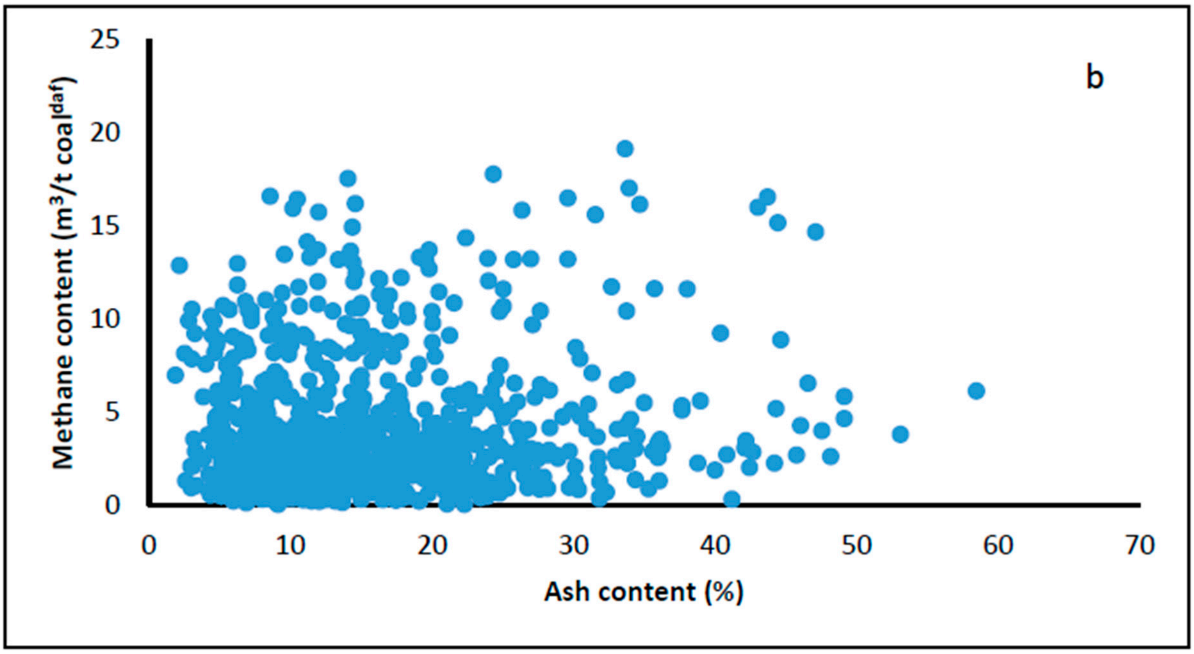


Figure 12. Methane content vs. moisture content (**a**) and ash content (**b**).

5.2.2. Moisture and Ash Content

With decreasing moisture contents, methane contents increase (Figure 12a). No such relationship is evident between methane and ash contents (Figure 12b). The distribution of moisture content (M^a) and methane content (G) shows that G >8–10 m^3/t $coal^{daf}$ is characteristic of coal seams in which M^a does not exceed 5 wt. %. Moisture content has a negative influence on coal sorption capacity [41,42]. The coal seams in the Cracow Sandstone Series have the highest moisture contents (4–8 wt.% on average; Figures 5 and 6). Those within the other Carboniferous Series have lower moisture contents (1–3 wt.% on average). Increased coal seam moisture contents, and the high porosity and permeability of the Łaziska sandstones that host them, seem to both be responsible for the low methane contents of coal seams in the Cracow Sandstone Series.

The horizontal variability of methane and moisture content displayed in Figures 7 and 8 shows that, in the central part of sub-area 1 in the vicinity of the MB-81 and MB-82 wells, the maximum moisture content of coal seams, exceeding 9%, is accompanied by the lowest methane content of coal seams, <1 m3/t coal^{daf}. This can be explained by the maximum thickness of the Krakow Sandstone Series (Figure 10), which, as mentioned, includes coal seams with a high moisture content. The analysis of the maps in Figures 7 and 9 does not confirm the influence of ash on the methane content in coal seams in the study area.

