

# Journal of Geology, Geography and Geoecology

Journal home page: [geology-dnu-dp.ua](http://geology-dnu-dp.ua)

ISSN 2617-2909 (print)  
ISSN 2617-2119 (online)

Journ. Geol. Geograph.  
Geology,  
29(4), 722–730.  
[doi: 10.15421/112065](https://doi.org/10.15421/112065)

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## New data about the distribution of nickel, lead and chromium in the coal seams of the Donetsk-Makiivka geological and industrial district of the Donbas

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Received: 16.03.2020

Received in revised form: 13.06.2020

Accepted: 18.10.2020

**Abstract.** A modern and scientifically based indicators forecast of toxic and potentially toxic element concentrations allows us to develop and plan organizational and technical-technological measures aimed at reducing the negative impact of the coal industry and heating enterprises on the ecological state of the environment. For this purpose it is necessary

to have data about concentration, character and features of the distribution of toxic and potentially toxic elements, including nickel, lead and chromium in coal and the rocks that contain it. Toxic elements are one of the main sources of environmental pollution that negatively affects human health. Research in this direction is conducted to reduce the degree of negative effects and additional pollution of the environment. Increasing requirements for environmental protection in the coal-mining industry sector of Ukraine stipulates the need for new scientifically grounded methods for forecasting the content of toxic and potentially toxic elements in the rock mass which is extracted by mines, the waste of coal extraction and coal enrichment and also the influence of the coal-heating enterprises on the environment. In the article, the results of investigations of toxic elements in coal seams of the Donetsk-Makiivka geological and industrial area of the Donbas are considered. The research covered the whole territory of one of the most studied geological and industrial districts of the Donbas – Donetsk-Makiivka. As a result of the study, correlation coefficients were calculated that allow us to predict the concentration of nickel, lead and chromium in the products and wastes of coal enrichment and correct the technological schemes of coal enrichment taking into account their content. We also calculated the regression equation between these elements and the ash content of the coal, which will allow us to predict their concentration in the main working coal seams of the Donetsk-Makiivka geological and industrial districts relative to the values of coal ash content. The character of the distribution is established and the weighted average concentrations and basic descriptive statistics for nickel, lead, and chromium in the coal seams and suites are calculated. The composition and character of their typomorphic geochemical associations, as well as the features and regularities of their accumulation in the coal seams of the Donetsk-Makiivka geological and industrial districts are revealed.

**Keywords:** toxic elements, potentially toxic elements, geological and industrial area, geochemical association, correlation coefficient, regression equation, statistical relationship

## Нові дані про розподіл нікелю, свинцю та хрому у вугільних пластах Донецько-Макіївського геолого-промислового району Донбасу

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**Анотація.** Сучасний та науково обґрунтований прогноз показників концентрацій токсичних і потенційно токсичних елементів дозволяє розробляти та планувати організаційні і техніко-технологічні заходи, що спрямовані на зменшення негативного впливу вуглевидобувної промисловості та підприємств теплоенергетики на екологічний стан навколишнього середовища. Для цього необхідно мати дані про концентрацію, характер й особливості розподілу токсичних і потенційно токсичних елементів, у тому числі нікелю, свинцю й хрому у вугіллі та породах, які його вміщують. Токсичні елементи є головним джерелом забруднення навколишнього середовища, що негативно впливає на здоров'я людини. Дослідження в цьому напрямі прово-

дяться для зменшення ступеня негативного впливу і додаткового забруднення навколишнього середовища. Зростання вимог до охорони навколишнього середовища у вуглевидобувній галузі України зумовлює потребу в нових науково обґрунтованих методах прогнозу вмісту токсичних і потенційно токсичних елементів в гірничій масі, що видобувається шахтами та у відходах вуглевидобутку і вуглезбагачення, а також впливу підприємств вугільної теплоенергетики на навколишнє середовище. В статті розглянуто результати досліджень токсичних елементів у вугільних пластах Донецько-Майківського геолого-промислового району Донбасу. Дослідження охопили всю територію одного з найбільш вивчених геолого-промислових районів Донбасу – Донецько-Майківського. В результаті дослідження розраховані коефіцієнти кореляції, які дозволять прогнозувати концентрацію нікелю, свинцю та хрому у продуктах та відходах вуглезбагачення й корегувати технологічні схеми збагачення вугілля з урахуванням їх вмісту. А також рівняння регресії між цими елементами і зольністю вугілля, що дозволить прогнозувати їх концентрацію у основних робочих вугільних пластах Донецько-Майківського геолого-промислового району відносно значень зольності вугілля. Встановлено характер розподілу та розраховані середньозважені концентрації та основні описові статистики для нікелю, свинцю та хрому у вугіллі основних пластів і світ. Виявлено склад і характер їх типоморфних геохімічних асоціацій, а також особливості й закономірності їх накопичення у вугільних пластах Донецько-Майківського геолого-промислового району.

