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KRYSTIAN PROBIERZ*, MAREK MARCISZ*

THE EFFECT OF THE PETROGRAPHIC COMPOSITION ON THE VARIATION OF CRI AND CSR INDICES IN THE PNIÓWEK DEPOSIT IN THE SW PART OF THE UPPER SILESIAN COAL BASIN (POLAND)

WPŁYW SKŁADU PETROGRAFICZNEGO NA ZMIANY WARTOŚCI WSKAŹNIKÓW CRI I CSR W ZŁOŻU PNIÓWEK, SW CZĘŚĆ GÓRNOŚLĄSKIEGO ZAGŁĘBIA WĘGLOWEGO (POLSKA)

The characteristics of variation of the CRI (*Coke Reactivity Index*) and CSR (*Coke Strength after Reaction*) indices as well as the variation of the petrographic composition of coking coal in the Pniówek deposit (SW part of the Upper Silesian Coal Basin) have been presented. The area in which the research results have been obtained has a fundamental meaning to the Polish coking coal reserves, which are characterized by high variation both in quality and coalification. So far, no research related to the determination of the CRI and CSR variation in deposits that would be based on pillar samples collected from active workings has been performed for the Polish coking coal deposits. The samples have been obtained from 6 coal seams (Załęże Beds, a part of Mudstone Series-Westphalian A), at depths between –500 and –700 m.a.s.l. The variation of CRI and CSR values has been presented both along the depth of the deposit (vertically) as well as isolines maps (horizontal variations). The relationships between the CRI and CSR index values and the parameters which are fundamental for their values, that is the R vitrinite reflectance and the petrographic composition (content of the Vt^{mmf} vitrinite, L^{mmf} liptinite, and I^{mmf} inertinite macerals) have been analyzed. The examined coking coal of the Pniówek coal mine is characterized by the following values of the analyzed parameters: CRI = 19.9-60.8% (mean of 33.4%), CSR = 24.4-65.3% (mean of 49.5%), R = 0.98-1.14% (mean of 1.08%), Vt^{mmf} = 60-81% (mean of 74%), L^{mmf} = 4-11% (mean of 7%), I^{mmf} = 13-31% (mean of 19%). The analysis of the variation of the coal quality parameters has not indicated evident and distinct vertical variation tendencies. When considered together with the horizontal variation in the E-W direction, in the view of the tectonics of the deposit (strike, dip, course of the main faults), it indicated a relation between the quality parameters and the direction of bed dips. In the deposit of the Pniówek coal mine, presence of coals of various quality has been confirmed. In the east, at greater depths, less coalified coal characterized by lower CRI values and higher CSR values is present. Such coal has a lesser vitrinite content and a high inertinite content. In the western direction (opposite to the dip direction), higher coalified coals, with higher CRI values and lower CSR values occur-these coals have a high content of vitrinite and low part of inertinite. Inversion of coalification has been demonstrated, as the smaller the depth the lower the reflectance of the coal should be, whereas the case in the Pniówek coal mine is the opposite. Such inversion may be related, as it has been demonstrated numerous times, to the occurrence of thermal metamorphism which modified the regional structure of coalification. No evident relationship of CSR and CRI values and the petrographic content of coal has been found, which is exhibited by low values of correlation indices. High content of inertinite in the samples characterized by relatively low values of CRI, relatively high CSR values and the lowest reflectance, however, draws

* INSTYTUTE FOR CHEMICAL PROCESSING OF COAL, CENTRE FOR TECHNOLOGICAL RESEARCH; UL. ZAMKOWA 1; 41-803 ZABRZE, POLAND. E-MAIL: marek.marcisz@polsl.pl; krystian.probierz@polsl.pl

attention. This runs against expectations, as usually the coal with better coking properties is characterized by the lowest content of inertinite macerals. The explanation of this relation requires further research on the inertinite macerals, especially the typically inert macerals (that is fusinite, micrinite and sclerotinite). The found relationship between the CSR and CRI values does not deviate from the data provided in literature from around the world. The correlation of the CSR index and the Pniówek coal mine vitrinite reflectance, however, is only partially consistent with the results relating to other coals. This confirms the difference of the coal in the examined area, which was exhibited many times and which should be connected to a very specific course of the coalification processes, especially the effect of thermal metamorphism.

Keywords: CRI and CSR variation in deposit, coking coal, petrographic composition, vitrinite reflectance, Upper Silesian Coal Basin

Przedstawiono charakterystykę zmian wskaźników koksowniczych CRI (*coke reactivity index*) i CSR (*coke strength after reaction*) oraz składu petrograficznego węgli koksowych w złożu Pniówek (SW część GZW). Wyniki badań uzyskano w obszarze o podstawowym znaczeniu dla polskiej bazy zasobowej węgli koksowych, która charakteryzuje się znaczną zmiennością jakości i uwęglenia. Badania związane z określaniem zmienności wartości wskaźników CRI i CSR w przestrzeni złożowej, na podstawie próbek bruzdowych pobranych z czynnych wyrobisk górniczych, nie były dotychczas podejmowane w polskich złożach węgli koksowych. Próbki do badań pobrano z 6 pokładów warstw załęskich (Westphalian A) wchodzących w skład Serii Mułowcowej GZW, z przedziału głębokościowego od –500 do –700 m npm. Przedstawiono zmiany wartości wskaźników CRI i CSR zarówno z głębokością złoża (wertykalnie) jak i mapy izolinii (zmiany horyzontalne). Przeanalizowano zależności pomiędzy wartościami wskaźników CRI i CSR a zasadniczymi parametrami wpływającymi na ich wartości tj. refleksyjnością witrynitu R oraz składem petrograficznym (zawartość macerałów grupy witrynitu Vt^{mmf}, liptynitu L^{mmf} i inertynitu I^{mmf}). Badane węgle koksowe z KWK „Pniówek" charakteryzują się wartościami analizowanych parametrów: CRI = 19,9-60,8% (śr. 33,4%), CSR = 24,4-65,3% (śr. 49,5%), R = 0,98-1,14% (śr. 1,08%), Vt^{mmf} = 60-81% (śr. 74%), L^{mmf} = 4-11% (śr. 7%), I^{mmf} = 13-31% (śr. 19%). Analiza zmian parametrów jakości węgla nie wykazała wyraźnych wertykalnych tendencji zmian. Rozpatrywana jednakże łącznie z analizą zmian horyzontalnych w kierunku E–W, na tle tektoniki złoża (rozciągłość, upad, przebieg głównych uskoków), wykazała związek parametrów jakościowych z kierunkiem upadu warstw. W złożu KWK „Pniówek" wykazano obecność populacji węgli różniących się jakością. Na wschodzie, na większych głębokościach, występują węgle niżej uwęglone, o niższych wartościach CRI oraz wyższych CSR, charakteryzujące się niską zawartością witrynitu i podwyższonym udziałem inertynitu. W kierunku na zachód (przeciwnym do upadu) pojawiają się węgle wyżej uwęglone, o wyższych wartościach CRI i niższych CSR, wysokowitrynitowe i o niskim udziale inertynitu. Wykazano inwersję uwęglenia bowiem w miarę zmniejszania się głębokości występowania pokładów powinny pojawiać się węgle o niższej refleksyjności, a nie odwrotnie jak to jest w złożu KWK „Pniówek". Ta inwersja może mieć związek, jak to wielokrotnie wskazywano, z występowaniem metamorfizmu termalnego modyfikującego regionalny obraz uwęglenia. Wykazano brak wyraźnej zależności wskaźników CSR oraz CRI od składu petrograficznego węgli o czym świadczą niskie wartości współczynników korelacji. Zwraca uwagę wysoki udział inertynitu w próbkach charakteryzujących się względnie niskimi wartościami CRI, i względnie wysokimi wartościami CSR oraz najniższą refleksyjnością. Odbiega to od oczekiwań bowiem zazwyczaj węgle o lepszych własnościach koksowniczych charakteryzują się niższą zawartością macerałów grupy inertynitu. Wyjaśnienie tego związku wymaga dalszych badań macerałów grupy inertynitu, szczególnie udziału macerałów typowo inertnych (tj. fuzynitu, mikrynitu i sklerotynitu). Wykazana zależność wartości wskaźnika CSR od CRI nie odbiega od znanych z literatury światowej. Współzależność wartości wskaźnika CSR od zdolności odbicia światła witrynitu węgli z KWK „Pniowek" jest natomiast jedynie częściowo zgodna z wynikami badań innych węgli. Potwierdza to wielokrotnie wykazywaną odmienność węgli z obszaru badań, którą należy wiązać ze specyficznym przebiegiem procesów uwęglenia, szczególnie oddziaływaniem metamorfizmu termalnego.

