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Use of quantitative indicators of structural forms for geological and statistical modelling of complex structures

Wykorzystanie ilościowych wskaźników form strukturalnych do geologicznego i statystycznego modelowania struktur o złożonej budowie

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ABSTRACT: Computer processing of geological data is widely used to process geological information. Therefore, an assessment of the structures as potential reservoir traps for oil and gas was carried out on the basis of quantitative parameter analysis. This approach made it possible to reasonably confirm certain regularities. To identify these regularities in the relationships between the numerical parameters of complex structures, computer geological and statistical modeling of the studied objects of the Boryslav-Pokuttya zone was carried out using correlation and cluster analysis. In general, correlation analysis allows analyzing the set of determined values and is aimed at identifying and studying the systems that form some values included in this set. Classification of any objects by meaningful groups is carried out by the method of cluster analysis. To model the processes that formed local structures and to determine the patterns of their spread, a large volume of quantitative indicators was processed. On the basis of quantitative indicators, it was possible to evaluate the results of studies of the tectonic stresses and deformations distribution, which will contribute to more reliable determination of reservoir potential for oil and gas. In turn, this will significantly increase the geological effectiveness of oil and gas exploration in the Boryslav-Pokuttya area. The contemporary form of structures and their spatial arrangement result from the long-termimpact of tectonic forces over geological time. Different manifestations of tectonic activity in successive geological epochs leads to specific changes in the structural plan of geological formations, influencing the potential oil and gas content within them (formation, unforming, and reforming of traps and, accordingly, hydrocarbon reservoirs). The structures of the Boryslav-Pokuttya zone have undergone a complex and lengthy formation process: from the formation of flysch folds to very complex structural forms. This complexity is contributed to the influence of the magnitude and nature of the tectonic forces. The morphological diversity of the structures, can be described by numerical parameters, which can be used as a basis for classifying these structures in the Boryslav-Pokuttya zone.

Key words: parameters, modeling, structures, quantitative indicators.

STRESZCZENIE: Komputerowe przetwarzanie danych geologicznych jest szeroko stosowane do przetwarzania informacji geologicznej. W związku z tym przeprowadzona została ocena struktur, jako potencjalnych pułapek złożowych dla ropy i gazu, na podstawie analizy parametrów ilościowych. Takie podejście pozwoliło racjonalnie potwierdzić pewne prawidłowości. W celu identyfikacji tych prawidłowości w relacjach pomiędzy parametrami numerycznymi złożonych struktur, przeprowadzono komputerowe modelowanie geologiczne i statystyczne badanych obiektów strefy borysławsko-pokuckiej, z wykorzystaniem analizy korelacji zmiennych oraz analizy skupień. Zasadniczo analiza korelacji zmiennych pozwala analizować zbiór określonych wartości i ma na celu identyfikację i badanie zespołów, które tworzą pewne wartości zawarte w tym zbiorze. Natomiast klasyfikacja dowolnych obiektów za pomocą istotnych grup jest przeprowadzana metodą analizy skupień. Celem modelowania procesów, które utworzyły lokalne struktury i określenia wzorców ich występowania, przetworzono dużą liczbę wskaźników ilościowych. Na podstawie wskaźników ilościowych możliwa jest ocena wyników badań rozkładu naprężeń i deformacji tektonicznych, co przyczyni się do bardziej wiarygodnego określenia potencjału złożowego dla ropy i gazu. To z kolei powinno pozwolić na znaczne zwiększenie efektywności geologicznej poszukiwań ropy i gazu w obszarze jednostki borysławsko-pokuckiej. Współczesna forma struktur i ich układ przestrzenny wynikają z długotrwałego oddziaływania sił tektonicznych w czasie geologicznym. Różnego typu przejawy aktywności tektonicznej w poszczególnych epokach geologicznych prowadzą do określonych zmian w planie strukturalnym formacji geologicznych, a tym samym wpływają na potencjalną zawartość w ich obrębie ropy i gazu (formowanie, deformacja i ponowne formowanie pułapek, a tym samym złóż). Struktury w strefie borysławsko-pokuckiej przeszły złożony i długotrwały proces formowania: od formowania fałdów fliszowych do bardzo złożonych form

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strukturalnych, co jest wynikiem oddziaływania sił tektonicznych o zróżnicowanym charakterze i wielkości. Odmiany morfologiczne struktur można opisać za pomocą parametrów liczbowych, które mogą posłużyć jako podstawa do klasyfikacji tych struktur w strefie borysławsko-pokuckiej.

Słowa kluczowe: parametry, modelowanie, struktury, wskaźniki ilościowe.

Introduction

The analysis of existing classifications has shown that various authors adhere to nearly identical principles when approaching the typification of folds based on morphological features (Yakovlev, 1997; Mykhailiv, 1999; Mykhailiv and Omelchenko, 2000). These principles can be summarized as follows: the position of the axial surface; the ratio between the limbs of the folds; the shape of the lock; the variation in the thickness of the layers on the limbs and the crest; the ratio of the long and short axes. The basis for the classification of folds by genetic characteristics is the direction of application of forming tectonic forces (vertical or horizontal movements) and dynamic situations. The use of morphological and genetic classifications allows only a qualitative description of folded forms. The structural description should be based to the greatest possible extent on the measurements of angular, linear, and spatial parameters, to exclude subjectivism in the formulation of theoretical and practical conclusions.

Theoretical analysis

Determination of the quantitative characteristics of individual folds and, consequently, the deformations they underwent, is widely practiced among European and American geologists. In contrast, among Ukrainian scientists, only some of them have delved into the study of the quantitative characteristics of structures (Kurovets et al., 2017), but at the same time they each pursued their own goal, and other geologists have focused on the study of the features of the structural and tectonic structure of the Boryslav-Pokuttya zone, which is an integral part of the Carpathian Foredeep (Zderka, 2014; Zderka et al., 2015).

The primary structural and morphological features of the structure of the first, second, and third tectonic levels of the Boryslav-Pokuttya zone manifest in clear linearity, asymmetry, and disjunctive disturbance.