5.3. Coal Sorption Capacity and Methane Saturation

The sorption capacity of coal reflects the interplay of the negative influences of rock temperature and moisture content and the positive influences of hydrostatic and formation pressure [32,33,41–43]. Vitrinite-rich bright coal has a higher sorption capacity than inertinite-rich dull coal of the same rank [43,44].

Where the measured methane content is lower than the sorption capacity of coal, the coal seams are methane undersaturated (Table 2). Saturation with methane fluctuates between ca. 14 and 87%. The lowest methane saturation (<35%) characterizes those coal seams lying at depths <1100 m. At depths >1100 m, methane saturation increases to ca. 64–87%, with the highest value (86.9%) at a depth of 1140 m (Figure 13). The most methane-undersaturated coal seams occur within the Moskovian Łaziska sandstones (~14% saturation); high porosity and permeability of the surrounding sandstones and high coal moisture contents play key roles in this case (Section 5.2.2). Coal seams in the mudstones and claystones of the Mudstone Series show higher (>50%) methane saturation levels.

Table 2. Sorption capacities, measured methane contents, vitrinite reflectance (Ro) and rock temperatures (T) in Ćwiklice and Międzyrzecze sub-areas [15].

Depth (m below Ground Level)	Sorption Capacity (m^3/t coal^{daf})	Methane Content (m^3/t coal^{daf})	Methane Saturation (%)	Ro (%)	T (°C)
736	11.67	4.134	41.1	0.79	34
1075	7.02	1.000	14.2	0.80	43
1140	12.33	10.712	86.9	0.92	46
1347	13.25	8.527	64.4	1.05	51
1470	11.67	8.194	70.2	0.76	55

Coal undersaturation may also reflect the geological past of the basin. Permanent uplift from depth of the coal series in Mesozoic and Paleogene times and consequent cooling would have increased sorption capacity. If no additional methane was generated, the coal seams would have become undersaturated [13,33,43,45].

The current rock temperature at the level of 1000 m in the area fluctuates around 40° [46] (Table 2). These low (40 °C) temperatures, compared with those in the Carboniferous when coalification happened (>90 °C) [47,48], would support an increase in coal sorption capacity and, thus, a reduction in methane saturation.