Słowa kluczowe: Górnośląskie Zagłębie Węglowe, złoże Pniówek, węgiel koksowy, zmiany wartości wskaźników CRI i CSR w złożu, skład petrograficzny, refleksyjność witrynitu

1. Introduction

In all coal classifications, quality parameters of coking coal are mostly related to coking indices. In the Polish classification of types according to the Polish Standard PN-82/G-87002, these indices are the caking capability-the Roga Index (RI), the free swelling index (SI) and the dilatation parameter (b).

The producers' pursuit to obtain high-quality coke, however, require also the knowledge of other parameters such as the coal contraction (a), chlorine content (Cl) (Marcisz et al., 2015) or phosphorus content (P). Also new coking coal quality parameters are introduced and the importance order of the existing ones is changed. At the end of the 80's of the past century, the Nippon Steel Co (NSC) has introduced new coke testing results into the industry practice, namely the CRI reactivity and the coke strength after reaction index (CSR) (Karcz, 2008; Tramer, 2004).

The CRI (*Coke Reactivity Index*) characterizes the coke reactivity in CO_2, that is the mutual participation of CO and CO_2 in the gaseous phase-solid phase system for specific pressure and temperature conditions (in low temperatures, the CO_2 is mostly formed, whereas in high temperatures, higher amounts of CO are formed). The value of that index, expressed as a percentage, is determined based on the coke mass decrement resulting from the CO_2 effect on the coke sample in the temperature of 1100°C within 2 hours. The CSR index (*Coke Strength after Reaction*), on the other hand, characterizes the changes in the coke strength after the determination of reactivity (of the same coke sample). Its value, expressed as a percentage, is determined after specifying the mass percentage of grains larger than 10 mm which are left after mechanical processing (tumbling) of the gasified sample of coke (PN-C-04312:1996).

The CRI and CSR indices are currently among the most important coke quality indices and are relatively new in comparison to the remaining parameters which determine the suitability of coal in the coking processes. These indices are usually determined based on samples obtained from railway cars and their mass is usually over 20 kg. Using this method, however, there is no possibility to assign a given sample to their location in the deposit (bed). Since August, 2009, the Pniówek coal mine, which is a part of JSW S.A. (the largest business entity engaged in the exploitation of coking coal in Poland) also conducts the examination of CRI and CSR indices based on samples taken from active workings, that is, samples with strictly assigned coordinates (x, y, z). The introduction of this procedure results from the growing requirements of the clients and is-as it seems-one of the results of the POIG.01.01.02-24-017/08 *"Smart coke plant fulfilling requirements of best available techniques"* project realized by the Institute for Chemical Processing of Coal in Zabrze (among others: Probierz et al., 2012).

The research concerning the distribution of the CRI and CSR parameters has been performed in the area of the Pniówek coal mine, that is the area with a fundamental significance to the Polish coking coal reserves. The region of the research, which is characterized by high variability of quality and Rank level, has until now been a subject of long-standing research concerning the coking coal quality. The works concerned, among other matters, the problems of occurrence and distribution of different types of coal, quality variability depending on the petrographic structure of beds and the characteristics of the petrographic composition variation (Micorek et al., 2012; Probierz & Marcisz, 2010). The relationship between the quality variation of coal, Rank and the petrographic composition with the possibility of thermal metamorphism has also been noted (Komorek et al., 2010; Probierz, 1989; Probierz et al., 2003; Probierz & Lewandowska, 2003).

The purpose of the work was to indentify the variations of the CRI and CSR indices in a 3D deposit space of the Pniówek coal mine based upon pillar samples taken from active workings. An analysis of vertical and horizontal variation of these indices in the bed has been performed. The correlations between CRI and CSR values and the quality parameters of coal determined using petrographic methods, that is the R vitrinite reflectance and the content of macerals, have also been analyzed. Also an attempt to predict the variation of CRI and CSR values in the deposit was made, which should facilitate the supply of coking coal with required parameters.

2. The location and the geological characteristics of the research area

The Pniówek coal mine is located in the SW part of the Upper Silesian Coal Basin and conducts exploitation at a mining area of 28.55 km^2. In the west, it borders with the Zofiówka coal deposit, in the south-west with Borynia deposit and in the north, east and south with non-exploited mining fields. The Pniówek coal mine, like other surrounding coal mines, is a part of the Jastrzębska Spółka Węglowa S.A.-the largest coking coal producer in Poland.

The deposit includes Upper Carboniferous sediments: the Paralic Series, the Upper Silesian Sandstone Series and Mudstone Series (Fig. 1). The Paralic Series is represented by Poręba Beds

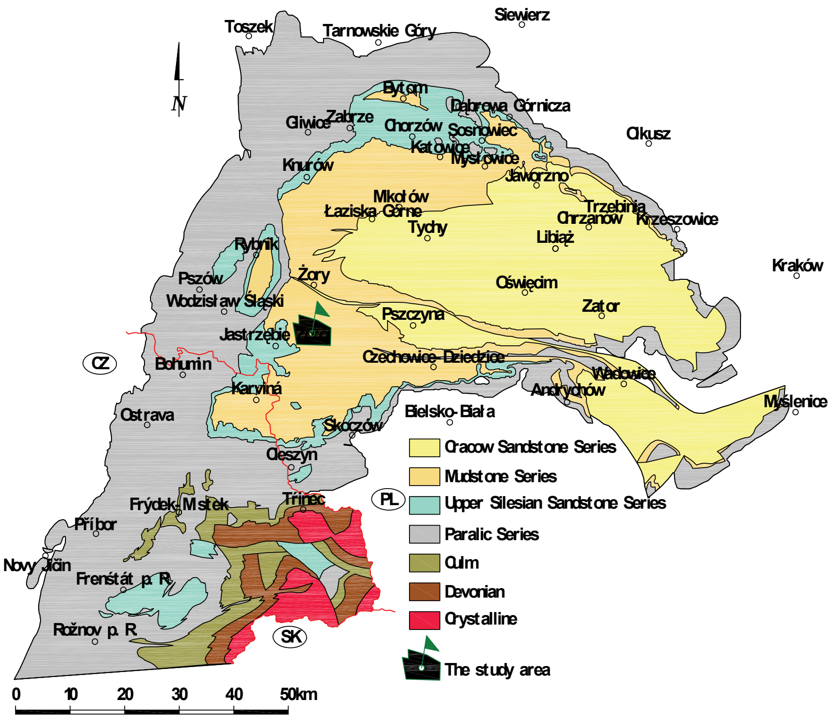

Fig. 1. The study area against the background of the Upper Silesian Coal basin geological structure (Probierz et al., 2012)

(beds with 600 series numbering)-the oldest seams recognized in the mining area of the coal mine. The Upper Silesian Sandstone Series is represented by Zabrze Beds (beds with 500 series numbering) and Ruda Beds (400 series numbering). The Mudstone Series is represented by Załęże Beds (300 series numbering). Some of its properties have been lised by Bukowski et al. (2012).