*Ключові слова:* токсичні елементи, потенційно токсичні елементи, геолого-промисловий район, геохімічна асоціація, коефіцієнт кореляції, рівняння регресії, статистичний зв'язок

**Introduction.** The Donetsk-Makiivka geological and industrial districts is located within Donetsk region, it occupies the central part of the industrial Donbas and has an area of 3170 km<sup>2</sup>. The area is represented by a wide range of grade composition of coal from early to late catagenesis (Baranov, 2014) (from coal of rank D and G in the west to T and semi-anthracite in the east).

In previous works V.V. Ishkov together with A.I. Chornobuk, D.Ya. Mykhalchonok, V.V. Dvoretzkyi, A.B. Moskalenko (Ishkov, 2000-2001) studied the peculiarities of the distribution of these elements in the products and enrichment wastes of a range of processing plants of Donbas. The forecast and assessment of concentrations of toxic and potentially toxic elements in coal within the Chystiakovo-Snizhnianskyi geological and industrial districts, in particular in the system of coal - rock mass - enrichment products were carried out by I.I. Kurmelov, V.V. Ishkov, M.A. Dobrohorskyi, V.P. Shevchenko, I.L. Safronov (Dobrohorskyi, 1999; Ishkov, 1999). V.V. Ishkov together with Ye.S. Kozii considered the peculiarities of distribution of toxic and potentially toxic elements in the coal seams of Pavlohrad-Petropavlivka (Ishkov, 2017; Kozii, 2017; Kozii, 2018; Nesterovskiy, 2020) and Chervonoarmiisk (Ishkov, 2019) geological and industrial areas. Ecological aspects of the geochemistry of toxic elements in the coal seams of many deposits in the world are considered in the works of D. Swaine (Godbeer, et al., 1984; Swaine, 1990). Numerous studies of their distribution in the coal of different deposits have shown that the composition and content of these elements and their distribution are different for each deposit, and within individual deposits also depends on the stage of carbonization (Martinez-Tarazona et al., 1992; Mercer et al., 1993; Pires and Teixeira, 1992; Solari et al., 1989; Spears and Martinez-Tarazona, 1993; Vassilev, 1994).

**Research methodology.** Samples were taken in the mines strata samples taken by the furrow method) (GOST, 1975) and from duplicates of the core personally by the authors with the participation of employees of geological services of coal mining enterprises and production exploration organizations in the period from 1981 to 2013. The volume of the control sampling was 5% of the total sample volume. All analytical works were performed in the central certified laboratories of industrial geology-prospecting organizations. The content of the elements was determined by quantitative emission spectral analysis (GOST, 1991). 7% of duplicate samples were sent for internal laboratory control. 10% of duplicate samples (correctness and reproducibility) were evaluated as the significance of the average systematic error, which is checked by Student's test, and the significance of the average random error, which is checked by Fisher's test. As the above-mentioned discrepancies in the level of significance 0.95 are not significant, the quality of the analyses is considered satisfactory.

Using Excel 2016 and Statistica 11.0 at the initial stage of processing primary geochemical information, the values of basic descriptive statistical indicators were calculated, frequency histograms of content were constructed and the law of distribution of nickel, lead and chromium was established. When assessing the relationship of these elements with the organic or mineral part of the coal we used the coefficients of affinity with organic matter  $F_o$ , which shows the ratio of the content of elements in coal with low (<1.6) and high density (> 1.7), the coefficients of the concentration  $F_{nk}$  showing the ratio of the content of elements in the fraction  $i(C_i)$  to the content in the original coal, the correlation coefficients of the content of the investigated elements and the ash content of coal and the coefficients of the reduced extraction of the element in the fraction of different densities.

In the construction of graphs and calculation of correlation coefficients, all values of elements concentrations and technological parameters of coal were normalized according to the formula:

$X_{\text{norm.}} = (X_i - X_{\text{min}}) / (X_{\text{max}} - X_{\text{min}})$ , where:  $X_i$  is the result of a single value of the element concentration;  $X_{\text{max}}$  - the result of the maximum value of the element concentration;  $X_{\text{min}}$  is the result of the minimum value of the element concentration. Normalizing was performed for transformation of the data selection to the same scale, regardless of the units and scale of the samples.

