A new perspective on the geological prospection of the Bzie-Dębina deposit, with an emphasis on the correlation of seams and coal quality parameters

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Abstract. It is described a geological exploration and mining operation in the Bzie-Dębina area. The drilling of five new surface boreholes to a depth of 1.300 meters in the southern part of the "Bzie-Dębina 2-West" deposit suggests a significant effort to better understand the geology and potential resources of the area. By employing more accurate prospecting techniques and utilizing digital models of the deposit, the correlation of deposits and geological interpretation underwent changes. This suggests that the new data obtained from the boreholes and mine workings challenged or refined previous understandings of the geological formations and structures in the area. Moreover, the interpolation of qualitative data from the coal seams within the "Bzie-Dębina 2-West" and "Bzie-Dębina 1-West" deposits has been altered. This could imply adjustments to estimations regarding the quality, quantity, or distribution of coal within these seams, which are crucial for planning and optimizing mining operations. Overall, these developments indicate a dynamic process of exploration and refinement, driven by advances in technology and methodologies for studying and exploiting mineral resources.

1 Introduction

Geological prospection, especially in the context of coal mining, is a multifaceted process that requires a deep understanding of geological formations, structural features, and the distribution of valuable resources like coal seams [1]. Emphasizing the correlation of seams and coal quality parameters is crucial for effective resource assessment and mining planning. Especially it is evident during hazardous coal seams mining [2, 3]. Understanding the correlation between different coal seams within a deposit is essential for delineating the extent of mineable reserves [4, 5]. This involves identifying the continuity of seams both laterally and vertically, which can vary significantly across a deposit [5, 6]. By accurately correlating seams, miners can better predict the distribution of coal resources and plan mining

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activities accordingly [7].

Coal quality parameters encompass various characteristics such as calorific value, ash content, sulfur content, moisture content, and volatile matter [8, 9]. These parameters have significant implications for the economic viability of mining operations and the suitability of coal for specific industrial applications [10, 11]. Prospection efforts should focus on assessing these parameters with precision, as variations in coal quality can influence decisions regarding extraction methods, processing techniques, and marketability [11 – 13].

Effective geological prospection requires the integration of various types of data, including geological mapping, borehole logging, geophysical surveys, and laboratory analysis of coal samples [13, 14]. By integrating data from different sources, geologists and mining engineers can build comprehensive models of coal deposits, incorporating information about seam correlation and coal quality parameters [15]. This integrated approach enhances the accuracy of resource estimates and improves decision-making throughout the mining lifecycle [16, 17].

Advances in technology, such as 3D modelling software, remote sensing techniques, and geophysical imaging tools, have revolutionized geological prospection in recent years [18 – 20]. These technologies enable geoscientists to visualize subsurface structures with unprecedented detail, facilitating more precise delineation of coal seams and characterization of coal quality parameters [21]. Additionally, innovations in drilling equipment and data analysis algorithms have enhanced the efficiency and accuracy of borehole investigations [22].

Geological prospection is an iterative process that involves continual refinement based on new data and insights gained from ongoing exploration activities. As it is demonstrated, the correlation of seams and coal quality parameters may evolve as additional boreholes are drilled, new technologies are employed, and geological models are updated [22, 23]. This continual refinement is essential for optimizing mining operations and maximizing the recovery of valuable resources.

The correlation of seams and assessment of coal quality parameters are fundamental aspects of geological prospection in the coal mining industry [1, 24]. By leveraging advanced technologies and integrating multidisciplinary data, mining companies can enhance their understanding of coal deposits, improve resource estimation accuracy, and make informed decisions to sustainably extract and utilize coal resources [25].

JSW SA is the only Polish mining company producing high-quality coke for the metallurgical industry. The quality of coking coal has a significant impact on the parameters of the coke produced, and consequently on the economic evaluation of mining projects. Monitoring the quality of coking coal allows for optimization of production processes and early identification of quality issues [26]. A key element of the JSW Capital Group's business strategy has become the implementation of the “Quality Program” in 2018, which included several measures enabling the introduction of a unified procedure for modelling deposits, planning production, scheduling, as well as monitoring and ongoing supervision of the quality of the commercial product [27]. The methodology of selecting IT tools to use for the construction of a system was developed in 2018 – 2020. The created system consisted of geological model of coal deposits and design and scheduling of mining production in JSW SA, including the development of a model for the deposits “Bzie-Dębina 2-West” and “Bzie-Dębina 1-West” [28].