The overburden is represented by Miocene and Quaternary formations, which are characterized by diversified lithological characteristics and diversified depth.

The Pniówek deposit is located within the borders of the Zofiówka monocline in the SW part of the Upper Silesian Coal Basin. Such location results in its monoclinal structure with a slight but variable direction of subsidence from 5° to a maximum of 20° in the SEE direction. It is also characterized by intensive fault tectonics-the mining area of the coal mine is situated between two large fault zones with a regional range, that is the Żory-Piasek Jawiszowice-Wysoka fault zone in the north and the Gorzyce-Bzie Zameckie-Czechowice-Kęty fault zone in the south (Fig. 2).

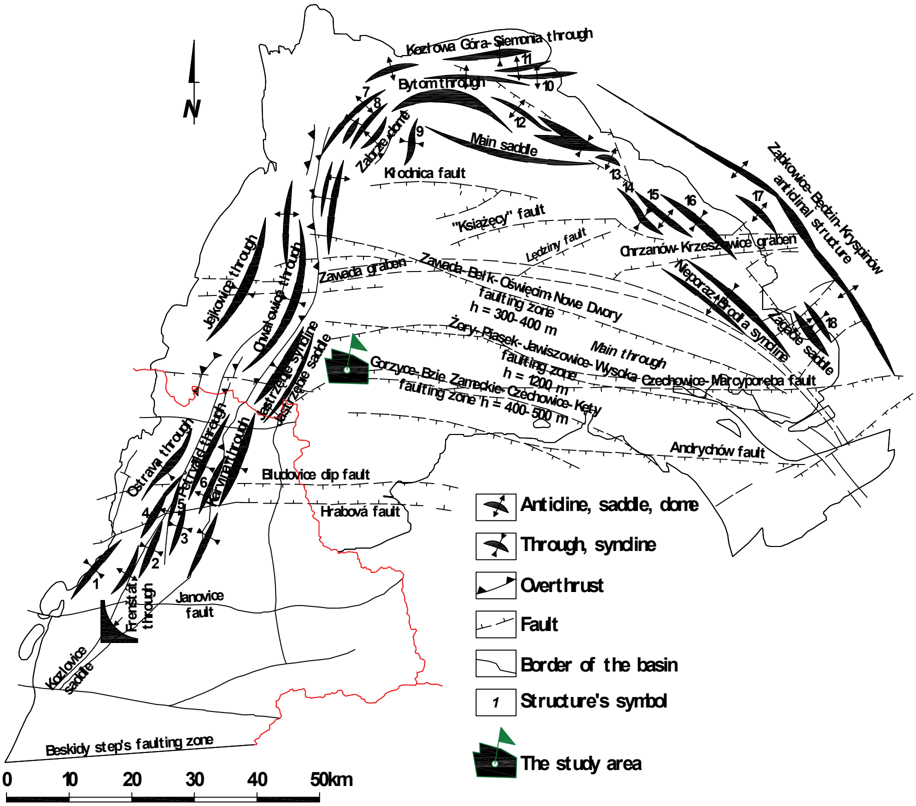

Fig. 2. The study area against the background of the Upper Silesian Coal basin tectonics (Probierz et al., 2012)

1 – Přibor trough, 2 – Stařice trough, 3 – Svinov trough, 4 – Paskov saddle, 5 – Michałkowice saddle, 6 – Orlova fold, 7 – Sośnica-Knurów fold, 8 – Concordia trough, 9 – Ruda syncline, 10 – Malinowice trough, 11 – Sarnów saddle, 12 – Grodków saddle, 13 – Maczki dome fold, 14 – Długoszyn-Wilkoszyn syncline, 15 – Ciężkowice-Trzebinia saddle, 16 – Siersza trough, 17 – Miękinia antycline, 18 – Nowa Wieś Szlachecka trough (only the structures marked by numbers have been explained)

In the Pniówek coal deposit is observed a complicated tectonics (i.a., numerous faults forming areas of tectonic displacement which render the exploitation difficult) and high variation in thickness of the whole seam and the dirt bands (numerous barren rock interlayers).

The resources of the Pniówek coal mine exceed 270 million Mg, while the reserves exceed 60 million Mg with an output of 2.6 million Mg a year. The coking coals of the Zofiówka monocline, which have been recognized in a range of depths between 0 m.a.s.l. and –1200 m.a.s.l., are characterized by the following variation ranges of main quality parameters (following Probierz et al. 2012): ash content A^d = 1-59%, content of volatile parts V^{daf} = 3.2-45.5%, sulphur content S_t^d = 0.2-2.3%, Free Swelling index, SI = 0-9, dilatation parameter b = –27-298%, vitrinite reflectance R = 0.88-1.33%, and the petrographic composition-content of macerals (as a percentage of volume): Vt^{mmf} vitrinite = 46-91% vol., L^{mmf} exinite = 1-14% vol., I^{mmf} inertinite = 6-43% vol. The data has been compiled based on the study of more than 30 coal seams that are or will be exploited in the future, starting with the 360/1 coal seam (Westphalian A) up to the 510 coal seam (Namurian B).

3. Data and methods

The source data analyzed in this work has been obtained from the Pniówek mine database, that is the deposit analysis sheets of pillar samples covering the period from 2009 to 2010. During this period, the analyzed parameters were determined for 19 pillar samples from six coal seams: 360/1 (4 samples), 361 (1 sample), 401/1 (3 samples), 403/3 (2 samples), 404/1 (4 samples) and 404/2 (5 samples). The analyzed samples were collected from Załęże Beds (Westphalian A) included in the Mudstone Series of the Upper Silesian Coal Basin.

The characteristics of variations of CRI and CSR values have been analyzed using statistical methods.

The study involved an analysis of changes in the CRI and CSR values for the entire population of samples and for separated subpopulations. In the case of vertical variations, the subpopulations were analyzed in 100 m depth intervals. The horizontal variation analysis was conducted in the W-E and N-S directions in 500 m wide blocks (belts), oriented in relation to meridians and parallels of latitude (Fig. 3).

Planar variations of CRI and CSR indexes in a deposit, in the form of isolines maps, have also been presented. The maps have been prepared using the Golden Software Surfer 8 software with the use of the RBF (*Radial Basis Function*) contouring method. A constant distance of 50 m between grid nodes has been assumed (in line with the recommendation for the multi-seam Upper Silesian coal deposits). In order to keep the maps as clear as possible, the minor elements such as grid lines, the location of sampling points, etc. have been omitted, leaving only the outline of the mine's mining area and the course of the given quality parameter isolines.

The correlation between CRI and CSR indices and the parameters that influence their values: the R vitrinite reflectance and the petrographic composition (the content of the Vt^{mmf} vitrinite L^{mmf} liptinite and and I^{mmf} inertinite group of macerals) has been specified using rectilinear correlation. An attempt was made to specify the correlations between the analyzed parameters using the multiple correlation method.