**Research results.** During the study, the main tasks of studying the geochemistry of potentially toxic elements in the main working coal seams of the district were the revision of previous studies of nickel, lead and chromium, the formation of representative samples of their content in individual coal seams and the districts as a whole; analysis of the distribution of their content in the whole area; establishing the average content of these elements in the coal seams, the suites and the districts as a whole; identification of connections and calculation of regression equations between the content of these elements, the petrographic composition of coal and its main technological parameters. The source material characterizes the concentration of nickel, lead and chromium in 64 coal seams belonging to the suites  $C_2^2$  (seams  $g_2^B$ ),  $C_2^3$  (seams  $h_1, h_2, h_2^1, h_3, h_4, h_5, h_6, h_6^1, h_8, h_{10}^H, h_{10}^B, h_{10}^1$ ),  $C_2^4$  (seams  $i_1^5, i_2^1$ ),  $C_2^5$  (seams  $k_1, k_2, k_2^2, k_3^H, k_3^{B+H}, k_3^B, k_3^1, k_4^{2H}, k_4^2, k_4^{2B}, k_5, k_5^1, k_6^H, k_6, k_7, k_7^1, k_8^H, k_8$ ),  $C_2^6$  (seams  $l_1^H, l_1, l_1^B, l_1^1, l_2, l_2^1, l_3, l_3^1, l_4, l_6, l_6^1, l_7, l_7^1, l_8, l_8^1$ ),  $C_2^7$  (seams  $m_1, m_1^1, m_2, m_2^1, m_3, m_4, m_4^1, m_5, m_5^1, m_7, m_9$ ) and  $C_3^1$  (seams  $n_1^H, n_1, n_1^B$ ) of the middle and upper parts of the coal period. For the purpose of obtaining the most objective and comparable data, the results of semi-quantitative, quantitative analyses of coal core samples of mine fields, as well as reserve and exploration areas and sites within the district performed after 1983 in the central certified laboratories of geological exploration organizations were used. In some cases, they were supplemented by analyses of stratum-differentiated samples taken personally by the authors or together with employees of geological services of industrial exploration and production organizations. The most representative (Beus, 1981, Havryshyn, 1980) results were obtained in 52 seams:  $g_2^B, h_2, h_2^1, h_3, h_4, h_5, h_6, h_6^1, h_8, h_{10}^H, h_{10}^B, h_{10}^1, i_1^5, i_2^1, k_1, k_2, k_2^2, k_3^H, k_3^{B+H}, k_3^B, k_3^1, k_4^{2H}, k_4^2, k_4^{2B}, k_5, k_5^1, k_6^H, k_6, k_7, k_7^1, k_8^H, k_8, l_1^H, l_1, l_1^B, l_1^1, l_2, l_2^1, l_3, l_3^1, l_4, l_6, l_6^1, l_7, l_7^1, l_8, l_8^1, m_2, m_3, m_5, m_5^1, m_7, m_9, n_1^H, n_1$  and  $n_1^B$ , lying within the fields of the mines «O.F. Zasyadka», «Pokhila», «Hlyboka», «Kalynivska

Skhidna», «Chaikino», «Panfilovska», «№10-bis», «named after. E. Kalinin», «№ 2», «№ 12-18», «named after V.I. Lenin», «named after O.O. Skochynskoho», «Zhovtnevyi Rudnyk», «Butivska», «Butivka-Donetska», «Yasynivska Hlyboka», «Mushketivska», «Zaperevalna», «№6 Chervona Zirka», «Lidiyivka», «named after Chelyuskintsev», «named after Batova», «Proletarskaya-Kruta», «named after Ordzhonikidze», «named after E.T. Abakumov», «named after S.M. Kirov», «named after K.I. Pochenkova», «Trudovskaya», «Soviet», «named after V.M. Bazhanov», «№9 Capitalna», «№11-bis», «№13-bis», «№21», «named after Gorkyi», «Gruzsk-pokhila», «Kuibyshevskaya», «Zhovtneva», «60 years of Soviet Ukraine», «Mospinska», as well as the exploration and reserve areas and fields «Novomospinska Zahidna», «Makiiv-Smolyanyivska», «Butivska Hlyboka №2», «Abakumivska-Hlyboka», «Ordzhonikidzevska-Hlyboka №2-4», «Ordzhonikidzevska-Hlyboka №3-5», «Georgiivska-Hlyboka», «Kirovska-Hlyboka», «Rutchenkivska», «Avdiivskii», «Trudovska-Hlyboka». To obtain representative estimates of the concentrations of nickel, lead and chromium in coal, both individual seams, suites and the district as a whole, individual determinations were combined for individual seams in 52 sampled objects, and further calculation of average content values was performed as weighted averages on the volume of the object. The volume calculations took into account the average thickness of the formation within the object, and the areas of reliably established erosion and protrusion of the seams were not taken into account. The sample average content in coal seams by suites is:

for Ni

$C_2^2 - 23.5$  gramm/ton,  $C_2^3 - 21.0$  gramm/ton,  $C_2^4 - 38.3$  gramm/ton,  $C_2^5 - 20.9$  gramm/ton,  $C_2^6 - 18.6$  gramm/ton,  $C_2^7 - 12.9$  gramm/ton,  $C_3^1 - 17.2$  gramm/ton, as a whole within the district – 18.3 gramm/ton;

for Pb

$C_2^2 - 10.3$  gramm/ton,  $C_2^3 - 10.6$  gramm/ton,  $C_2^4 - 8.3$  gramm/ton,  $C_2^5 - 12.1$  gramm/ton,  $C_2^6 - 8.9$  gramm/ton,  $C_2^7 - 4.5$  gramm/ton,  $C_3^1 - 8.5$  gramm/ton, as a whole within the district – 9.0 gramm/ton;