Three-dimensional modelling techniques have become popular in the mining industry, as they have made it possible to access geological and technical data on mining activities in a much more convenient form than 2D vector maps [29, 30]. Every decision, and even more so in mining, can have far-reaching consequences, and the consequences are often very complex. An important stage of business activity is the pre-investment, or planning phase, which follows the exploration phase of the deposit. During this phase, one of the options for future investment is selected. Activities undertaken at this stage do not require large financial

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outlays, however, errors and negligence committed at this stage, as well as the lack of a comprehensive approach to investment planning, may result in significant expenses in subsequent stages of the investment process [31]. The mining production planning process always involves operating in an incomplete information environment. This uncertainty occurs due to the lack of full knowledge about the deposit, its structure and the variability of the quality parameters of the resource. These cause some of the risks and uncertainties associated with an internal mining project [32]. One way to mitigate these risks and reduce uncertainty is to conduct additional exploratory work in the deposit.

In late 2018 and early 2019, five boreholes were drilled from the surface in the "Bzie-Dębina 2-West" deposit. The purpose of the drillings was to obtain geological information, including the identification of hydrogeological, geological, and gas conditions, enabling additional recognition of the deposit in its planned exploitation. All of the drilled holes were drilled to a depth of 1300 m [33, 34].

This article presents a comparative analysis of the structural deposit model and quality parameter model along with newly drilled boreholes.

1.1 Location of boreholes

Administratively, the "Bzie-Dębina 1-West" and "Bzie-Dębina 2-West" coal deposits are in the southern part of the Silesian Voivodeship in the counties: Jastrzębie-Zdrój (municipal county), Cieszyn and Pszczyna. Geographically, it lies on the territory of the Rybnik Plateau, which is part of the Silesia region. The boundaries of the mining area are defined by: Fault A in the west, Fault B in the east, Fault III in the south, and in the north it borders the Zofiówka deposit [35].

The newly drilled boreholes, on the other hand, are in the southern part of the "Bzie-Dębina 2-Zachód" deposit, within the Jastrzębie-Zdrój district (Fig. 1).