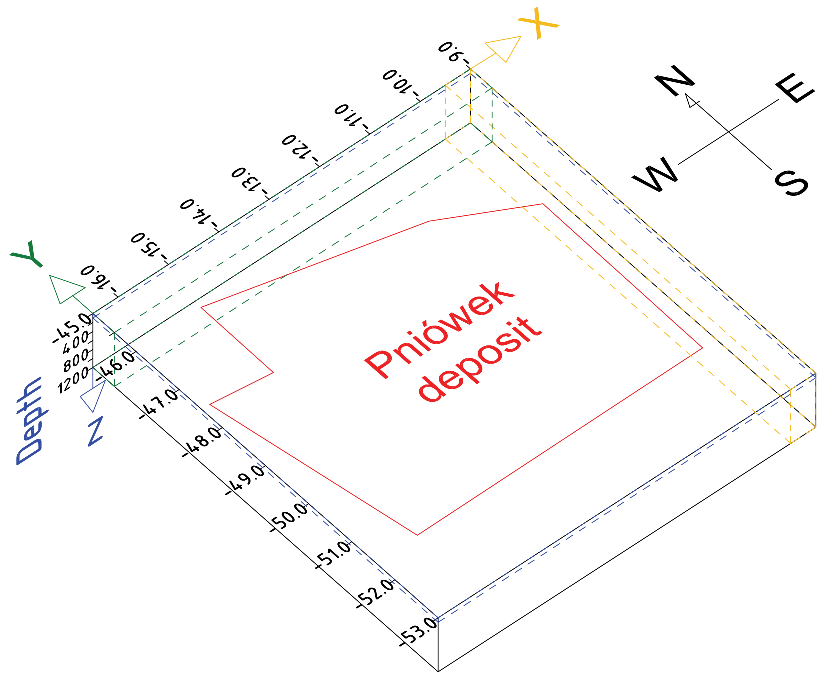

Fig. 3. Sketch of variability analysis of the CRI and CSR indices values in vertical and horizontal directions (Probierz et al., 2012)

4. Results and discussion

The results of CRI and CSR indices values determination, as well as the vitrinite reflectance and petrographic composition results, have been presented in Table 1.

TABLE 1

Variation of CRI and CSR indices as well as the variation of vitrinite reflectance and petrographic composition with depth in the Pniówek deposit

No.	Depth Z, m	CRI, %	CSR, %	R, %	Vt^{mmf}, %	L^{mmf}, %	I^{mmf}, %
1	2	3	4	5	6	7	8
1	–500.5	41.3	27.2	1.12	81	6	13
2	–508.4	33.6	47.2	1.09	78	6	16
3	–514.9	34.0	51.7	1.00	74	5	21
4	–530.1	24.2	61.8	1.12	72	6	22
5	–535.2	19.9	65.3	1.08	80	7	13
6	–540.4	25.7	60.9	1.12	74	7	19
7	–548.7	33.6	49.3	1.13	74	9	17
8	–552.7	60.8	24.4	1.04	78	8	14
9	–569.9	40.6	34.2	0.98	70	11	19

1	2	3	4	5	6	7	8
10	–593.1	58.3	27.6	1.14	81	5	14
11	–631.0	30.6	52.8	1.10	74	9	17
12	–640.2	23.4	59.1	1.08	81	4	15
13	–646.5	34.2	49.9	1.08	74	5	21
14	–653.8	27.7	60.7	1.06	60	9	31
15	–662.3	31.2	47.1	1.10	77	10	13
16	–671.5	24.6	63.3	1.05	65	10	25
17	–672.3	30.9	53.6	1.12	70	8	22
18	–684.2	29.3	55.2	1.06	64	7	29
19	–694.8	30.7	49.7	1.10	72	9	19
min.	–694.8	19.9	24.4	0.98	60	4	13
max.	–500.5	60.8	65.3	1.14	81	11	31
mean	–597.4	33.4	49.5	1.08	74	7	19
depths from –500 to –600							
min.	–593.1	19.9	24.4	0.98	70	5	13
max.	–500.5	60.8	65.3	1.14	81	11	22
mean	–539.4	37.2	45.0	1.08	76	7	17
depths from –600 to –700							
min.	–694.8	23.4	47.1	1.05	60	4	13
max.	–631.0	34.2	63.3	1.12	81	10	31
mean	–661.8	29.2	54.6	1.08	71	8	21

The conducted research concerning the coal in the Pniówek coal mine have indicated the variation of the analyzed parameters in the following ranges, respectively: CRI = 19.9-60.8% (mean of 33.4%), CSR = 24.4-65.3% (mean of 49.5%), R = 0.98-1.14% (mean of 1.08%), Vt^{mmf} = 60-81% (mean of 74%), L^{mmf} = 4-11% (mean of 7%), L^{mmf} = 13-31% (mean of 19%). The results of the CRI and CSR indices designation compiled in Table 1 allowed for the characterization of their variability in the Pniówek coal mine.

4.1. Characteristics of vertical variability (with depth)

The analysis of the CRI and CSR vertical variability was, unfortunately, conducted only for depths of the deposit between –500 and –700 m, which was caused by the sampling possibilities conditioned by the locations of the currently active underground workings. The entire recognized profile of the Pniówek deposit, as mentioned earlier, reaches depths from 0 to –1200 m. The vertical variations of CRI and CSR values in the Pniówek deposit have been presented in Fig. 4.

The density of points, due to sampling of only two 100 m depth sections, has not allowed to observe clear variation tendencies (low values of the r correlation factor). Recognition of change tendencies in the 100 m depth sections also has not provided clear results (Table 1).

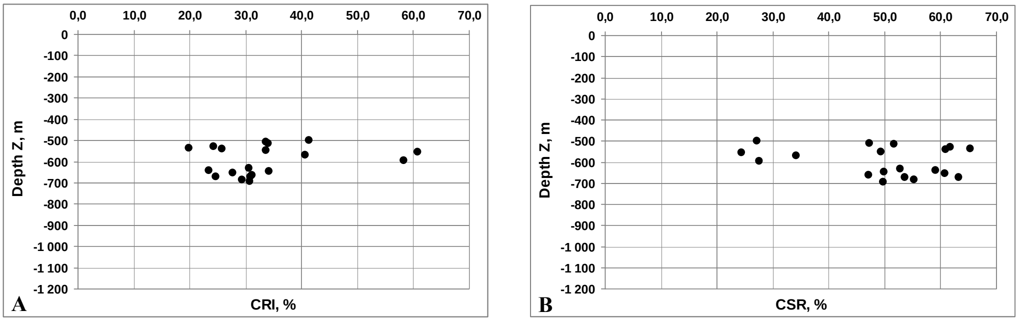

Fig. 4. Variation of the CRI (A) and CSR (B) values with depth in the Pniówek deposit

4.2. Characteristics of horizontal variability in the E-W direction

The analysis of horizontal variability in the E-W direction was conducted at a 7 km wide section of the deposit, within blocks of 500 m in width (from –9.0 to –16.5, Fig. 3). The results of CRI and CSR values determination for the separated blocks of the deposit have been presented in Table 2.

TABLE 2

CRI and CSR variations in the E-W direction of the Pniówek deposit

No.	The separated block of deposit in the E-W direction (500 m wide)	No. of observations n	CRI value, % (for the separated block)			CSR value, % (for the separated block)		
			min.	max.	mean	min.	max.	mean
1	–9.5-–10.5	1	24.6			63.3		
2	–10.0-–10.5	2	30.6	30.7	30.7	49.7	52.8	51.3
3	–10.5-–11.0	2	31.2	40.6	35.9	34.2	47.1	40.7
4	–11.0-–11.5	0	–	–	–	–	–	–
5	–11.5-–12.0	0	–	–	–	–	–	–
6	–12.0-–12.5	0	–	–	–	–	–	–
7	–12.5-–13.0	2	23.4	29.3	26.4	55.2	59.1	57.2
8	–13.0-–13.5	5	27.7	34.2	32.0	47.2	60.7	52.1
9	–13.5-–14.0	1	19.9			65.3		
10	–14.0-–14.5	1	24.2			61.8		
11	–14.5-–15.0	2	25.7	60.8	43.3	24.4	60.9	42.7
12	–15.0-–15.5	0	–	–	–	–	–	–
13	–15.5-–16.0	2	34.0	58.3	46.2	27.6	51.7	39.7
14	–16.0-–16.5	1	41.3			27.2		

Notice: the depth range of the separated blocks of deposit encompasses depths between –500 and –700 m, as given in Fig. 4.

As may be noticed in Table 2, in certain parts of the deposit no CRI and CSR values were determined, while in some, only single samples were analyzed (no min. and max. values), which was a result of the location of samples and the sampling possibility.