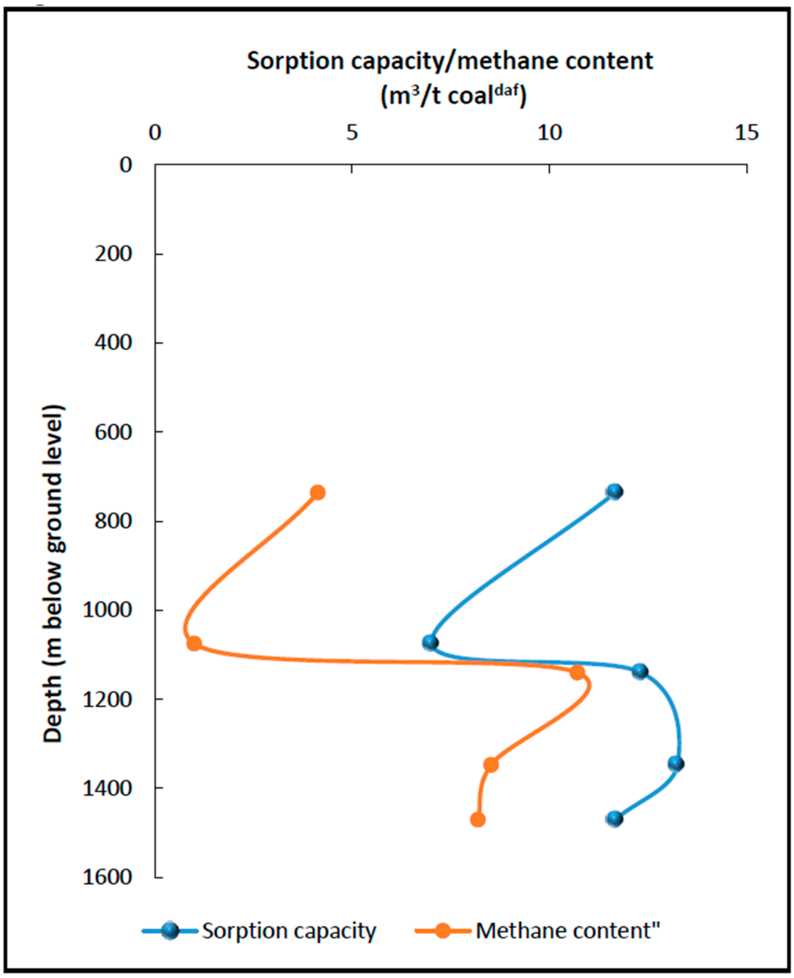


Figure 13. Sorption capacity and measured methane content vs. depth in Ćwiklice area, after [15].

5.4. Coal Permeability

Permeability determinates the ability of a coal seam to conduct fluids and gases. It is a crucial parameter characterizing the potential for methane exploitation. The phenomenon of permeability is determined by the cleat systems in the coal seam, through which the migration of fluids (water and gas) takes place. Research and observations so far [49,50] have confirmed the existence of two main systems of cleats: face cleats, which are long and run through most parts of the seam, and butt cleats, which are shorter and run perpendicularly between face cleats. In addition to the above-mentioned systems, the master cleats system is distinguished, in which the cleats run not only through the coal seam, but also through the surrounding rocks. The formation of cleats is caused by various processes; the most important are the cracking of the coal substance due to its shrinkage caused by the reduction of moisture or volatiles during the coalification process, and tectonic stress, because the orientation of the cleats is often convergent with the main tectonic directions in the studied areas [10].

Coal permeability depends on many factors, the most important of which are cleat orientation in the coal (e.g., [49]), the degree to which cleats are filled with mineral matter and the degree of cleat closure due to tectonic stress. Research elsewhere has revealed that the direction of such stress has a strong effect on the orientation of coal permeability [8–10]. In addition, maceral composition influences the cleat spacing [50]; it is smaller in bright, vitrinite-rich coal than in dull, inertinite-rich coal.

Coal permeability studies in the USCB have been conducted during methane borehole mining tests since the 1990s [30]. They have shown that coal permeability is not high and ranges from <1 to 3 mD on average [51,52]. Higher values occur locally. Table 3 shows the

USCB coal permeability laboratory results performed on a Temco apparatus using nitrogen as the working gas. They supplement the in situ permeability tests performed during the drilling of CBM exploitation testing holes.

Table 3. Coal permeability in the southern USCB. Laboratory measurements on samples taken from various locations [15,51], CSS—Krakow Sandstone Series, MS—Mudstone series, USSS—Upper Silesian Sandstones Series, PS—Paralic Series.

Depth (m below Ground Level)	Stratigraphy	Coal Permeability (mD)
395	CSS	299.270
490	CSS	143.890
700	MS	0.076
705	USSS	0.891
865	MS	15.843
900	MS	1.194
903	USSS	1.190
1034	PS	0.023

Laboratory and in situ permeability tests for the southern part of the USCB reveal that, at depths <1200 m, permeability values are scattered (0.02 ≥ 100 mD, Table 3). Deeper, a decrease in permeability with increasing depth is evident [51,52]. Moreover, laboratory tests have shown that coal seams in the Moskovian Cracow Sandstone Series (Łaziska Sandstones) have greater permeability (>100 mD) than seams in the other Carboniferous series (Table 3) [51]. Higher coal permeability could have facilitated methane migration in the geological past, implying that coal seams in the Cracow Sandstone Series have lowered methane contents now.

Local pockets of increased coal permeability can occur near faults. Called "gas pockets", these can accumulate and rapidly give back free gas. Such have been recognized in the Bzie-Czechowice Fault Zone. They were the cause of gas outbursts in the nearby Pniówek and Zofiówka coal mines [14,53].

The weakly permeable coals in the area probably reflect the closure of cleats due to tectonic stresses related to the evolution of the Carpathians and Sudetes orogens and overburden pressures. Places of increased permeability are limited. Thus, exploitation may require the use of methods to stimulate methane extraction, e.g., coal fracturing.