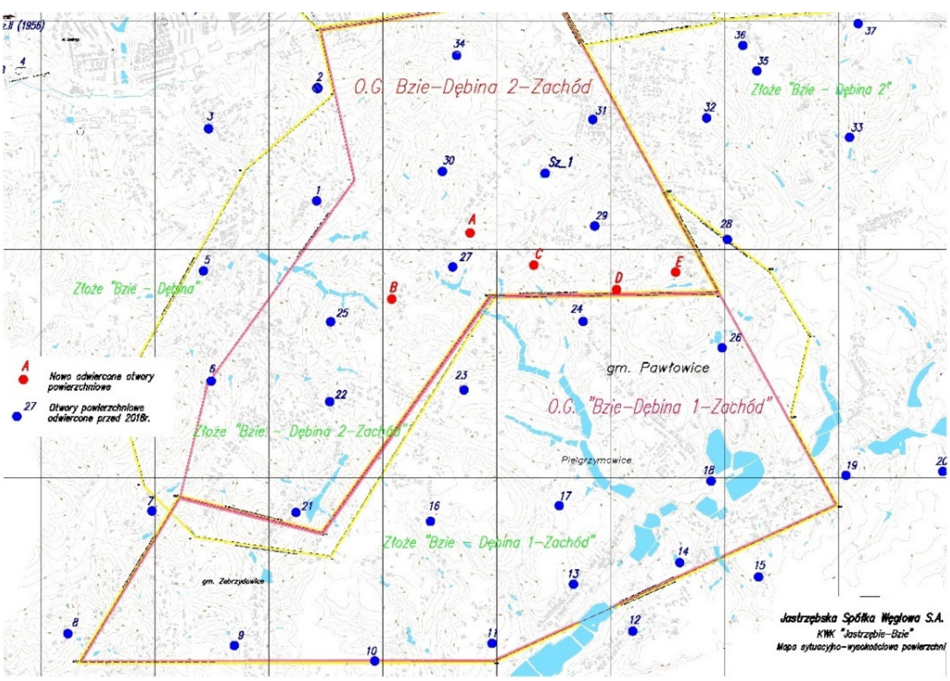

Fig. 1. Localisation of boreholes on the topographic map (red dots – new boreholes).

1.2 Geology of the deposit area

The "Bzie-Dębina 1-West" and "Bzie-Dębina 2-West" hard coal deposits are located on the SW slope of the GZW main basin. In relation to the most important structural elements of this part of the GZW, it is located to the SW of the Jastrzębie-Moszczenica anticline and the area of the "Bzie-Dębina 2-Zachód" deposit is divided by the Gorzyce-Bzie-Czechowice fault with a latitudinal extension, throwing layers in a southerly direction, the throw is about 600 – 800 m [35].

As a result of mining works in the deposit, other associated faults with latitudinal extension having a northward throw (Ruptawski I, Ruptawski II and Ruptawski III) have also been recognized. Quaternary sediments consist of loess and fluvioglacial sands and gravels of Pleistocene age, colluvial clays, sands and deluvial clays of Pleistocene-Holocene age, fluvial sands and gravels and valley bottom silts of Holocene age (with a total thickness of 10 to 30 m) [35, 36].

Neogene sediments are developed throughout the area and lie directly on the Carboniferous floor. The thickness of the sediments ranges from 590 to 930 m. This variable thickness of the formations is associated with the varied relief of the Carboniferous surface on which they were deposited. In terms of lithology, the Neogene is built from the Skawinski strata representing siltstone and claystone, then underneath them lie the Debowiec strata built from clastic formations represented by sandstone and occasionally by conglomerates [35, 36].

Productive Carboniferous strata are represented by: Siltstone series: Westphal B – Orzesze layers (seams of group 300), Westphal A – Upper Ruda layers (seams of group 400 – 407/3); Upper Silesian Sandstone Series: represented by Westphal A - Lower Ruda layers (seams of group 400 below 407/3 seam) and Namur B-C Anticline and Poreba layers (seams of group 500 and 600) [35, 36].

In Orzesze strata, due to the folded, eroded, and faulted surface of the formations, the thickness of the series varies. In the western part of the "Bzie-Dębina 1-West" deposit, the seams are subject to erosional leaching. In terms of the facial structure, the Orzesze strata belong to the lake and marsh zone. The lithological profile is dominated by claystones and siltstones, which account for 40 – 60% of all rocks, the remainder being sandstones and numerous coal seams. The Ruda strata are characterized in two ways in terms of lithological formation. The boundary of lithological changes runs near the 407/3 deposit and divides them into Upper and Lower Ruda layers. The Upper-Ruda strata are similar to the Orzesze strata in terms of lithology. They are dominated by silty-clay sediments over sandy ones, and there are numerous inserts and mineable coal seams [35, 36].

Below the 407 seams, the lithological character of the rocks changes quite abruptly. Thick-bedded sandstones transitioning to conglomerates, punctuated by claystones and siltstones, begin to predominate decisively. In this section of the Ruda strata, the development of deltaic-riverine facies is observed, with the largest share of trough facies (about 55%). The Anticline and Poreba strata cover the entire documentation area. They occur below 418/2 seam, however, due to the considerable depth of deposition (below the documentation depth of 1300 m) they were not documented [35, 36].

The borehole profiles are formed by the following stratigraphic formations: Quaternary sediments represented by Pleistocene sediments of fluvial-glacial origin, (with a thickness of 10 – 26 m), Neogene formations developed in the form of clay and siltstone under which lie the sandstones and conglomerates of the Debowiec strata (Miocene, with a thickness of 821.4 – 890.6 m) and sediments of the Upper Carboniferous which are represented by the Orzesze strata (the thickness of the layers varies from 82.6 to 155.7 m) and the Ruda strata with a thickness of: 246,7-303.3 m. In the layers reached by boreholes there are seams from 358/2 to 408/1-2 [33, 34].