The data compiled in Table 2 allows for a general characterization of the CRI and CSR indices variability in the Pniówek deposit. It does not, however, allow for the differentiation of the variability in individual parts of the area of study. Due to the above, a diagram has been plotted, which gives consideration to both the location of samples in individual blocks of the Pniówek deposit and the CRI and CSR index values of the sampled coal (Fig. 5).

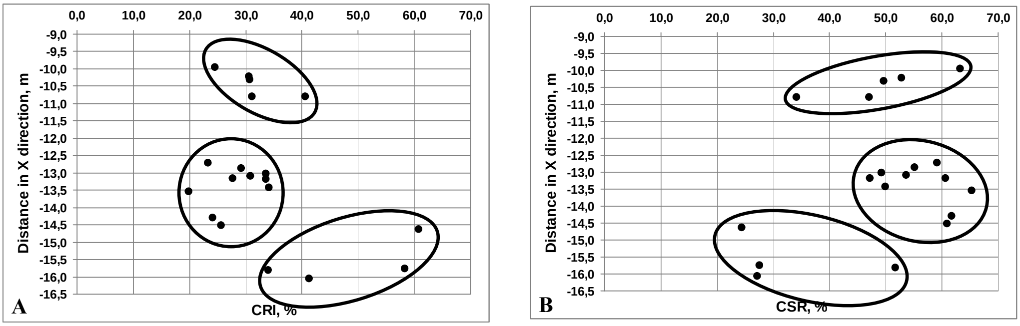

Fig. 5. Variability of the CRI (A) and CSR (B) values in the E-W direction in the Pniówek deposit

The data presented in Fig. 5 indicates that the coal of the western part of the studied area is characterized by the highest CRI values. As it seems, three populations of samples may be distinguished, different both in the CRI and CRS parameters and the reflectance as well as the petrographic composition. Mean values of the CRI index, mean reflectance and mean part of vitrinite, liptinite and inertinite macerals of these three populations were determined and presented in Table 3. The CSR index values were presented in the same way (Table 4).

TABLE 3

CRI variability against the background of vitrinite reflectance and petrographic composition of the separated populations in the E-W analysis direction

Parameter value	CRI,%	R, %	Vt^{mmf},% vol.	L^{mmf}, % vol.	I^{mmf}, % vol.
Eastern part					
min.	24.6	0.98	65	9	13
max.	40.6	1.04	77	11	25
mean	31.5	1.00	72	10	19
Central part					
min.	19.9	1.06	60	4	13
max.	34.2	1.13	81	9	31
mean	28.3	1.10	73	7	21
Western part					
min.	34.0	1.08	74	5	13
max.	60.8	1.14	81	8	21
mean	48.6	1.11	79	6	16

TABLE 4

CRS variability against the background of vitrinite reflectance and petrographic composition of the separated populations in the E-W analysis direction

Parameter value	CSR,%	R,%	Vt^{mmf},% vol.	L^{mmf},% vol.	I^{mmf},% vol.
Eastern part					
min.	34.2	0.98	65	9	13
max.	63.3	1.04	77	11	25
mean	49.4	1.00	72	10	19
Central Part					
min.	47.2	1.06	60	4	13
max.	65.3	1.13	81	9	31
mean	55.9	1.10	73	7	21
Western part					
min.	24.4	1.08	78	5	13
max.	27.6	1.14	81	8	14
mean	26.4	1.11	80	6	14

The analysis of the distribution of CRI and CRS index values in the E-W direction, conducted for 500 m blocks of the deposit, oriented south (Fig. 5, Tables 3 and 4), confirms the existence of 3 populations of samples that differ in terms of these parameters, in the Pniówek coal mine area.

The lowest values of CRI (mean value of 28.3%) are indicated in coals in the central part of the deposit, which are also characterized by the highest mean content of inertinite macerals (21% mean). The highest values of CRI (48.6% mean) are, on the other hand, indicated by coals in the western part of the studied area and are characterized by the highest mean content of vitrinite macerals (mean value of 79%), the lowest inertinite content (mean value of 16%) and the highest vitrinite reflectance (mean value of 1.11%). The coals in the eastern part of the Pniówek coal mine deposit are characterized by intermediate values of CRI (mean value of 31.5%). The CRI values of the coal from the eastern part are, however, very similar to the coals of the central part of the Pniówek deposit. What draws attention is the highest-as compared to other populations-liptinite content in the composition (10% mean).

The distribution of the CSR values of the examined coals also allows for the separation of 3 populations of samples. In this case, however, the central part of the deposit contains the coal with the highest CSR value (mean value of 55.9%) and the highest content of inertinite (mean of 21%). In the western part, the coal is characterized by the lowest CSR values (mean of 26.4%), the highest content of vitrinite macerals (mean value of 80%), the lowest inertinite content (mean value of 14%) and the highest vitrinite reflectance (mean value of 1.11%). The samples taken from the eastern part are characterized by intermediate values of CSR (mean of 49.4%) and the lowest vitrinite reflectance. Analogically to the CRI distribution, also the CSR index values indicate similarities to the coals of the central and eastern part of the Pniówek deposit.

To recapitulate, it may be well exhibited that the coals of the eastern part of the Pniówek mining region are characterized by relatively low CRI values and relatively high CSR values as well as the lowest vitrinite reflectance, the lowest vitrinite content, the highest liptinite content and relatively high content of inertinite. The observed high liptinite part falls away from expectations, as usually the high coking quality coals are characterized by lower content of macerals of this group (Komorek et al., 2010; Probierz, 1989).

The western part, however, contains coals with the highest CRI values and the lowest CSR values. These coals are characterized by the highest vitrinite reflectance values, highest content of vitrinite group macerals and the lowest part of liptinite and inertinite. The coals of the central part of the deposit exhibit intermediate parameters. This means that the analysis of the quality parameters of the Pniówek deposit conducted in the E-W direction has indicated their diversification which depends on the direction of beds subsidence in the deposit. This is because the direction of subsidence causes the coals of the eastern part of the deposit to be at greater depths than in the west.

The characterization of the vertical variations of the coal quality parameters, which covered the depth range from –500 to –700 m, has not indicated any clear variation tendencies. When considered together with the horizontal variation in the E-W direction, against the background of the deposit tectonics, especially the strike and dip, it allowed to indicate a correlation between the quality parameters and the direction of dip of the carboniferous beds. This is evidenced by the populations of coal samples which are different in quality, depending on the dip direction. In the east, at greater depths, coals characterized by lower coalification, lower CRI, higher CSR occur. These coals are characterized by low vitrinite content and an increased inertinite part. In the western direction, opposite to the dip direction, appear coals characterized by a higher Rank. These are characterized by higher CRI and lower CSR values, include a high content of vitrinite and a low part of inertinite. Fig. 6 presents the locations of the sample populations the parameters of which are similar.