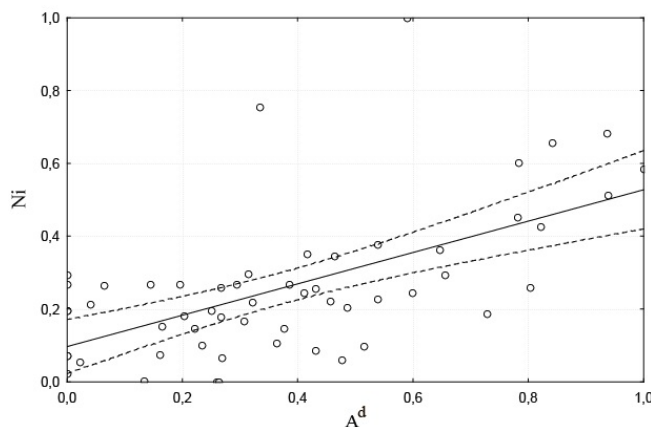
for Cr

$C_2^2 - 36.3$  gramm/ton,  $C_2^3 - 24.8$  gramm/ton,  $C_2^4 - 31.7$  gramm/ton,  $C_2^5 - 35.3$  gramm/ton,  $C_2^6 - 26.4$  gramm/ton,  $C_2^7 - 8.7$  gramm/ton,  $C_3^1 - 22.6$  gramm/ton, as a whole within the district – 23.0 gramm/ton.

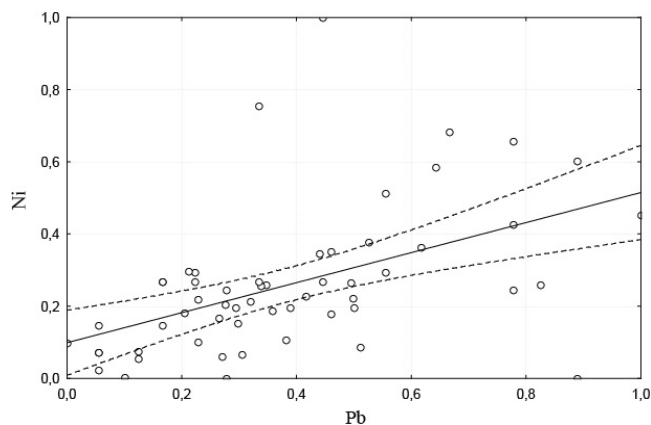
It was found that for lead in five, and for nickel and chromium in two cases, the differences be-

tween the sample average concentrations in the coal of the closest stratigraphically investigated seams are statistically insignificant. Accordingly, these are pairs of seams:  $h_2^1 - h_3$ ;  $h_7 - h_8$ ;  $k_2 - k_2^2$ ;  $m_5^1 - m_7$ ;  $n_1 - n_1^a$ ;  $h_8 - h_{10}^a$ ;  $m_5 - m_5^1$ ;  $h_2 - h_2^1$ ;  $m_5^1 - m_7$ ; the difference between the sample average content of these elements in the coal seams of neighboring suites is significant in all cases, the gradient between the sample average concentrations of these elements in the coal seams reaches the highest value in suites  $C_2^4$  and  $C_2^6$ , and the lowest in suites  $C_2^3$  and  $C_2^7$ . The significance of the differences between the sample average content of the mentioned elements in the coal of the nearest stratigraphic section seams and the suites was established using the program Statistica 11.0 (Borovykov, 2001) by calculating the t-test and Mann-Whitney U-test (as the most powerful nonparametric alternative to t-test) with a significance level of  $p \leq 0.05$ .

The analysis revealed the direct correlation of the nickel content with chromium  $r = 0.74$ , with the ash content of coal  $r = 0.59$ , the average relationship with lead  $r = 0.49$ , and also the weak direct correlation of this element with the total sulfur content  $r = 0.16$ . Linear regression equations (Fig. 1-4):