In general, the features of the structural and tectonic structure of the Boryslav-Pokuttya zone can be summarized as follows:

- morphologically, folds are grouped in lines that collectively, under a common overthrust, form skybas ;
- the fold levels form a flaky structure with a sculpture-like arrangement of crests of anticlinal folds, practically devoid of synclines;
- all folds are separated by tectonic overthrusts, as a result of which their northeastern limbs are steep, in most cases overturned and disrupted by tectonic fractures of highly varying amplitude and configuration;
- clearly pronounced steep and overturned limbs are evident only in those structures that traversed considerable distances during formation. This is due to their greater amplitude and more significant internal dislocations in the forefront segments of the folds;
- overturned limbs are reduced and cut at a varying distances from the anticlinal fold, further complicated by numerous disjunctive dislocations branching off from the main overthrust. In addition to longitudinal disturbances, the overturned limbs are broken by transverse and diagonal disturbances.

Methodology of the research

The formation of folds occurs under the influence of forming movements, which are always reflected in their structure. In other words, the forces that have formed the structure will always be reflected in its morphology and can be described using linear, angular, and spatial quantitative indicators. These indicators should be rationally categorized into the following groups:

1. A group of structural and tectonic indicators encompassing: the amplitude of the structure, its area, the coefficient of intensity, the volume of the structure, and the stress of rocks.

The amplitude of the structure (h) reflects the algebraic sum of differentiated movements that have led to the formation of the structure. Amplitude is defined as the difference between the marks of the highest point and the last isohypse in the block where the crest is preserved. If the crest of the fold is destroyed, then the amplitude is determined in any tectonic block where it attains the maximum value. The area (s) denotes the territory where structure-forming forces act, and is taken as a value equal to the sum of the areas of each tectonic block of the structure. The intensity coefficient (i) reflects the magnitude of the applied fold-forming forces per unit area and is defined as the ratio of the structure amplitude (in meters) to its area:

$$i = h/s$$

where:
h – amplitude of the fold [m],
s – area of the fold [km^2].

The volume of the fold (V) determines the total amount of deformation that was caused by the fold-forming movements and is determined as the product of the area and half of the amplitude.

$$V = 1/2 \cdot h \cdot s$$

The stress of rocks (δ) arises under the influence of tangentially directed tectonic forces in the process of folding. Quantifying tectonic stresses is highly challenging as folds are formed by layers with varying rock properties. However, employing the technique developed by prof. O.O. Orlova, it is possible to approximate rock stress by evaluating the excess pressure magnitude in a fluid-saturated reservoir saturated using the following dependence

$$\sigma = f(\Delta P, m, m \cdot \beta_f, \beta_{SK})$$

where:
ΔP – excessive formation pressure [MPa],
m – porosity coefficient, parts of a unit,
β_f – coefficient of reservoir fluid [1/Pa],
β_{SK} – coefficient of elasticity of the reservoir skeleton [1/Pa].

2. The group of linear-geometric indicators includes linear dimensions of the structure (long axis, short axis), and elongation coefficient.

The dimensions of the structure indicate the area of the structure-forming forces and are determined by direct measurement on structural maps. In this case, the length (a) should be determined taking into account the position of the extreme faults limiting the fold, and the width (b) should be determined in the block where the crest is preserved and the short axis is traced or it is taken by the size of the widest block. The coefficient of elongation (Ke) is defined as the ratio of the long axis to the short axis.

3. The group of indicators of tectonic disturbance of the fold structure includes the density of tectonic disturbances, the coefficients of disjunctive (longitudinal and transverse), and plicative complication.

Tectonic disturbances in the Boryslav-Pokuttya zone are associated with structure-forming processes and occurred directly during the formation of folds. The density of tectonic disturbances (D_d) is defined as the ratio of the total length of all tectonic disturbances complicating the structure (including overthrusts limiting the fold in the longitudinal direction) to the area of the fold. The coefficient of transverse disjunctive complication (Kt) is the ratio of the number of transverse faults complicating the structure to its length. The coefficient of longitudinal disjunctive complication (Kl) is the ratio of the number of longitudinal disturbances complicating the structure to its width. This group of quantitative indicators should also include the coefficient of plicative complication ($Kpl.$), which characterizes the degree of complication of the structure of micro-folding (smaller folds) formed under horizontal tectonic movements of a magnitude leading only to the bending of rocks, and not to the destruction of their integrity. This coefficient is defined as the ratio of the sum of the areas where complications, in the form of small crests, occur to the total area of the structure. Sometimes these small folds look like semi-enclosed structural noses, in such cases, it is possible, in our opinion, to extrapolate the last isohypse.

4. The group of angular indicators includes the angle of inclination of the axial surface and the angle of rocks dip on the limbs.

The inclination angle of the axial surface (α) identifies the structure's morphological type (symmetrical or asymmetrical) and is determined through direct measurement of geological cross-sections. The angle of rock dips on the limbs (β) characterizes the steepness of the limbs of the fold and is taken from the actual data or in the case of their absence is determined through calculations based on a structural map.

The method we propose allowed a qualitative description of 108 folding structures of the Boryslav-Pokuttya (32 anticlines in the first layer, 44 in the second, and 35 and in the third). These structures have been characterized by a comprehensive set of 17 quantitative indicators (Figure 1).

Experimental part

The contemporary structure of the Boryslav-Pokuttya zone is formed by varying magnitudes and types of operating tectonic forces, resulting in a diverse array of morphological structural forms, each described by numerical parameters (Lozynskyi et al., 2008).

The use of correlation and cluster analysis allowed to carry out mathematical and statistical processing of the determined quantitative indicators of the plicative structures within the Boryslav-Pokuttya zone as a system of random variables.