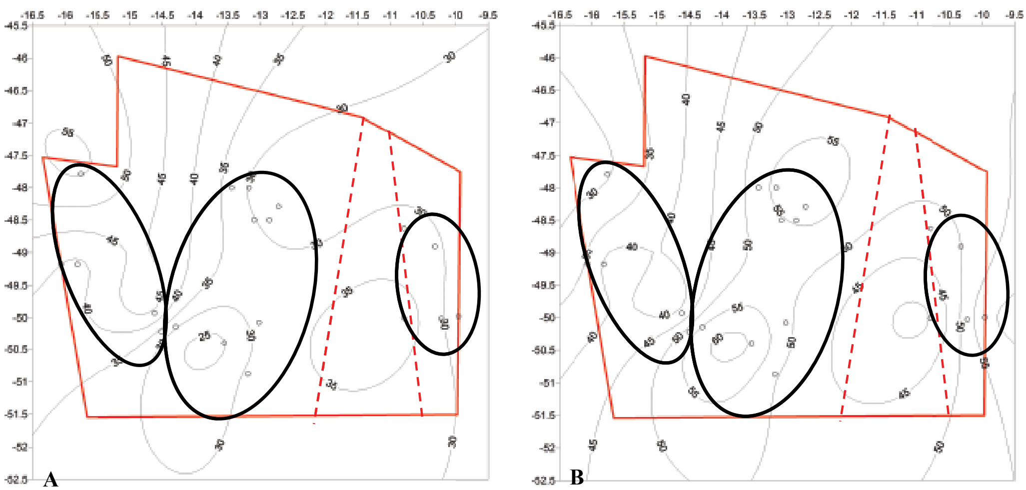

Fig. 6. Locations of separated sample populations with similar CRI (A) and CSR (B) values against the background of the isolines map of their values in the Pniówek deposit
Notice: The main faults have been marked with a broken line

The plotted maps (Fig. 6) confirm what had been confirmed earlier by statistical analysis conducted during the characterization of horizontal variation in the E-W direction-the grounds for separation of three populations of samples. The samples, as far as the CRI index is concerned, present the highest values in the western part, the lowest values in the eastern part and intermediate values of CRI in the central part. The CSR parameter exhibits reverse properties, as its values are lowest in the west and highest in the east. The presented CRI and CSR maps are in a way "virtual" maps as they do not concern a single level, bed or layer of the deposit. The plotting of maps for actual beds or layers is hindered by an insufficient number of samples which is caused by sampling possibilities (only 1-2 samples of a given coal seam were possible to obtain). The knowledge of the CRI and CSE parameters in the Pniówek coal mine deposit is, however, of great significance to the coking industry. Attempts to identify these variations have not been made neither for this deposit or any other Polish coking coal deposits. It seems that the non-standard method applied in the work allowed for effective determination of variations of parameters in the deposit and even making predictions of the parameters of the deposit space. Thus, it helped to by-pass the inconvenience caused by insufficient number of samples necessary in the traditional method of determination of deposit parameters variation (especially when disposing of a small number of samples, that is <30).

It has also been exhibited that the inversion of Rank, referred to earlier (higher vitrinite reflectance coal should occur with depth, while in the Pniówek deposit it is the opposite) may be explained, as it has been demonstrated numerous times, by the occurrence of thermal metamorphism modifying the regional structure of Rank (Komorek et al., 2010; Probierz, 1989; Probierz et al., 2003, Probierz & Lewandowska, 2003). The presence of a meridional graben in the central-eastern part of the Pniówek coal mine deposit must also be taken into consideration, as it may have an effect on the ranges of distribution of the central and eastern populations (Fig. 6). In this graben, the exploitation is very limited because its surroundings provide better mining conditions and the deposit is better recognized and sampled. This, however, doesn't seem to have any effect on the vitrinite reflectance inversion.

4.3. Characteristics of horizontal variability in the N-S direction

The analysis of horizontal variation in the N-S direction was conducted at a 4 km wide area of the deposit, within separated 500 m wide blocks (from –47.0 to –51.0, Fig. 3). The results of the CRI and CSR determinations for the separated blocks have been presented in Table 5, while the location of the samples and the corresponding CRI and CSR values in the deposit area have been presented in Figure 7.

TABLE 5

CRI and CSR variability in the N-S direction in the Pniówek deposit

No.	The separated block of deposit in the N-S direction (500 m wide)	No. of observations n	CRI value, % (for the separated block)			CSR value, % (for the separated block)		
			min.	max.	mean	min.	max.	mean
1	–47.0-–47.5	0	–	–	–	–	–	–
2	–47.5-–48.0	3	27.7	58.3	40.1	27.6	60.7	46.1
3	–48.0-–48.5	3	23.4	30.9	27.9	53.6	59.1	56.0
4	–48.5-–49.0	2	30.7	31.2	31.0	47.1	49.7	48.4
5	–49.0-–49.5	2	34.0	41.3	37.7	27.2	51.7	39.5
6	–49.5-–50.0	2	24.6	60.8	42.7	24.4	63.3	43.9
7	–50.0-–50.5	6	19.9	40.6	29.1	34.2	65.3	54.1
8	–50.5-–51.0	1		33.6			47.2	

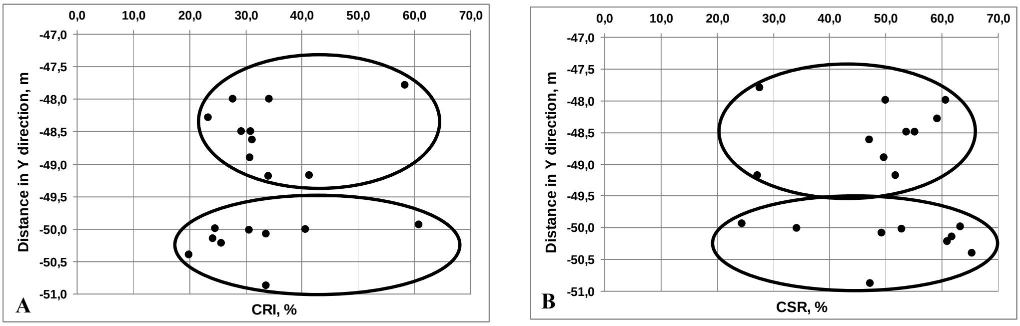

Fig. 7. Variability of the CRI (A) and CSR (B) values in the N–S direction in the Pniówek deposit

The distribution of the CRI and CRS index values provided in the charts (Fig. 7) does not allow for a determination of a clear variation tendency. It is possible to separate two populations of samples-the northern and the southern groups, however the differences of the CRI and CSR parameters in the two groups are insignificant (Tables 6 and 7).

TABLE 6

CRI variability in the context of reflectance and petrographic composition in the separated populations for the N-S direction of analysis

Parameter value	**CRI, %**	**R, %**	**Vt^{mmf}, % vol.**	**L^{mmf}, % vol.**	**I^{mmf}, % vol.**
Northern part					
min.	23.4	1.00	60	4	13
max.	58.3	1.14	81	10	31
mean	34.1	1.08	73	7	20
Southern part					
min.	19.9	1.0	65.0	6.0	13.0
max.	60.8	1.1	80.0	11.0	25.0
mean	32.6	1.1	73.9	8.1	18.0

TABLE 7

CSR variability in the context of reflectance and petrographic composition in the separated populations for the N-S direction of analysis

Parameter value	**CSR, %**	**R, %**	**Vt^{mmf}, % vol.**	**L^{mmf}, % vol.**	**I^{mmf}, % vol.**
Northern part					
min.	27.2	1.00	60	4	13
max.	60.7	1.14	81	10	31
mean	48.2	1.08	73	7	20
Southern part					
min.	47.2	0.98	65	6	13
max.	65.3	1.12	80	10	25
mean	57.2	1.07	74	8	18

The analysis of the distribution of the values of the CRI and CSR indices, conducted in separated 500 m latitudinal blocks of the deposit (Fig. 7, Tab. 6 and 8), confirms the presence of two populations of samples that differ insignificantly as far as these indices are concerned.

As provided by Tables 6 and 7, the coals exhibit slightly higher CRI values in the northern part of the deposit (mean of 34.1%) than in the southern of study area (mean value of CRI = 32.6%).

When it comes to the CSR values distribution, it has been exhibited that in the northern part of the deposit, coals with a mean CSR value of 48.2% are present, while in the southern part the values of this parameter are slightly higher and their mean value is 57.2%.

The demonstrated insignificant variability of the CRI and CSR parameters in the northern and southern parts of the Pniówek coal deposit seems to confirm the correlation with the dip. The analysis of the horizontal quality parameters in the N–S direction, that is, along the stretch of the Carboniferous seams, has not provided any significant or noteworthy variability.