**Fig. 1.** Regression line between the weighted average normalized value of nickel content and ash content of coal



**Fig. 3.** Regression line between the weighted average normalized values of nickel and lead content

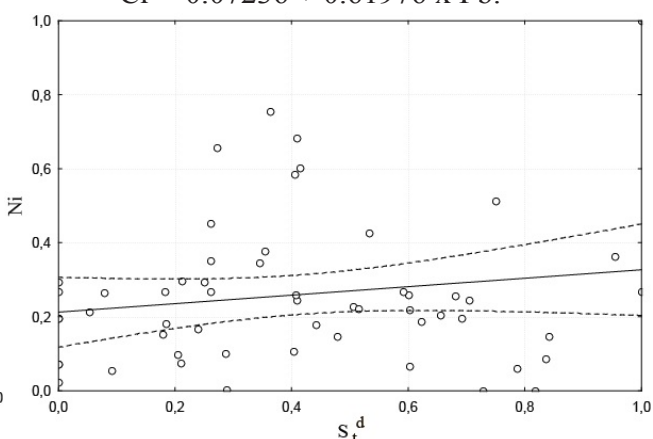
$$\begin{aligned} Ni &= 0.09676 + 0.43074 \times A^d; \\ Ni &= 0.21231 + 0.11468 \times S_t^d; \\ Ni &= 0.09865 + 0.41619 \times Pb; \\ Ni &= 0.04461 + 0.68900 \times Cr. \end{aligned}$$

The analysis revealed the direct correlation of the lead content with chromium  $r = 0.68$ , with the ash content of coal  $r = 0.66$ , the average bond with nickel  $r = 0.49$ , and also a weak direct relationship of this element with the total sulfur content  $r = 0.23$ . Linear regression equations (Fig. 5-8):

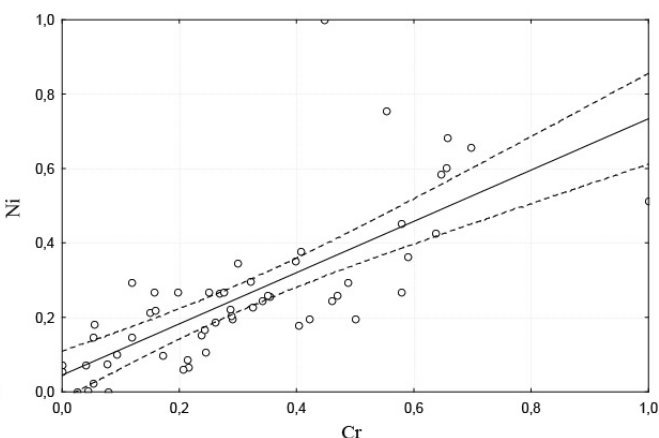
$$\begin{aligned} Pb &= 0.17147 + 0.56865 \times A^d; \\ Pb &= 0.30743 + 0.19181 \times S_t^d; \\ Pb &= 0.23384 + 0.58704 \times Ni; \\ Pb &= 0.15054 + 0.75583 \times Cr. \end{aligned}$$

The analysis revealed the direct correlation of the chromium content with nickel  $r = 0.74$ , with lead  $r = 0.68$ , with the ash content of coal  $r = 0.69$ , and also a weak direct correlation of this element with the sulfur content of total  $r = 0.18$ . Linear regression equations (Fig. 9-12):

$$\begin{aligned} Cr &= 10900 + 0.53691 \times A^d; \\ Cr &= 0.25561 + 0.13663 \times S_t^d; \\ Cr &= 0.10497 + 0.79690 \times Ni; \\ Cr &= 0.07236 + 0.61976 \times Pb. \end{aligned}$$