In general, correlation analysis enables the analysis of a set of determined values and is aimed at identifying and studying the systems that form some values included in this set. When studying a system of random variables, it is insufficient to study individual components in isolation, as the system possesses additional properties associated with potential connections between its components. Therefore, in addition to studying the properties of one individual random variable, it is necessary to identify the connections between the components of the system. Solving such a problem becomes possible through the

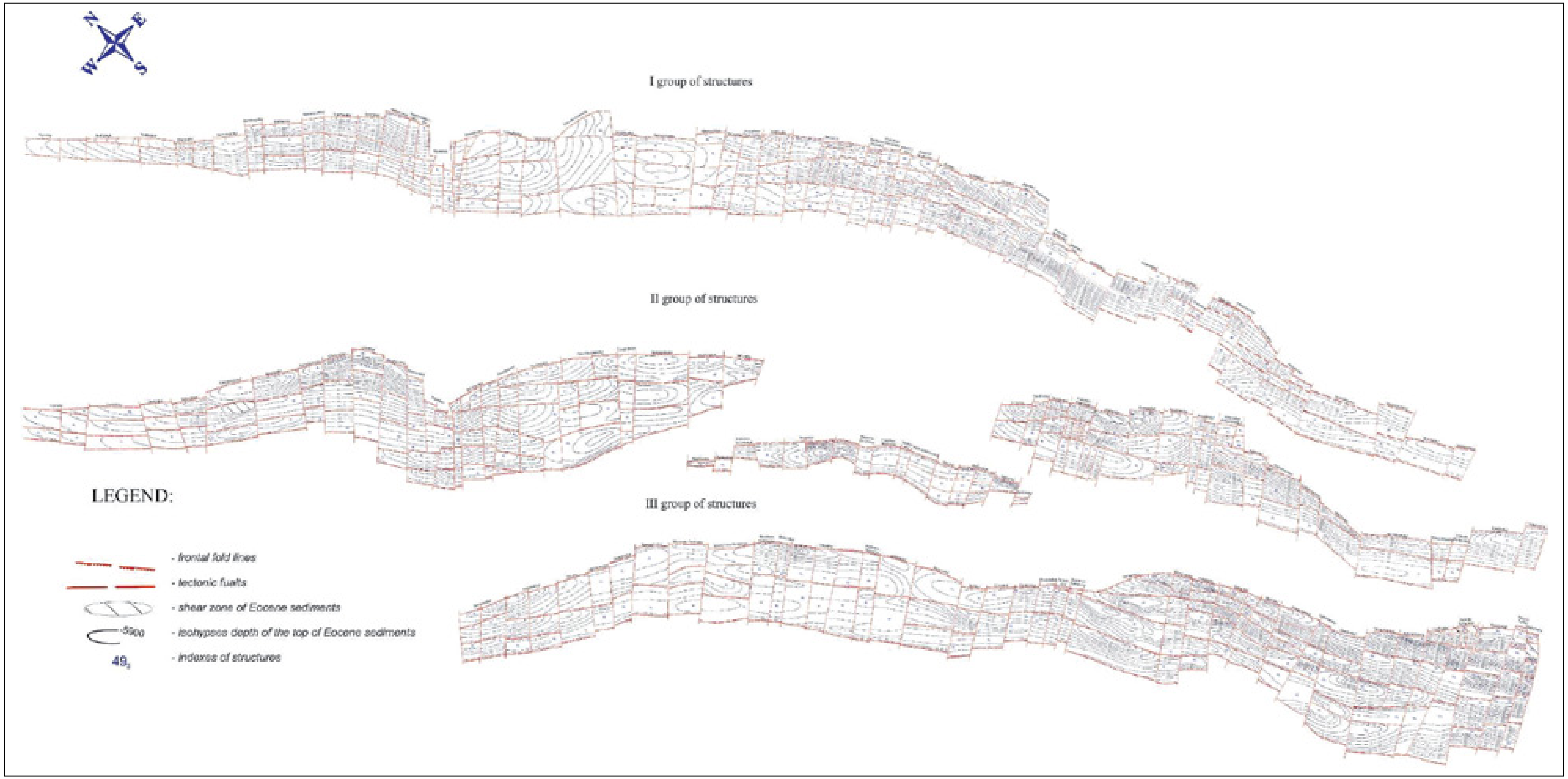

Figure 1. Structural map of the top of Eocene sediments in the Boryslav-Pokuttya zone (compiled by: L.M. Kuzmyk, M.I. Savyuk, I.T. Sturmak, V.V. Andrusyshyn)

Rysunek 1. Mapa strukturalna wyższej części osadów eocenu w strefie borysławsko-pokuckiej (opracowana przez: L.M. Kuzmyk, M.I. Savyuk, I.T. Sturmak, V.V. Andrusyshyn)

Table 1. Correlation matrix of relationships among quantitative indicators in the structures of the Boryslav-Pokuttya zone

Tabela 1. Macierz korelacji zależności pomiędzy wskaźnikami ilościowymi w strukturach strefy borysławsko-pokuckiej