4.4. The correlation between the CRI and CSR indices, the R vitrinite reflectance and the petrographic composition

The explanation of the analyzed index variations, both in vertical in horizontal direction, has been sought in the mutual correlations between the CRI and CSR indices and the parameters which significantly influence these indices, that is the R vitrinite reflectance and the petrographic composition (Fig. 8).

The obtained *r* correlation coefficient values (Table 8) allow for a conclusion that the two indicators, CRI and CSR, are mostly dependent on the content of the V^{tmmf} vitrinite group macerals (the *r* value: 0.29 and 0.40, respectively) and the I^{mmf} inertinite (*r* value: –0.30 and –0.42, respectively).

TABLE 8

Values of the *r* correlation coefficient for the correlation between the CRI and CSR indices and the R vitrinite reflectance and petrographic composition

Parameter	R, %	Vt^{mmf}, % vol.	L^{mmf}, % vol.	I^{mmf}, % vol.	CRI, %
CRI,%	0.10	0.29	–0.06	–0.30	–
CSR,%	0.01	–0.40	0.07	0.42	–0.94

It should be noted that the CRI index exhibits positive correlation in relation to the Vt^{mmf} vitrinite and a negative correlation with the I^{mmf} inertinite content. The characteristics of these correlations is opposite in case of the CSR index.

The observed correlation with the inertinite group indicates a necessity to conduct further, more detailed research, which would investigate the relations between the CRI and CSR indices and the individual macerals of the inertinite group, with a particular consideration for typically inert macerals (that is fusinite, micrinite and sclerotinite).

The correlations between the CRI and CSR parameters, reflectivity and petrographic composition are not as clear as demonstrated in other works, i.a.: Diez & Alvarez & Barriocanal 2002, Pusz & Buszko 2012, Tiwari & Banerjee & Saxena 2013. One should, however, mention that the cited works usually concerned selected seams or coal blends. No correlation may also be linked to number of available samples. It should be also remembered that the low value of the correlation coefficient does not mean that no relation exists among random variables. Such a relation

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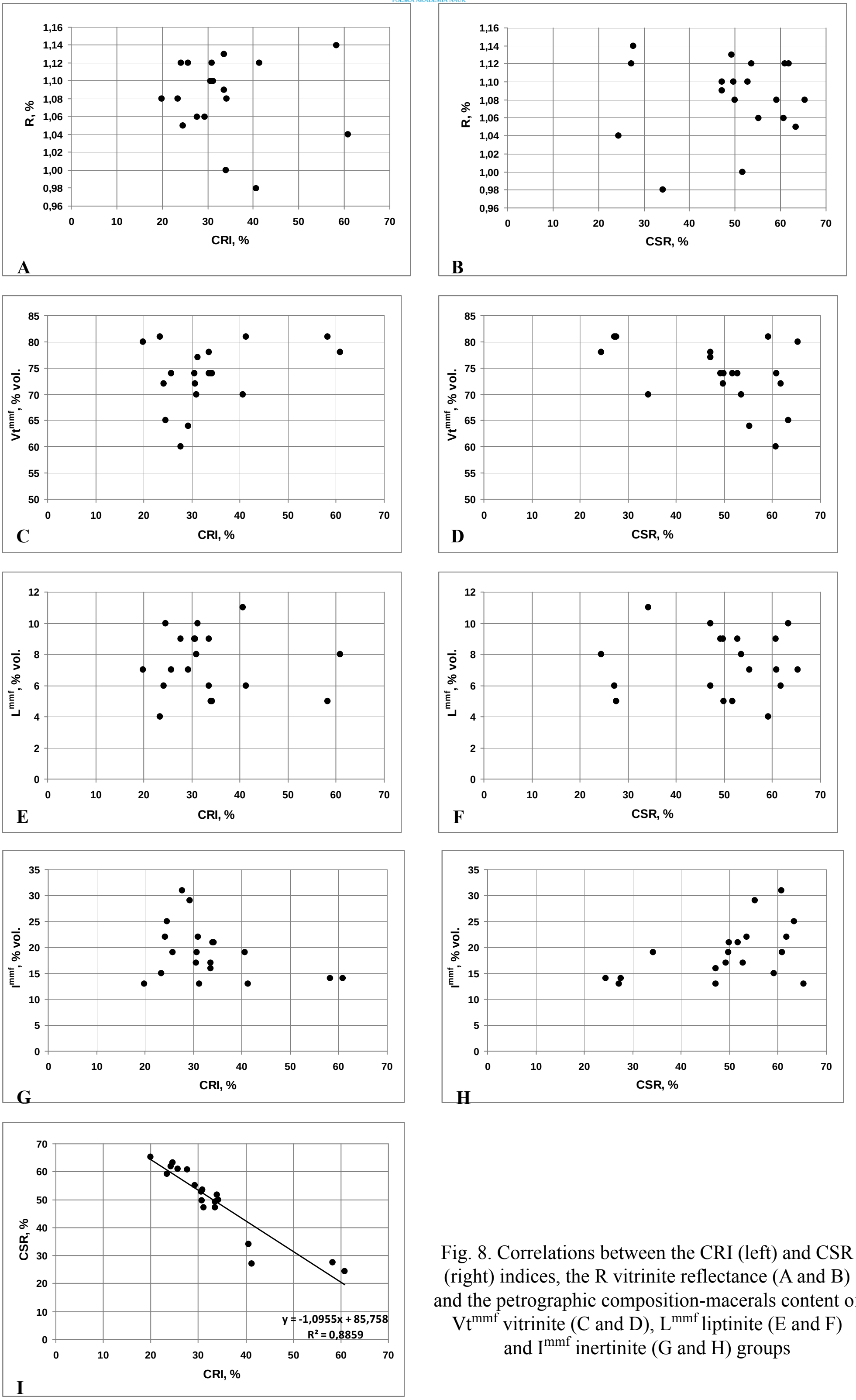

Fig. 8. Correlations between the CRI (left) and CSR (right) indices, the R vitrinite reflectance (A and B) and the petrographic composition-macerals content of Vt^{mmf} vitrinite (C and D), L^{mmf} liptinite (E and F) and I^{mmf} inertinite (G and H) groups

may exist, yet have a non-linear (rectilinear) character. Similarly, when the correlation coefficient is close to one, it does not necessarily mean that a cause and effect relation exists between the random variables. It is then referred to as a strong stochastic relation (random similarity of two samples may occur). The value of the correlation coefficient in the study may also be underrated if measurement errors occur in one or both variables (there are statistical measures which give consideration to such errors).

5. Conclusion

The knowledge of the distribution of CRI and CSR parameters in coking coal deposits is extremely significant for the coking industry due to the possibility of obtaining coal with the highest quality parameters, which is expected by the customers.

So far, no identification of CRI and CSR parameters variability and their relationship with the petrographic composition of coal (the content of vitrinite, liptinite and inertinite macerals) as well as their Rank (coalification level) have been performed based upon pillar samples in the Upper Silesian Coal Basin conditions.

The attempt that was made to characterize the variability of the CRI (coke reactivity index) and CSR (coke strength after reaction) in the Pniówek coking coal is connected with significance of that deposit to the Polish coking coal reserves. The Pniówek coal mine deposit has got coal reserves which allows the coal mine to operate for another few dozen years (resources are 270 million Mg, while the reserves are >60 million Mg). The coals of that deposit are characterized by good quality parameters and high variability of coking properties, coalification level (Rank) and petrographic composition.