2 Methodology

In the following geological cross-section of No-No´ (Fig. 2), we can see that the strata in the eastern part of the cross-section in the vicinity of the newly drilled test boreholes lie practically horizontally. On the other hand, in the western part up to the Ruptawski Fault III, the strata collapse monoclinal to the east. The surface of the Carboniferous floor is topographically differentiated, and in the place of it lowering the Debowiec layers have increased thickness.

Throughout the entire length of the cross-section, there are no seam wedging, and also the distance between the beds does not change significantly, however the distances between the two beds of the Ruda strata to the east of the fault are, according to model interpolation, much lower than to the west.

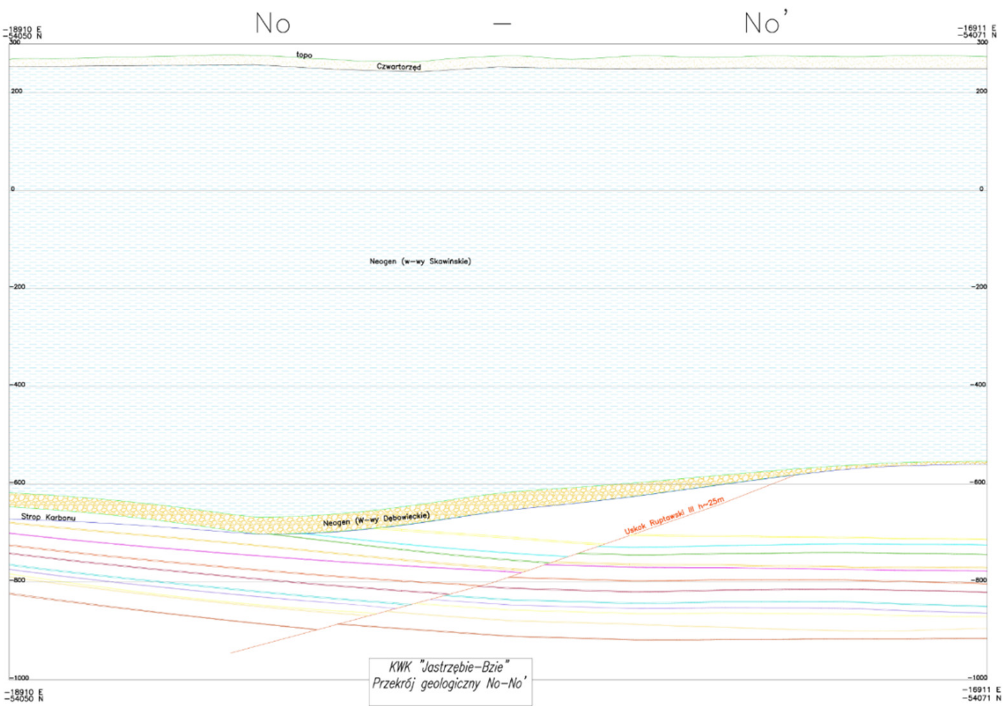

Fig. 2. Cross section No-No´ through the “Bzie-Dębina 2-Zachód” deposit.

On the map below (Fig. 3) we can see the general course of the seams. The direction of sinking of the deposit is monoclinal eastern, like that of the neighbouring “Zofiówka” deposit, but the sinking of the layers occurs at a smaller angle. In addition, on the border of the “Bzie-Dębina 1-West” deposit and the “Bzie-Dębina 2-West” deposit there is a depression of the seam (trough). The depth of the seam is from about 450 m below sea level in the vicinity of the seam wedging to about 900 m below sea level in the trough near the eastern border of the deposit.