	Amplitude [m]	Area [km²]	Coefficient of structure formation intensity [m/km²]	Fold volume [km³]	Strength [MPa]	Long axis [km]	Short axis [km]	Extension coefficient	Number of transverse faults	Number of longitudinal faults	Number of blocks	Transverse complication rate	Longitudinal complication rate	Total length of faults [km]	Fault density [km/km²]	Angle of inclination of the axial surface [deg.]	The average inclination angle of the limbs [deg.]
Amplitude [m]	1	0.74	–0.08	0.80	–0.03	0.66	0.50	0.11	0.59	0.29	0.62	–0.19	–0.35	0.82	–0.19	0.53	0.19
Area [km²]	0.74	1	–0,57	0.88	–0.52	0.71	0.73	0.06	0.50	0.40	0.62	–0.37	–0.47	0.94	–0.52	–0,02	–0.21
Coefficient of structure formation intensity [m/km²]	–0.08	–0,57	1	–0.24	0.90	–0.42	–0,45	–0.06	–0.16	–0.09	–0.21	0.60	0.50	–0,41	0.83	0.43	0.75
Fold volume [km³]	0.80	0.88	–0.24	1	–0.21	0.58	0.63	0.03	0.47	0.43	0.62	–0.20	–0.31	0.89	–0.26	0.17	–0.04
Strength [MPa]	–0.03	–0.52	0.90	–0.21	1	–0.37	–0,41	–0.05	–0.18	–0.17	–0.21	0.42	0.44	–0.36	0.76	0.51	0.42
Long axis [km]	0.66	0.71	–0.42	0.58	–0.37	1	0.22	0.63	0.68	0.21	0.67	–0.47	–0.17	0,79	–0,28	0.20	–0.04
Short axis [km]	0.50	0.73	–0,45	0.63	–0,41	0.22	1	–0.48	0.14	0.43	0.28	–0.21	–0.67	0.59	–0.53	–0.08	–0.25
Extension coefficient	0.11	0.06	–0.06	0.03	–0,05	0.63	–0,48	1	0.38	–0.08	0.30	–0.30	0.46	0.17	0.11	0.14	0.15
Number of transverse faults	0.59	0.50	–0.16	0.47	–0.18	0.68	0.14	0.38	1	0.31	0.81	0.14	–0.04	0.68	0.03	0.30	0.07
Number of longitudinal faults	0.29	0.40	–0.09	0.43	–0.17	0.21	0.43	–0.08	0.31	1	0.50	–0.04	0.15	0.46	0	0.06	0.12
Number of blocks	0.62	0.62	–0.21	0.62	–0.21	0.67	0.28	0.30	0.81	0.50	1	–0.07	–0.06	0.77	–0.04	0.30	0.07
Transverse complication rate	–0.19	–0.37	0.60	–0.20	0.42	–0.47	–0.21	–0.30	0.14	–0.04	–0.07	1	0.20	–0,28	0.54	0	0.06
Longitudinal complication rate	–0.35	–0.47	0.50	–0.31	0.44	–0.17	–0.67	0.46	–0.04	0.15	–0.06	0.20	1	–0.35	0.68	0.02	0.34
Total length of faults [km]	0.82	0.94	–0,41	0.89	–0.36	0,79	0.59	0.17	0.68	0.46	0.77	–0,28	–0.35	1	–0.29	0.19	–0.06
Fault density [km/km²]	–0.19	–0.52	0.83	–0.26	0.76	–0.28	–0.53	0.11	0.03	0	–0.04	0.54	0.68	–0.29	1	0.29	0.38
Angle of inclination of the axial surface [deg.]	0.53	–0,02	0.43	0.17	0.51	0.20	–0.08	0.14	0.30	0.06	0.30	0	0.02	0.19	0.29	1	0.56
The average inclination angle of the limbs [deg.]	0.19	–0.21	0.75	–0.04	0.42	–0.04	–0.25	0.15	0.07	0.12	0.07	0.06	0.34	–0.06	0.38	0.56	1

construction of a correlation matrix between individual components of the system. Given that the numerical characteristics of the structural form (as well as of any geological objects in general) constitute a system with a complex structure, the connections between the parameters of this system are not clear. Construction a correlation matrix enables a comprehensive understanding of potential correlation links between individual components of the system. Conducting such correlation analysis is advisable to determine the nature and strength of the links between the quantitative parameters of the structures of the Boryslav-Pokuttya zone.

We have developed a correlation matrix for the quantitative indicators of folded structures of the Boryslav-Pokuttya zone, treated a system of random variables, given in Table 1. Analysis of this matrix revealed close correlations among specific parameters.

Of particular significance are the correlations of the angle of dipping of rocks on the southwest limb and the coefficient of the intensity of structure formation ($\beta = f(i)$), as well as the density of tectonic faults and the coefficient of the intensity of structure formation ($Df = f(i)$):

a) Correlation $\beta = f(i)$: The value of the coefficient of intensity of structure allows an assessment of the degree of rock folding and, accordingly, characterizes the steepness of the limbs. In other words, the higher coefficient of intensity of structure formation, the stronger layer deformation and crumpling into a fold with larger angles of rocks dip on its limbs. The existence of a direct correlation between these parameters in the structures of the Boryslav-Pokuttya zone is confirmed by the data in Table 1. Thus, for the majority of structures of this zone, there is a direct correlation between the coefficient of intensity of structure formation and the angle of rock dip on the southwest limb (considering the asymmetry of the structure of the studied structures).

Calculations of the type of such a relationship employing the method of least squares showed that the correlation $\beta = f(i)$is expressed by the following regression equations (Figure 2):

- for folds of the first group $\beta = 15.42 + 0.44i$;
- for folds of the second group $\beta = 18.47 + 0.26i$;
- for folds of the third group $\beta = 18.84 + 0.49i$.

The correlation coefficients are $r = 0.816$, $r = 0.712$, and $r = 0.842$, respectively.

High values of correlation coefficients indicate a relatively strong relationship between the coefficient of the intensity of structure formation and the angle of dip of rocks on the southwest limbs for the folds of the Boryslav-Pokuttya zone. The reliability of such a correlation was assessed according to the criterion of R.A. Fischer:

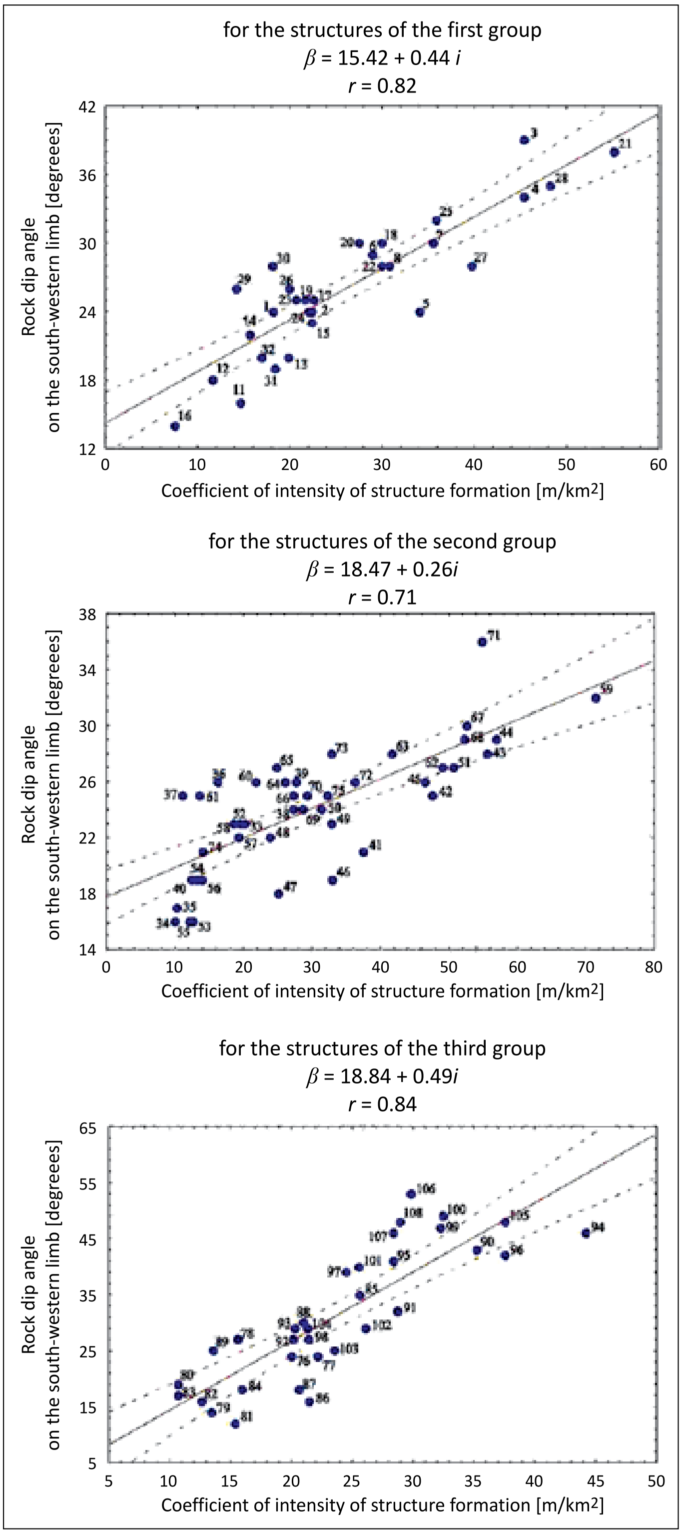

Figure 2. Dependence of the rock dip angle on the southwest limbs on the coefficient of intensity of structure formation

Rysunek 2. Zależność kąta nachylenia skały na południowo-wschodnich skrzydłach od współczynnika intensywności formowania struktury

$$\theta = z\sqrt{n-1} \qquad (1)$$

where:

θ – the estimate of the correlation coefficient,

z – a quantity that is related to the correlation coefficient and is numerically equal to

$$z = \frac{1}{2}\ln\frac{1+r}{1-r} \qquad (2)$$

where:
n – the sample size,
r – the correlation coefficient.

With $\theta \geq 2.5$ for samples with a small volume, the correlation is considered reliable.

The assessment of the reliability of the correlation coefficients obtained for the structures of different groups is:

- for the structures of the first group:

$$\theta = \frac{1}{2}\ln\frac{1+0.816}{1-0.816}\sqrt{30-1} = 6.17 > 2.5$$

- for structures of the second group:

$$\theta = \frac{1}{2}\ln\frac{1+0.712}{1-0.712}\sqrt{42-1} = 5.70 > 2.5$$

- for structures of the third group:

$$\theta = \frac{1}{2}\ln\frac{1+0.842}{1-0.842}\sqrt{33-1} = 6.95 > 2.5$$

b) Corellation $Df = f(i)$. The existence of such a correlation is explained by the fact that the folds of the Boryslav-Pokuttya zone are known for a strong complexity of tectonic faults (significant breakdown into blocks), which arose during the formation of their contemporary appearance. Simultaneously, the magnitude of the coefficient of intensity of structure formation provides insights into the cause of structure formation. Hence, it can be assumed that there is a direct correlation between the density of discontinuous faults and the coefficient of intensity of structure formation.

Calculations for $Df = f(i)$ were conducted through the method of least squares separately for the structures of each of the three tectonic groups. The obtained dependencies are expressed by the following regression equations (Figure 3):

- for folds of the first group $Df = 0.65 + 0.19i$;
- for folds of the second group $Df = 0.53 + 0.25i$;
- for the folds of the third group $Df = 0.59 + 0.22i$.

The coefficients of paired correlation, respectively, are 0.85; 0.82, and 0.83, indicating a fairly strong relationship between the studied parameters. The reliability of such a correlation relationship is confirmed by Fisher's criterion.

- for the structures of the first group:

$$\theta = \frac{1}{2}\ln\frac{1+0.85}{1-0.85}\sqrt{30-1} = 6.77 > 2.5$$

- for structures of the second group:

$$\theta = \frac{1}{2}\ln\frac{1+0.82}{1-0.82}\sqrt{42-1} = 7.40 > 2.5$$

- for structures of the third group:

$$\theta = \frac{1}{2}\ln\frac{1+0.83}{1-0.83}\sqrt{33-1} = 6.72 > 2.5$$

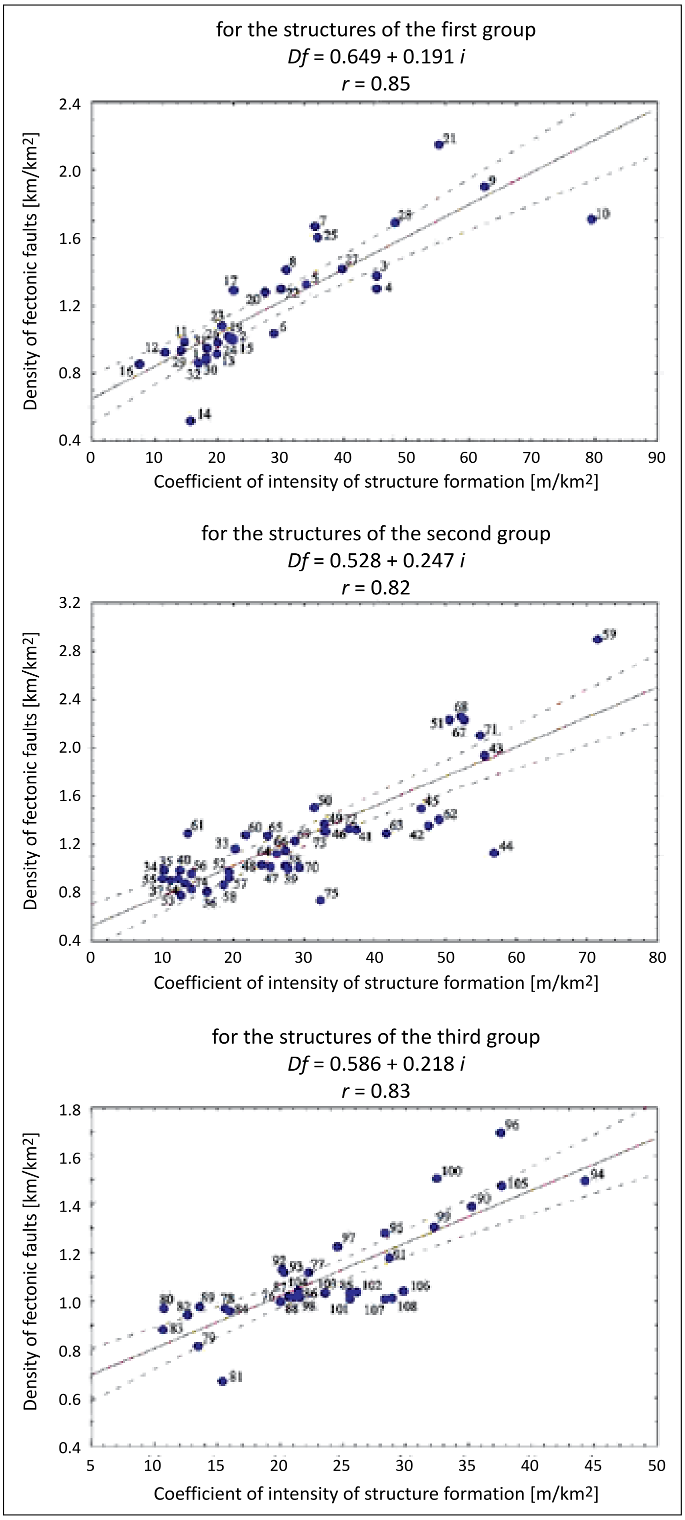

Figure 3. Dependence of the density of tectonic faults on the coefficient of intensity of structure formation

Rysunek 3. Zależność gęstości uskoków od współczynnika intensywności formowania struktury

Thus, the identified correlation relationships show that there are stochastic dependencies between individual quantitative indicators of the structures of the Boryslav-Pokuttya zone, which are expressed by the corresponding regression equations with a high degree of reliability of correlation coefficients.

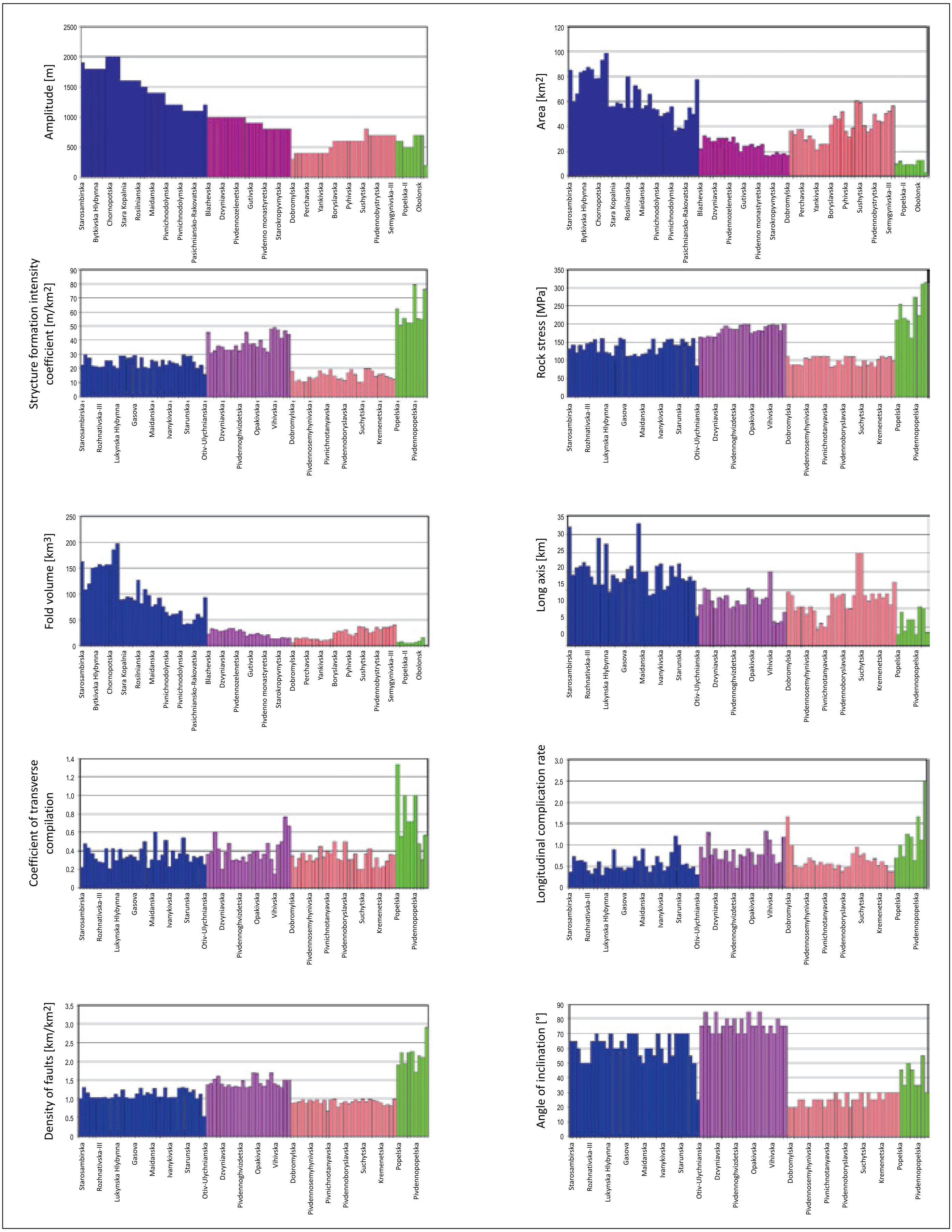

Figure 4. Diagrams of the distribution of quantitative indicators of the structures of the Boryslav-Pokuttya zone
Rysunek 4. Wykresy rozmieszczenia wskaźników ilościowych struktur strefy borysławsko-pokuckiej

Cluster analysis (Figure 4) enabled the differentiation of four clusters (groups) of folded structures of the Boryslav-Pokuttya zone, united by genetic characteristics. These clusters encompass a combination of structures at both meso- and micro-levels within these groups, indicating that, amidst the influence of regional tectonic forces from the southwest to the northeast, certain structures of the Boryslav-Pokuttya zone were formed under the impact of tectonic movements with varying strengths and directions.