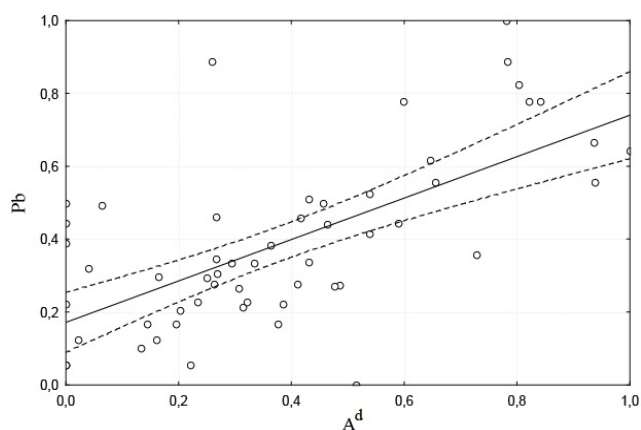


**Fig. 2.** The regression line between the weighted average normalized values of nickel and total sulfur

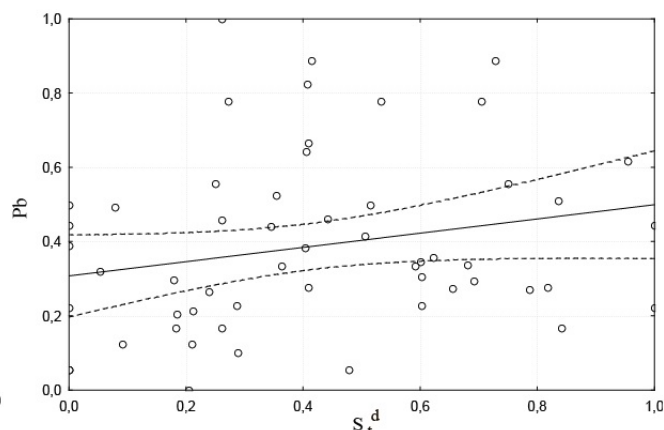


**Fig. 4.** The regression line between the weighted average normalized values of nickel and chromium

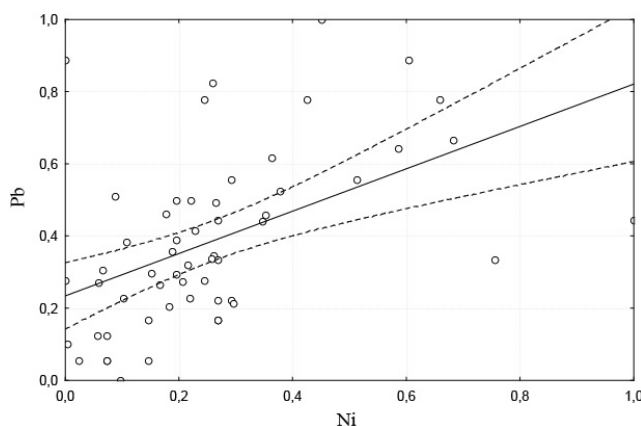




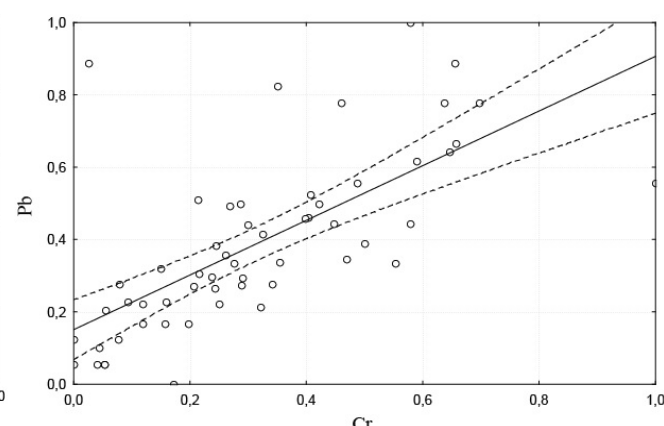
**Fig. 5.** The regression line between the weighted average normalized value of lead content and ash content of coal



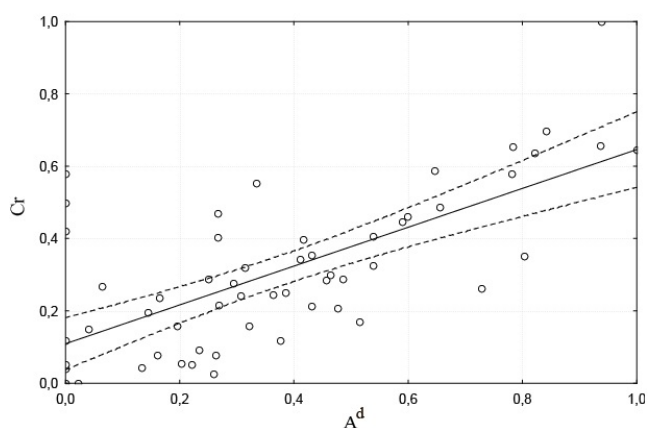
**Fig. 6.** The regression line between the weighted average normalized values of lead and total sulfur



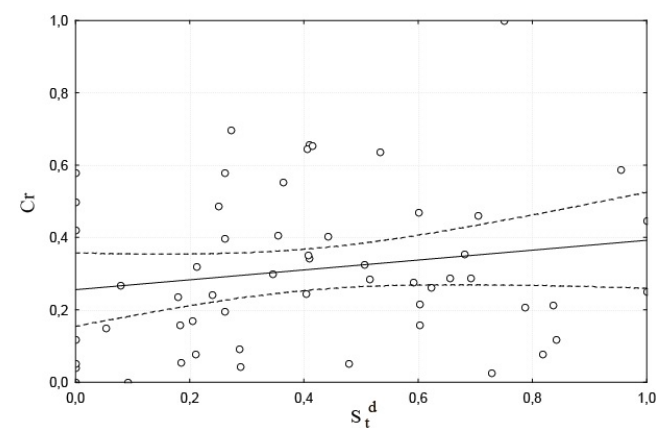
**Fig. 7.** Regression line between weighted average normalized values of lead and nickel content.