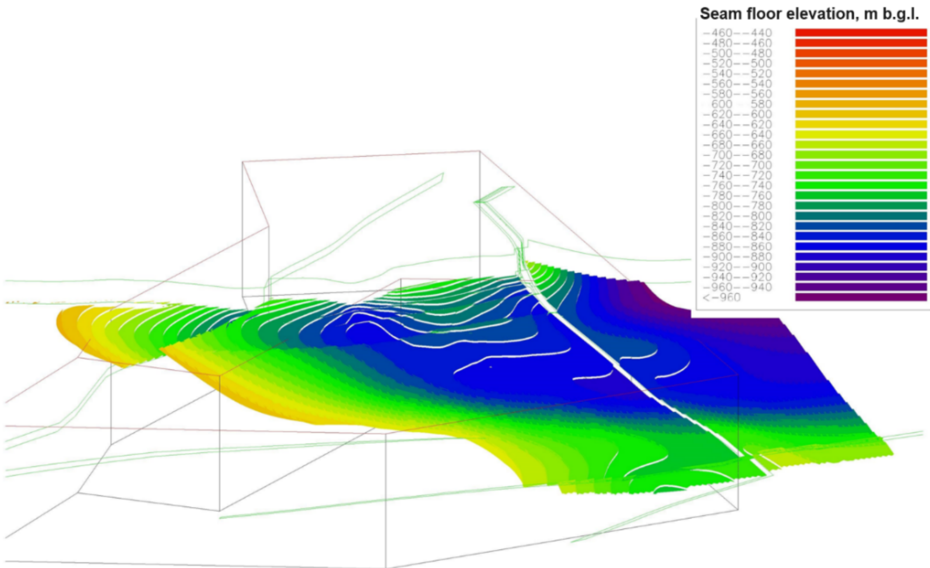

Fig. 3. Structural map of the floor of coal seam.

2.1 Comparative analysis of quality parameters

The established database of deposit quality parameters consists of indicators: technical analysis (moisture, ash, volatile parts, and calorific value and heat of combustion), elemental analysis (content of sulfur, chlorine and phosphorus, and other trace elements), coking (Sintering behaviour – Roga Index, the free swelling index, dilation and contraction), physical analysis (density, mechanical properties (shear strength, millability), and from optical-petrographic indicators. The following section (Results) shows a comparison according to the old reconnaissance with new information from drilled test boreholes (sulfur content, coal type and Roga Index) [37, 38].

The current standard for the classification of hard coal at JSW SA mines is the previous PN-82/G-97002 standard, and it considers five quality parameters for coking coals: volatile matter content V^{daf}, sinterability *RI*, dilatation b, free swelling index SI and inertinite content I, which is a supplementary parameter for subtypes 35.2A and 35.2B (Table 1). The new classification of hard coal (standard: PN-G-97002:2018-11) differs from the previous one in the inclusion of the vitrinite reflectivity parameter *R* and the heat of combustion of hard coal q_{daf}, the lack of inclusion of the free swelling index *SI*, as well as other parameter limits [38, 39].

3 Results

3.1 Type of coal

Based on the above parameters (Table 1), a digital model was created to determine the variability of the coal type in the seam. In the case of the maps below, we can observe that in the new interpretation the seam is mostly classified as ortho-coking coal type 35.1, only the area in the NW edge together with one of the new boreholes BD-63 was classified as coal 34.2. Furthermore, the NE part of the area was classified as coal types 35.2A and 35.2B. (Fig. 4).

Table 1. Coal Classification according to Polish norm PN-82/G-97002 [39].

Coal type		Classification parameters			
Name	Indicator	Volatile matter content, V^{daf}	Sinterability, *RI*	Dilatation, *b*	Free swelling index, *SI*
Gas-coking coal	34.1	> 28	> 55	none or < 0	not normalized
	34.2			≥ 0	
Ortho-coking coal	35.1	26 – 31	> 45	> 30	
	35.2A*	20 – 26		>0	> 7.5
	35.2B*				≤ 7.5
Meta-coking coal	36	14 – 20	> 45	> 0	not normalized
Semi-coking coal	37.1	20 – 28	≥ 5	not normalized	
	37.2	14 – 20			
Lean coal	38	14 – 28	< 5		
Anthracite coal	41	10 – 14	not normalized		
Anthracite	42	3 – 10			
Meta-anthracite	43	< 3			

*Complementary parameter differentiating coal type 35.2A from 35.2B is inertinite content, which shouldn't excess 30% in coal type 35.2A.