This observation is further supported by the orientation of fractures, as described in the works of Orlov and Trubenko (Orlov et al., 1999).

After analyzing the current structural plan of the Boryslav--Pokuttya zone, four groups of folds were identified, the specifics of the morphological structure of which are characterized by their quantitative parameters (Figure 5).

Group I comprises preserved folds, specifically compressed folds. The coefficient of structure formation intensity and the stress coefficient have intermediate values (20–30 m/km^2 and 110–160 MPa, respectively). The current stress state of these folds is determined by tectonic and geometric indicators and is characterized by substantial amplitudes (exceeding 1100 m) and areas (exceeding 50 km^2). Folds in this group exhibit significant volumes (exceeding 40 km^3). This group includes only linearly-elongated anticlines of considerable size, with lengths exceeding 16 km and widths ranging from 3–5 km. These structures also exhibit well-preserved crest, limbs, and periclines, allowing for the traceability of the shape of the fold. It should be noted that the fold can be partially destroyed by transverse and longitudinal tectonic disturbances. This is evidenced by the absence of a clearly expressed pericline and the partial or complete absence of the northeastern limb. This is reflected in the intermediate values of the density of tectonic disturbances (1.0–1.3 km/km^2). In general, the folds are asymmetrical, with axial surfaces inclined at angles between 50–700. Within this group of folds, two morphological varieties exist: structures with preserved limbs (North Dolyn, Low Struktynska, Bytkivska Depth) and structures where the overturned limb is cut (Dolynska, Kosmatska, Starosambirska, Ivanykivska, Maidanska, and others).

Group II is represented by partially destroyed folds, specifically highly compressed folds. The intensity coefficient of structure formation for such folds falls within the range of 30–50 m/km^2, and the rock stress is between 160–200 MPa, which means that the indicators of the stressed state have high values. Structures in this group are characterized by average values of amplitudes (800–1000 m), with areas varying in the narrow range from 15 to 35 km^2, and volumes spanning from 10–40 km^3. They are characterized by the preservation of crests and limbs and the complete absence of periclinal parts. While the crest may be preserved, it can be partially destroyed by local tectonic disturbances. The same applies to the limbs, which remain traceable. Folds of this type are characterized by a greater degree of destruction, which is confirmed by high values of the density of tectonic disturbances (1.3–1.7 km/km^2). Due to strong compression, these folds are marked by almost vertical axial planes (the angle of inclination is more than 750). The dimensions of such folds are smaller compared to those in Group I, measuring 8–16 km in length and 2–4 km in width. Additionally, besides linearly elongated ones, they are also include the brachyanticline. Structures in this group encompass Monastyretska, Bukhtivetska, Dovbushanska, Vilkhivska, Dzvynyatska, Pnivska, and others.

Group III is represented by destroyed folds, which are weakly compressed. For these folds, the coefficient of intensity of structure formation and rock stress are at minimum values (less than 20 m/km^2 and less than 110 MPa, respectively). They were destroyed during the pulling-over process, which was accompanied by the "unloading" of stresses. The folds in this group are characterized by small amplitudes, ranging from 400–800 m, while their areas vary significantly (from 15 to 50 km^2). In general, these folds are characterized by a strong degree of destruction. Only some individual elements can be traced, namely the crest (Semyhynivska, Yankivska), limb (Sushytska, Zavodivska), or pericline (Boryslav, Oriv--Ulychnyanska). These elements may be to some extent complicated by local tectonic disturbances, and the density of tectonic disturbances for these folds is minimal (less than 1 km/km^2). Folds in this group are strongly inclined, up to the reclining ones (with the inclination angle of the axial surface up to 30°) and are characterized by significant dimensions (8–14 km in length and 2–6 km in width). Linearly-elongated and brachyanticlinal folds are found by the ratio of axes.

Group IV is represented by heavily destroyed folds, characterized by strong compression. The intensity of structure formation and rock stress for this group exceeds 50 m/km^2 and 200 MPa respectively, reaching maximum values. Only individual fragments of structural elements (such as limbs, periclines, etc.) are traceable in the structure of folds within this group. Accordingly, they are characterized by minimal values of amplitudes (ranging from 200 to 700 m) and areas (not exceeding 15 km^2). The elements of these folds are strongly compressed, broken, and clamped between tectonic disturbances, which is reflected in the maximum values of the density of tectonic disturbances (exceeding 1.7 km/km^2) and small dimensions (up to 4 km in length and 1–4 km in width). Predominantly, brachyanticlines with inclined axial planes (30–500) are common among the folds in this group. This group includes Popelska, Obolonska, Babchenka, and Molodkivska folds.