**Fig. 8.** The regression line between the weighted average normalized values of lead and chromium



**Fig. 9.** Regression line between the weighted average normalized value of chromium content and ash content of coal

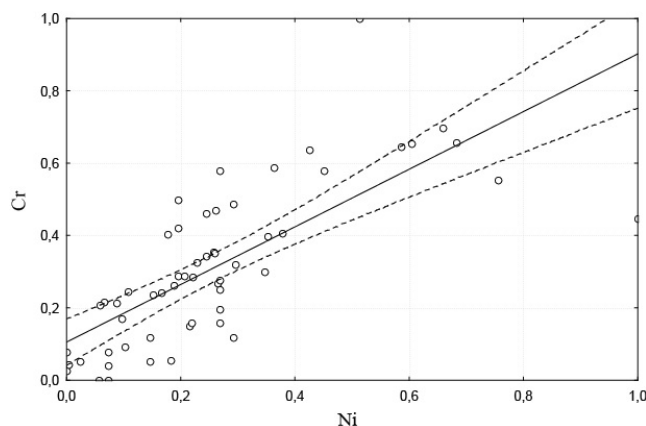


**Fig. 10.** The regression line between the weighted average normalized values of chromium and total sulfur

**Conclusions.** Based on the obtained results, we can assume that the main factors controlling the accumulation of nickel, lead and chromium in the coal of the region, in the process of formation of neighboring seams and subsequent transformation of the coal seam changed significantly, and the integrated influence of these factors on the concentration of these elements in coal seams was greatest for seams of suites  $C_2^4$  and  $C_2^6$ . For the purpose of establishing the main factors controlling the accumulation of nickel,

lead and chromium in the coal seams of the area, correlation and regression analyses of their content with the main technological parameters, as well as the petrographic composition of coal were performed. For the Donetsk-Makiivka geological and industrial district it is established that:

- There is a statistically significant increase in the content of nickel, lead and chromium in local areas of coal seams with immediate siltstone-argillite bedrock and argillite overlying bed (for example, sections of



**Fig. 11.** Regression line between weighted average normalized values of chromium and nickel content.

seams  $l_1$  and  $l_1^1$  of the field of the mine «Proletarska Glyboka», seam  $h_3$  of the field of the mine named after Gorkii, seam  $k_7$  of field of the mine named after Rumyantsev, seam  $h_{10}$  of the fields of the mines «60 years of Soviet Ukraine» and named after «M.I. Kalinin», etc.);

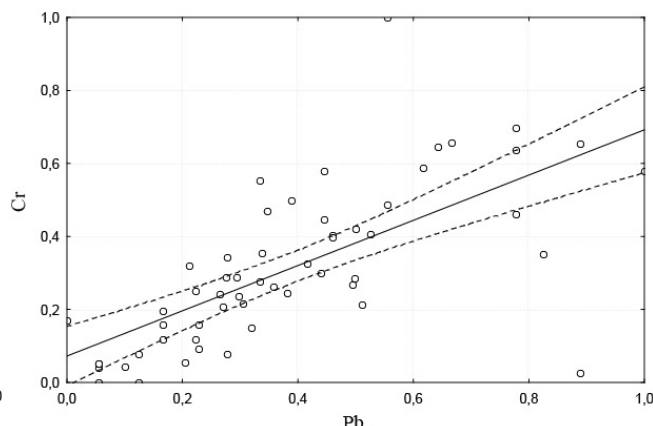
- There is no statistically significant relationship between nickel and chromium concentrations and total sulfur in contrast to lead, while in some coal seams and their areas with abnormally high concentrations such a relationship is established (example of seams  $i_2^1$  and  $k_1$ ).

- In some areas of the studied seams (using the method of V.A. Chervyakov [17] a significant positive correlation was found between the content of nickel and chromium with the content of gelled microcomponents).

- There is quite a sharp increase in the concentration of nickel, lead and chromium in the coal seams in areas where there is a layer of sapropelite in their upper part (for example seam  $m_3$  of the field of the «Yasynivska Hlyboka» mine, etc.).

- All studied coal seams are characterized by a slight increase in lead content with increasing degree of coal carbonization, complication of the structure of the seams and a decrease in their thickness, increase in the number of intralayer mineralized layers, fracturing and the degree of recoverable coal. When splitting the seams, the enrichment of coal with lead occurs in a pack with less thickness. Thus, seam  $n_1$  of the «Butivska» mine field splits into two independent seams  $n_1^B$  and  $n_1^H$ . In the north-eastern part of the mine's field, more lead enriched the upper low-thickness assise, and in the south-eastern part the lead is concentrated in the lower assise, which has less thickness.

- There is a statistically significant decrease in the concentration of lead in the areas of coal seams that are directly adjacent to the intraformational erosions.



**Fig. 12.** The regression line between the weighted average normalized values of chromium and lead

- In general, in the study area, the decrease in the thickness of coal seams is accompanied by an increase in the affinity of lead to the organic component of coal.

- Lead forms a geochemical association with chromium (correlation coefficient 0.39), linear regression equation:  $Pb = 0.03747 + 0.22927Cr$ . At the same time, in some areas of the studied seams (using the method (Chervyakov, 1978)) a significant positive correlation of lead concentration with the content of fusinized microcomponents was established, which indicates the presence of sorption form of lead in coal. In areas of low-reduction coal, a sharp increase in lead significantly correlates with an increase in the content of germanium, which proves the presence of its elemental compounds in coal.