6. Potential for Methane Extraction

Successful exploitation of coal-bed methane requires a combination of favorable factors which can be divided into two main groups, namely, factors related to gas content and factors related to the productivity (possibility of gas output) of the coal-bearing series. Factors such as the gas content of coal seams, seam methane saturation, coal rank and gas generation, tectonic setting, depositional environment and coal distribution belong to the first group. The second group includes coal permeability and hydrodynamic conditions [33].

In sub-area 1 (Ćwiklice), methane contents are low and changes with depth are not evident (Section 5.1). Lower methane contents in coal seams coincide with the occurrence of permeable Łaziska sandstones (Section 5.2.1). The thickness of these sandstones ranges from several hundred to >1000 m in the central part of sub-area 1. As noted above, increased moisture contents in the coal here (Cracow Sandstone Series) negatively influence methane contents (Section 5.2.2). Within sub-area 2 (Dankowice), the increase in methane content with depth is evident. The coal seams of the entire area are rather irregular and thin (0.5–3 m). The thicker seams occur in the Upper Silesian Sandstone Series.

The north-eastern fragment of sub-area 1 adjacent to Jawiszowice Falult and sub-area 2 (50–150 m^3/m^2) are characterized by the most favorable methane resources (50–200 m^3/m^2). Much of sub-area 1 has the worst methane resources (<90 m^3/m^2; Figure 14). In addition, the methane content in the area adjacent to the Jawiszowice Fault (sub-area 1) exceeds the value of 4.5 m^3/t coal^{daf} (Figure 7), which is considered the limit value for the profitability of methane extraction from virgin areas (as the main mineral commodity) [6]. The average value of the methane content is higher than the residual value (about 2 m^3/t of $coal^{daf}$), which is an additional argument favoring the possibility of borehole extraction of methane. In sub-area 2 (Dankowice), the methane content of seams only exceeds the limit value of 4.5 m^3/t $coal^{daf}$ locally (Figure 7), but in most of the area it exceeds the residual value, i.e., the gas may be released spontaneously; therefore, methane extraction as a result of methane drainage of mining excavations after the start of coal exploitation in this area is more probable.