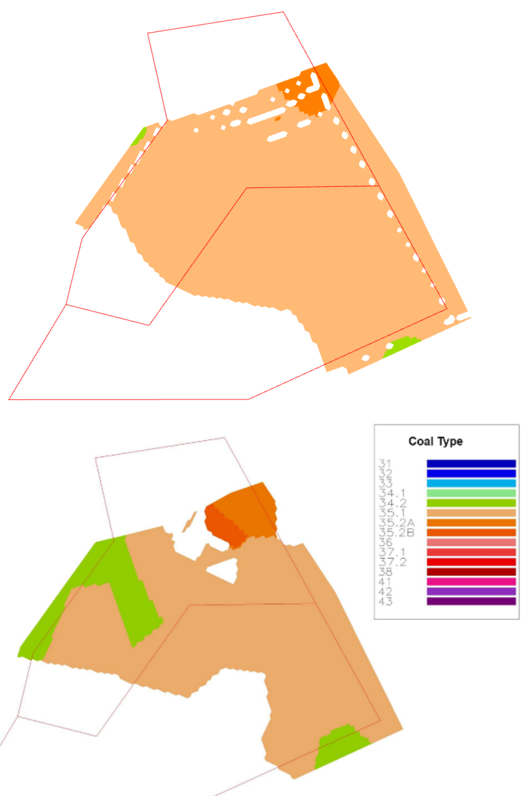

Fig. 4. Coal type parameter comparison (map on the left: according to old geological recognition, map on the right: according to new geological recognition).

3.2 Total sulphur content

Sulphur is the most undesirable component of coke; due to the adverse effect it has during blast furnace processes. The elevated content makes the metal "hot brittle", reduces furnace efficiency, and has a detrimental effect on the environment. On the total sulphur content map below, we can see that practically the entire seam has a sulphur content of less than 1%, there are only two anomalous values in the western part of the "Bzie-Dębina 2-West" and "Bzie-Dębina 1-West" deposits. (Fig. 5) [37, 40].

Comparing the old and new interpretations of sulphur content in each seam in both correlations does not change significantly. One can only notice a reduction in sulphur content according to the new interpretation in the SW part of the seam near the wedging [7].

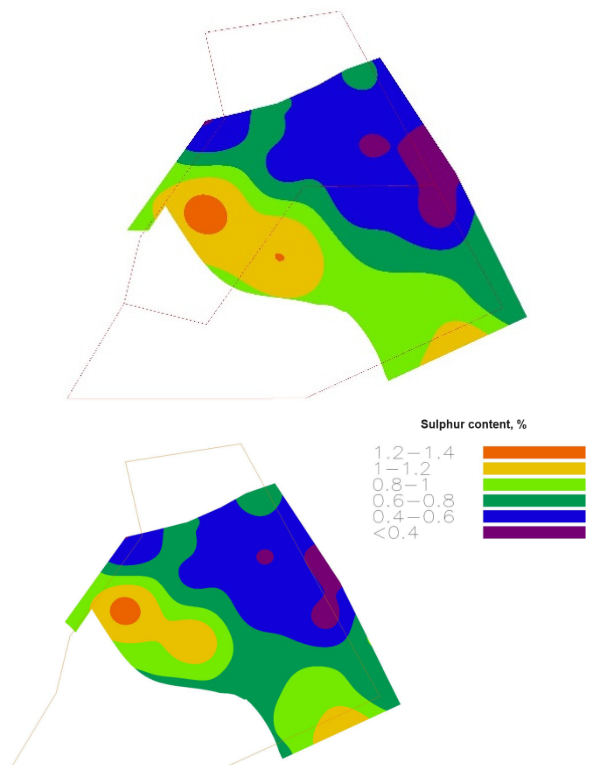

Fig. 5. Sulphur content parameter comparison (map on the left: according to old geological recognition, map on the right: according to new geological recognition).