- There is a statistically significant relationship of lead content in the coal seams of the area with ash content (correlation coefficient 0.48), linear regression equation:  $Pb = 0.2189 + 0.803A^d$

- There is a statistically significant relationship of lead content in the coal seams of the area with the total sulfur content (correlation coefficient 0.59), linear regression equation:  $Pb = 0.138 + 0.5963S_{total}$ .

- In the stratigraphic section of the seams, the lead content in the coal usually increases in the upper part of the coal seam.

- The relationship between lead concentrations and the lithological composition of coal-bearing rocks is marked by a statistically significant increase in its content in local areas of coal seams with direct siltstone-argillite bedrock and argillite overlying bed.

- The geochemical association of lead with chromium is typomorphic for the coal seams. Their joint accumulation is due to the bituminous nature of the sorbent. The neutral and alkaline environment of the paleobasins of peat accumulation promotes the absorption of lead by phenolic derivatives of lignin, and the acidic environment is unfavourable for this process.

- There is a geochemical association of chromium with cobalt (correlation coefficient - 0.49), lead (correlation coefficient - 0.52), nickel (correlation coefficient - 0.56). Linear regression equations:

$$\text{Cr} = 0.10 + 0.96 \times \text{Co},$$

$$\text{Cr} = 0.14 + 0.41 \times \text{Pb},$$

$$\text{Cr} = 0.05 + 0.81 \times \text{Ni}.$$

- There is a geochemical association of nickel with chromium (correlation coefficient - 0.56), cobalt (correlation coefficient - 0.44), lead (correlation coefficient - 0.56). Linear regression equations:

$$\text{Ni} = 0.15 + 0.36 \times \text{Cr},$$

$$\text{Ni} = 0.15 + 0.57 \times \text{Co},$$

$$\text{Ni} = 0.16 + 0.30 \times \text{Pb}.$$

- There is a statistically significant relationship of nickel content (correlation coefficient -0.61) and chromium (correlation coefficient - 0.71) with the ash content of coal, linear regression equations:

$$\text{Ni} = 0.097 + 0.43 \times A^d,$$

$$\text{Cr} = 0.109 + 0.537 \times A^d.$$

- The average lead content in coal of only one  $k_5^1$  seam among all the main working seams of the area exceeds the values of maximum permissible concentration in coal.

- The sample size is characterized by an average value of  $9 \pm 1$  g/t of lead. Thus, its average concentration in the coal seams of the area corresponds to the average lead content in the coal deposits of the former USSR - 10 g/t (Kler, 1979). The background concentration is 5.8 g/t. The distribution of the concentration of lead selection in the coal seams of the geological and industrial district by 97% is a combination of two superimposed lognormal distributions. The results of factor analysis and the bimodal character of the sample indicate the polychronic and polygenic character of lead accumulation in the coal seams of the Donetsk-Makiivka geological and industrial district.

Based on the results obtained, the following conclusions can be drawn:

- It was found that the main factors influencing the concentration of nickel, lead and chromium in the stratigraphically closest section of coal seams in the process of coal accumulation and subsequent epigenetic transformations of the coal-bearing strata underwent significant variations.

- It is established that in general in the geological and industrial district there is a slight increase in the concentration of nickel, lead and chromium with increasing degree of coal carbonization, complication of formation and decrease in their thickness, increase in the number of intralayer mineralized layers and coal fractures. The presence of a significant direct statistical dependence of their content with ash

content predicts a decrease of their concentration in the process of coal enrichment. Also, a significant direct linear dependence of the concentration of lead with total sulfur content was established in the district, which indicates the presence of a sulfide form of this element in coal.

**The main scientific significance** of the obtained results is the establishment of the character of distribution and calculation of weighted average concentrations, basic descriptive statistics of nickel, lead and chromium in coal of the main seams and the suites, to identify the composition and character of their typomorphic geochemical associations, as well as to establish the features and regularities of their accumulation in the coal seams of the Donetsk-Makiivka geological and industrial district. The accumulation of these elements in the main coal seams is polygenic and polychronic. Variations in their concentrations in cross-section and area are mainly due to tectonic and facial features of coal-bearing strata, controlling the petrographic composition of coal, hydrodynamic regime of the peat accumulation basin, lithological-facial composition of the immediate and main roof of coal seams and fracturing of coal and rocks that contain them.

**The main practical significance** of the obtained results is the calculation of the regression equations between the elements that form geochemical associations and establishment of the relationship between their concentration and coal ash content. The calculated regression equations for nickel, lead and chromium will allow their concentration to be predicted in the main working coal seams of the Donetsk-Makiivka geological and industrial district regarding the values of ash content of the coal. And the calculated correlation coefficients will allow us to predict their content in products and wastes of coal beneficiation and to adjust technological schemes of coal enrichment taking into account the content of these elements.

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