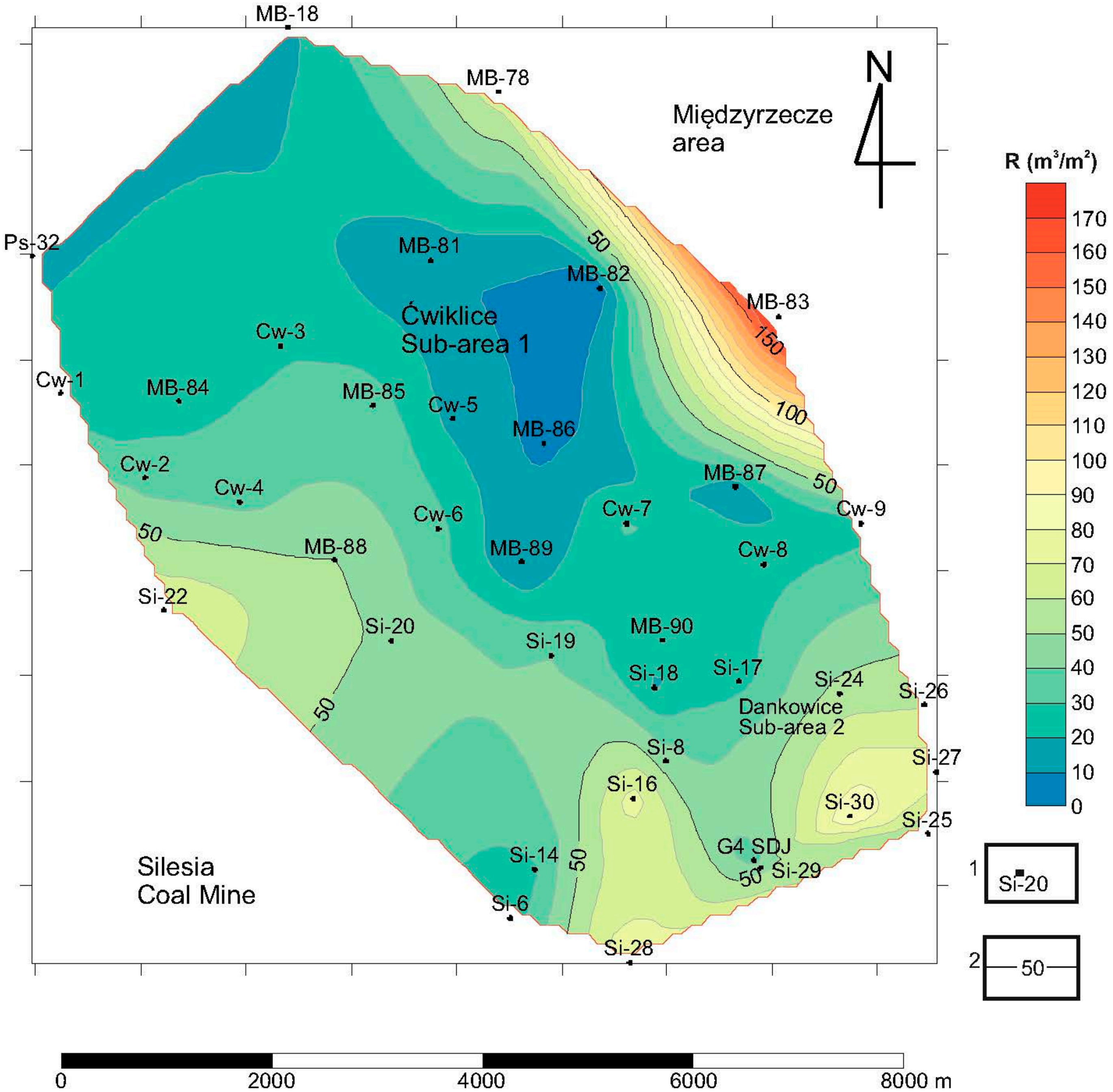


Figure 14. Methane resources in the Ćwiklice and Dankowice sub-areas at 800 m depth; 1—borehole, 2—line of methane resources (R).

In conclusion, conditions for CBM exploitation improve towards the north-east with increasing methane contents and resources. However, relatively low coal permeability and methane saturation levels could make CBM recovery problematic. Thus, the application of stimulation methods (horizontal drilling with hydraulic fracturing) might well be necessary for successful CBM extraction. This is evidenced by the results of the CBM production test carried out in the neighboring area of Międzyrzecze in 2017–2019 using the Gilowice 1 and 1H well doublet with artificial fracturing ("Geometan" project). In 510 coal seams lying at a depth of approximately 1000 m, methane yields of 5–10 thousand m^3/day were obtained, which was a record in the history of CBM production tests in the USCB. Recent tests of CBM drilling technologies in China under various geological conditions reveal that U-, V- and L-type horizontal wells are suitable for low coal permeability, as well as thin and complex lying seams with intact structure (17). The study area has similar geological features.

7. Environmental Impact

In the context of any future coal mining, the methane hazard in the Ćwiklice sub-area 1 is moderate. Below a depth of ~1000 m, a methane hazard of the highest category of emergency could occur, especially in the Dankowice sub-area 2.

The Dankowice 1 area (the part of Dankowice sub-area 2) is covered by a license application for the extraction of hard coal and methane as an accompanying commodity (Figure 1). This means that both coal and methane mining are planned in this area. Methane extraction is expected by underground methane drainage, as in other mines in the basin. The purpose of methane extraction is primarily to ensure the safety of miners at work and secondarily to obtain a source of energy. Unused methane is emitted into the atmosphere both through ventilation shafts and methane drainage stations, and contributes to the greenhouse effect.