3.3 Sinterability coal by Roga method

Sinterability is a method to quickly distinguish coking coals from non-coking coals. The method consists in examining the mechanical strength by tumbling of coke, obtained by degassing at 850 ºC a mixture of coal and reference anthracite under strictly standardized laboratory conditions. It is calculated based on the formula (1):

$$RI = \frac{100}{3Q}\left[\frac{a+d}{2} + b + c\right], \tag{1}$$

where Q is the weight of the sample after coking (before the first screening), g; a is the weight of the sample on the sieve before the first tumbling, g; b is the weight of the sample on the sieve after the first tumbling, g; *c* is the weight of the sample on the sieve after the second tumbling, g; *d* is the weight of the sample on the sieve after the third tumbling, g.

In the maps below (Fig. 6), we can see that the following seam in practically the entire area of the "Bzie-Dębina 2-West" and "Bzie-Dębina 1-West" deposits is classified as highly sinterable coal. In addition, the interpolation in the area with new data has changed. The values in this area are higher than in the case of earlier recognition.

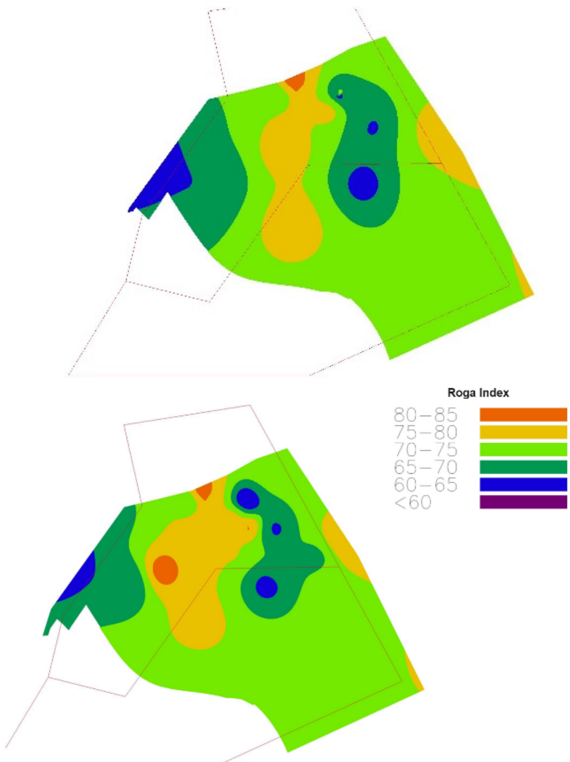

Fig. 6. Roga Index comparison (map on the left: according to old geological recognition, map on the right: according to new geological recognition).

3.4 Carbon content

For the "Bzie-Dębina 1-West" deposit, 4 balance seams have been documented for the Orzesze strata, while 26 balance seams have been documented for the Ruda strata. The carbon content of the Orzesze strata is 3% for the Ruda strata is in the range of 4.0 – 7.2%. In the "Bzie-Dębina 2-West" deposit, up to a depth of 1.300 meters, 10 seams of the Orzesze strata have been documented, while for the Ruda strata 26 balance seams have been documented. The carbon content of the Orzesze strata is in the range of 2.4 – 5.6%, with higher values in the southern part, while the carbon content of the Ruda strata varies from 4.0 to 7.2% [30, 31].

The carbon content for the Upper Ruda layers, according to the reported boreholes, ranges from 6% up to 12% in borehole BD-1 (Table 2). The carbon content of the Upper Ruda layers in the area of the "Bzie-Dębina 2-West" and "Bzie-Dębina 1-West" deposits is fairly evenly distributed, increased values occur in the SW part of the "Bzie-Dębina 1-West" deposit. (Table 2, Fig. 7).

Table 2. Total coal resources in the Upper Ruda beds in each borehole.