The samples were obtained from 6 coal seams of the Załęże Beds (Westphalian A) incorporated in the Mudstone Series of the Upper Silesian Coal Basin, from the depth range between –500 and –700 m.a.s.l. Despite the low density of sampling, an attempt to present the variability of the examined coking parameters in a 3D deposit space was made, as besides the determinations of the analyzed parameters, the samples were also identified as far as their coordinates are concerned (x, y, z). One of the results of the work was the development of CRI and CSR maps of the Pniówek deposit. The maps, however, are of a "virtual" character, as they do not relate to any specific level, seam or layer of the deposit. The creation of maps for "real" layers or seams is hindered by small number of samples, as only 1-2 samples were possible to obtain from a single coal seam.

The study incorporating the statistical analyses of the vertical and horizontal variations of CRI and CSR indices in the deposit were conducted for the entire population of samples, including the separated subpopulations. The vertical variation analysis (with deposit depth) was conducted within 100 m intervals of the deposit depth, while in the case of horizontal variation, the analysis was conducted within 500 m wide blocks of the deposit. These blocks were analyzed both with respect to the W-E and the N-S directions, which are roughly the directions of stretch and dip. One of the results of the horizontal analysis was the plotting of isolines maps of the CRI and CSR values.

It has been demonstrated that the studied coking coal of the Pniówek coal mine is characterized by the following values of coking parameters, Rank and petrographic composition: CRI = 19.9-60.8% (mean of 33.4%), CSR = 24.4-65.3% (mean of 49.5%), R = 0.98-1.14% (mean of 1.08%), Vt^{mmf} vitrinite = 60-81% (mean of 74%), L^{mmf} liptinite = 4-11% (mean of 7%), I^{mmf} inertinite = 13-31% (mean of 19%). The analysis of vertical variation of these parameters has not indicated evident variation tendencies. When considered together with the horizontal variation, in the E–W direction, against the background of the tectonics of the deposit (strike, dip, course of the main faults), however, it indicated a relation between the quality parameters and the direction of bed dips.

The presence of few populations of coals which differ in quality has been confirmed in the Pniówek coal mine deposit. The horizontal analysis of the variability for the W-E direction has indicated that in the east, where the depths of beds are greater, coals characterized by lower coalification occur. The coals are also characterized by lower CRI values, higher CSR values, low vitrinite content and an increased part of inertinite contents. In the western direction (opposite to the dip), more highly coalified coals, with higher CRI values and lower CSR values occur-these coals have a high content of vitrinite and low part of inertinite. Inversion of coalification has thus been demonstrated, as the smaller the depth, the lower the reflectance of the coal should be and the case in the Pniówek coal mine is the opposite. Such inversion may be related, as it has been demonstrated numerous times, to the occurrence of thermal metamorphism which modified the regional structure of coal rank (Komorek et al., 2010; Probierz, 1989; Probierz et al., 2003; Probierz & Lewandowska, 2003).

No evident relationship of CSR and CRI values and the petrographic content of coal has been found, which is evidenced by a low r correlation coefficient. However, the high inertinite content in the samples characterized by the lowest reflectance, relatively low values of CRI and relatively high CSR values, draws attention. This is against the expectations, as usually, the coal with better coking properties is characterized by the lowest content of inertinite macerals (Komorek et al., 2010; Probierz, 1989). The explanation of this relation requires further research on individual inertinite macerals, especially the typically inert macerals (that is, fusinite, micrinite and sclerotinite).

The obtained results of the determination of the CRI and CSR indices, the petrographic composition and the carbonization of the Pniówek coal mine coals were subjected to an attempt to interpret them in relation to results from other coal basins. This was also a result of the lack of determinations of these parameters as for the Polish coking coal. The only exception is a work in which the results of CRI and CSR determinations were presented in the context of bireflectance and the content of inertinite in coking coal blends from both the Polish and the Czech part of the Upper Silesian Coal Basin. Despite that, no CRI or CSR determinations for the Pniówek deposit have been made and the samples were not assigned locations in the deposit space (Pusz & Buszko, 2012). The CRI and CSR determination results, as well as the methods for predicting the coke quality for European, Australian, American (Kentucky) and Japanese coals are presented in the work by (Diez et al., 2002). Prediction results relating to 50 samples coming from Canada, USA, Australia, New Zealand, China, Indonesia and India, characterized by the vitrinite reflectance R between 0.72 and 1.60% that were obtained based on, among others, the knowledge of coal plasticity and the chemical composition of ash, have been presented in the work by (Tiwari et al., 2013). In the work by (Ryan & Price, 1992), presenting the results of the study of Australian and Canadian (British Columbia) coals, special attention has been given to the effect of the chemical composition of ash (its acidity) on the CSR values. Essentially, every of the cited works, including the works by (Menendez et al., 1999) and (Nakamura et al., 1977) gives consideration to the influence of the petrographic composition, the inert organic and non-organic components (ash) of the coal, its rheological properties (plasticity) and the rank of coal (level of coalification) on the value of the CRI and CSR indices. Of course, also the factor of the coking conditions is not omitted.

The position of the coals of the Pniówek coal mine in comparison to the results from other basins have been presented in Figure 9. As the possible similarities (or differences) may be

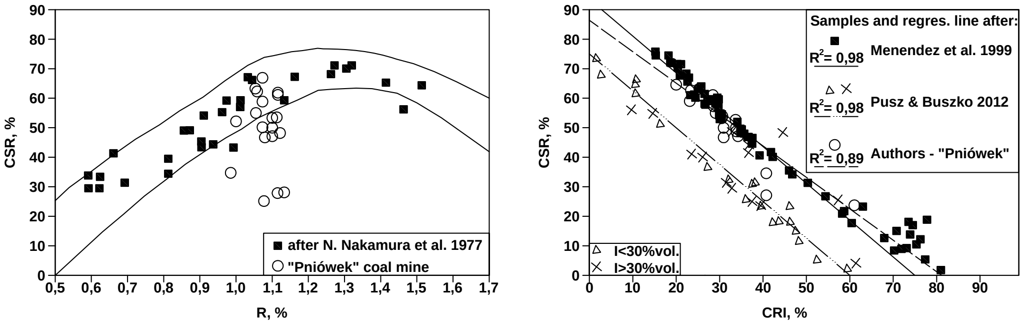

Fig. 9. The position of coals from the Pniówek coal mine in view of the correlation between the CRI, CSR and the vitrinite reflectance and results from other coal basins

presented most clearly by using the correlation between the CRI and CSR and the Rank, this relationship was used in the comparison with coals from international markets.

According to Fig. 9, the exhibited correlations of the CRI and CSR index do not significantly deviate from the relationships noted in other coal basins. The differences concern mostly the values of the R^2 determination coefficient and the shift of the regression line. The course of the regression lines for the coals of the Pniówek coal mine is nearly identical to the course provided in the work by (Menendez et al., 1999). The only difference is the coefficient of determination (R^2 = 0.89 to R^2 = 0.98, respectively). The shift of the regression line applies to coal blends both with high and low inertinite content presented in the work by (Pusz & Buszko, 2012). The correlation of the CSR factor value and the Pniówek deposit vitrinite reflectance is, however, consistent with the results obtained in other coal basins only to a small extent. A large part of the coals of the Pniówek deposit which fall within the narrow range of coalification (R = 0.98-1.14) is characterized by CSR values lower than 55% and none of the examined samples reached the value of CSR ≥ 70%, which corresponds to high-quality coking coal. Most of the samples from the Pniówek coal mine also fit outside the range of the correlation indicated in the work by (Nakamura et al., 1977). The Pniówek coals with a CSR value <55% also have a significant impact on the attenuation of the CRI and CSR correlation, which amounts only to R^2 = 0.89, as compared to the high correlation demonstrated in the work by (Menendez et al., 1999), amounting to R^2 = 0.98. The explanation to this observation requires further research, however, it seems to confirm the difference of the coals from the studied area, which has been demonstrated numerous times and which should be linked to the specific course of the coalification processes, especially the thermal metamorphism (i.a.: Probierz, 1989; Probierz et al., 2003).

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