The Brzeszcze and Silesia mines, which are closest to the study area (Figure 1), emitted 37.85 and 24.24 million m^3 of methane into the atmosphere in 2021, respectively. The amount of economically used methane captured by methane drainage stations of these mines at the same time was 49.94 and 4.07 million m^3 of methane, respectively (Table 4). Taking into account the roughly 30 times greater GPW of methane than of carbon dioxide, the combustion of 1 ton of methane means that about 28 tons of CO_2 will not be released into the atmosphere. That is why it is so important to manage the captured methane in mines. Each additional ton of methane emitted increases the greenhouse effect more than an additional ton of carbon dioxide; therefore, it is worth promoting the economic use of coal mine methane. Full use of methane captured by methane drainage stations is expected and necessary [54].

Table 4. Methane emissions from the Brzeszcze and Silesia mines, and total USCB in 2021, according to [31].

Coal Mine	Total Methane Emission (Million m^3)	Methane Used (Million m^3)	Methane Emission into the Atmosphere (Million m^3)	Equivalent CO_2 (Million t)	
				Methane Used	Methane Emission into the Atmosphere
Brzeszcze	87.79	49.94	37.85	1.07	0.81
Silesia	28.31	4.07	24.24	0.09	0.52
USCB (Polish part)	815.30	214.16	601.14	4.61	12.93

Thus, the planned mining of coal and methane in the area of Dankowice 1 will result in methane emissions into the atmosphere, so the economic use of the released gas is important both from the economic (production of energy from the own source) and the environmental point of view (reduction of greenhouse gas emissions).

Greenhouse gas emissions can also be reduced by CO_2 capture and storage (sequestration) combined with enhanced coalbed methane (ECBM) production. Numerous experiments on this were carried out globally and have shown that further research is advisable in this area [55,56]. This is because this action contributes to the reduction of carbon dioxide emissions into the atmosphere, and also favors even more effective CBM borehole exploitation.

During 2004–2005, a field experiment on the storage of carbon dioxide in coal seams associated with CBM production was undertaken in the Silesia mine. By using a doublet of CO_2 injection and CBM production wells, approximately 700 t of CO_2 were stored in this way. Methane recovery was low, due, probably, to low diffusion rates into and out of the coal [13] [and references therein]. However, the development of research and experimentation in this field so far [56] may be an incentive to re-investigate this issue in the study area.

The extraction and combustion of methane results in the emission of greenhouse gases into the atmosphere; therefore, any action contributing to the reduction of this problem is pro-ecological and will have a positive impact on the quality of the atmosphere, and will also encourage economic entities to use natural gas, a fuel with a high calorific value and which is available independently from weather conditions.

8. Conclusions

1. Porous and permeable Łaziska sandstones clearly influence the lower methane contents (ca. 1–3 $m^3/coal^{daf}$) in coal seams within them. Coal seams in the Upper Bashkirian Mudstone Series are distinguished by clearly higher methane contents (>3 $m^3/t\ coal^{daf}$).
2. Regional dislocations, e.g., the Jawiszowice Fault, are generally more methane saturated; the brittle fault zones act as gas pathways.
3. The saturation of coal seams with methane varies from 14% at 1075 m to 87% at 1140 m, with coals from the study area displaying substantial methane undersaturation.
4. At depths of <1200 m in the southern part of the USCB, permeability values are scattered (from 0.02 to more than 100 mD). Deeper, a decrease in permeability with increasing depth is evident. Thus, the coals are weakly permeable for gases.
5. From the point of view of CBM recovery, the north-eastern part of the Ćwiklice sub-area 1 adjacent to the Jawiszowice Fault (Gr—50–200 m^3/m^2) and Dankowice sub-area 2 (Gr—90–150 m^3/m^2) seem to be the most prospective.
6. Conditions for CBM exploitation improve towards the north-east with increasing methane contents and resources. However, relatively low coal permeability and methane saturation levels could inhibit CBM recovery. Stimulating recovery by, e.g., hydraulic fracturing, may be necessary.
7. The planned mining of coal and methane in the area of Dankowice 1 will involve the emission of methane to the atmosphere. Therefore, it is important to fully use the gas captured by methane drainage stations due to the need to reduce the greenhouse effect. Underground storage of CO_2 combined with borehole extraction of methane may also be helpful.

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