Borehole	Upper Ruda layers thickness, m	Upper Ruda coal seams thickness, m	Share, %
B_BD_07	245	18.4	8
B_BD_1	258.4	29.75	12
B_BD_2	233.8	19.27	8
B_BD_22	234.5	19.55	8
B_BD_23	228.4	20.05	9
B_BD_24	254.8	22.34	9
B_BD_25	236.4	21.73	9
B_BD_26	224.3	19.01	8
B_BD_27	234.9	14.3	6
B_BD_28	225.3	15.05	7
B_BD_29B	237	18.57	8
B_BD_30	229.6	17.34	8
B_BD_31	227	22.2	10
B_BD_32	229.1	18.63	8
B_BD_33	125.8	14.39	11
B_BD_34	93.6	6.8	7
B_BD_35	222.7	21.4	10
B_BD_36	236.8	17.8	8
B_BD_44	170.2	18.18	11
B_BD_45	166.8	17.73	11
B_BD_46	70	5.48	8
B_BD_47	84.5	8.9	11
B_BD_48	170	11.01	6
B_BD_49	318.1	25.15	8
B_BD_54	133	14.4	11
B_BD_55	238.6	19.1	8
B_BD_62	246.7	17.25	7
B_BD_63	280.55	16.75	6
B_BD_64	255.69	17.57	7
B_BD_65	226.75	13.8	6
B_BD_66	248	15.09	6
B_BD_SZ1B	149	11.81	8
P_IG_55	178.3	17.3	10

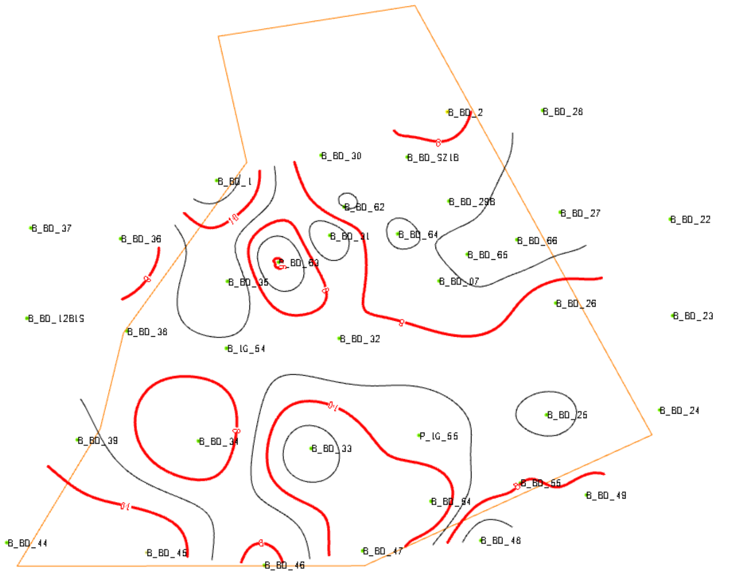

Fig. 7. Contour map of coal resources in the Upper Ruda beds in "Bzie-Dębina 2-Zachód" and "Bzie-Dębina 1-Zachód" deposits.

4 Conclusions

Digitization of surface borehole documentation, profiling and chemical analysis results allowed the creation of a digital deposit model. The impetus for its implementation was the “Quality Program” of 2018, which, in addition to deposit modelling, covered the area of production planning and scheduling, as well as monitoring the quality of the commercial product. In parallel with these activities, five boreholes were drilled from the surface in late 2018 and early 2019 to obtain additional information on the structure and quality of coal from the “Bzie-Dębina 2-West” deposit. The drilled boreholes and the information contained in them formed the basis for changing the correlation of the seams, but most importantly, the required amount of coal was obtained which, after coking, provided a sample for determining the CSR (*Coke Strength after Reaction*) and CRI (*Coke Reactivity Index*) parameters.

Comparing the old and new interpretations, the sulphur content, sinterability of coal (*Roga Index*) and coal type according to Polish standards, among others, were verified. In addition to verifying quality parameters, information on the thickness and location of coal seams was updated in the model, which made it possible to verify the number of resources possible to extract from the deposit. The activities at this stage are a way to mitigate the risks associated with the uncertainty of geological reconnaissance and provide a geological database for the design, planning and scheduling of mining.

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