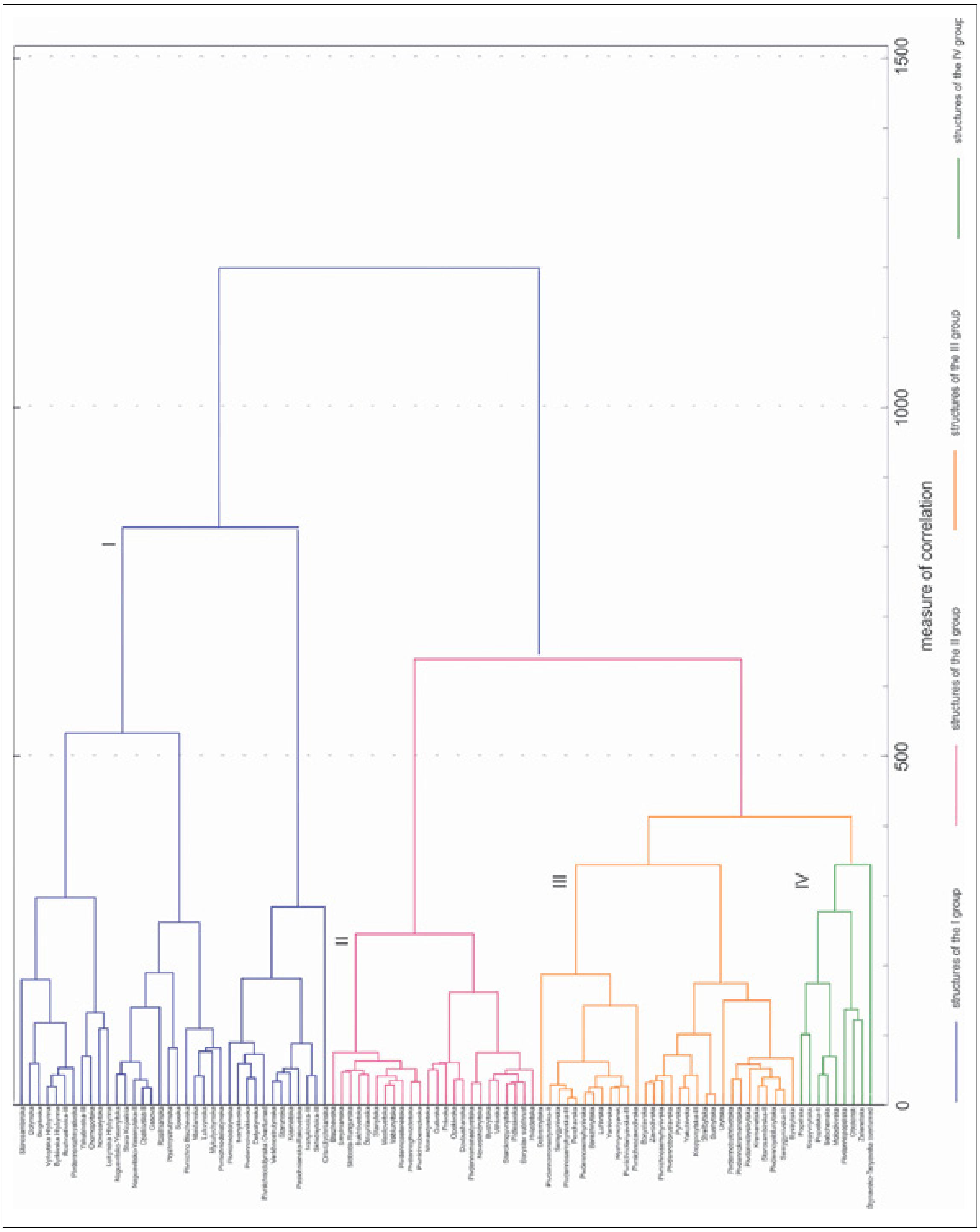

Figure 5. Dendrogram of the grouping of the structures of the Boryslav-Pokuttya zone based on a comprehensive set of quantitative indicators

Rysunek 5. Dendogram grupowania struktur strefy borysławsko-pokuckiej w oparciu o kompleksowy zestaw wskaźników ilościowych

Results and discussion

The material expressed in numerical values, as represented in the developed classification, serves the following purposes:

- to model the morphology of unsearchable structures using specific quantitative indicators and the nature of their relationship;
- to predict the phase state of expected deposits. Type I folds, characterized by the reduced overturned limbs, typically contain oil deposits (Starosambir Vytvytsa, Chechvynske, and others), while in the folds with preserved overturned limbs, the presence of a gas cap is noted (Severodolynske, Strutynske, Lukvynske, Bytkiv-Babchenske, Gas fold);

- type II folds contain oil, gas, and condensate deposits (Bukhtivetske, Dovbushanske, Bystrytsa, Boryslav, Novoskhidnytsa, and others);
- type III are oil-bearing folds (Boryslav, Oryv-Ulichnya, Pivdenno-Bystrytsa, Sushytska, and others);
- type IV folds contain deposits of oil, gas, and condensate (Popelska and Popelska-II), Babchenska, Molodkivska. Generally, structures with preserved crests may contain deposits with a gas (gas condensate) phase.

It should be noted that the morphological features of the structures are the basis of the methodology of prospecting and exploration for oil and gas. In structures of groups I and II, the presence of formation and tectonically screened deposits should be expected, while structures of groups III and IV are observed to contain tectonically screened deposits.

It is known from the basics of geotectonics that folding of the geosynclinal type is formed under the action of horizontally directed compressive tectonic forces. This occurs when the acting forces and the main axes of deformation have the following orientation: the axis of maximum deformation C is located perpendicular to the extension of the folding complex, the axis of small deformation B is oriented parallel to the extension of the folding complex, the axis A has a vertical position and reflects the growth of the amplitude of the fold. This arrangement of the acting forces and the main axes of deformations determines the kinematics of folding and provides an idea of the general situation of the deformation of the entire fold belt, but cannot explain the peculiarities of the folding process inside it. Simultaneously, the dynamic situation of the local fold formation process within the Boryslav-Pokuttya zone was determined by the active interplay of vertical and horizontal tectonic movements (Figure 6). The determining factor in the formation of folds of group I, characterized by the preservation of their structure, is the dominance of horizontal movements. The prolonged impact of such movements results in the breaking of folds into blocks, followed by the rotation of the steeper (northeastern) limb or its displacement. In some cases, the preserved overturned limb curves in the reverse direction, taking the form of a separate anticlinal fold. The determining factor in the formation of folds of group II, in addition to the prolonged impact of horizontal movements, should also be distinguished by lateral friction caused by these movements. These two forces lead to greater compression of the fold (tangential movements) and destruction of its periclinal parts (lateral friction). This process is also accompanied by the "alignment" of the axial surfaces, given that the folds have nearly vertical axial surfaces. In general, the folds of group II were formed with a total greater amount of tectonic forces than the folds of group I. The formation of folds of groups III and IV began with the destruction of rock integrity in the core of the anticlinal fold. In the formation of folds of the above-mentioned groups, in addition to tangential movements that cause the pulling-over of some folds on others, lateral friction plays a significant role. The long-term and significant action of horizontal movements and unilateral

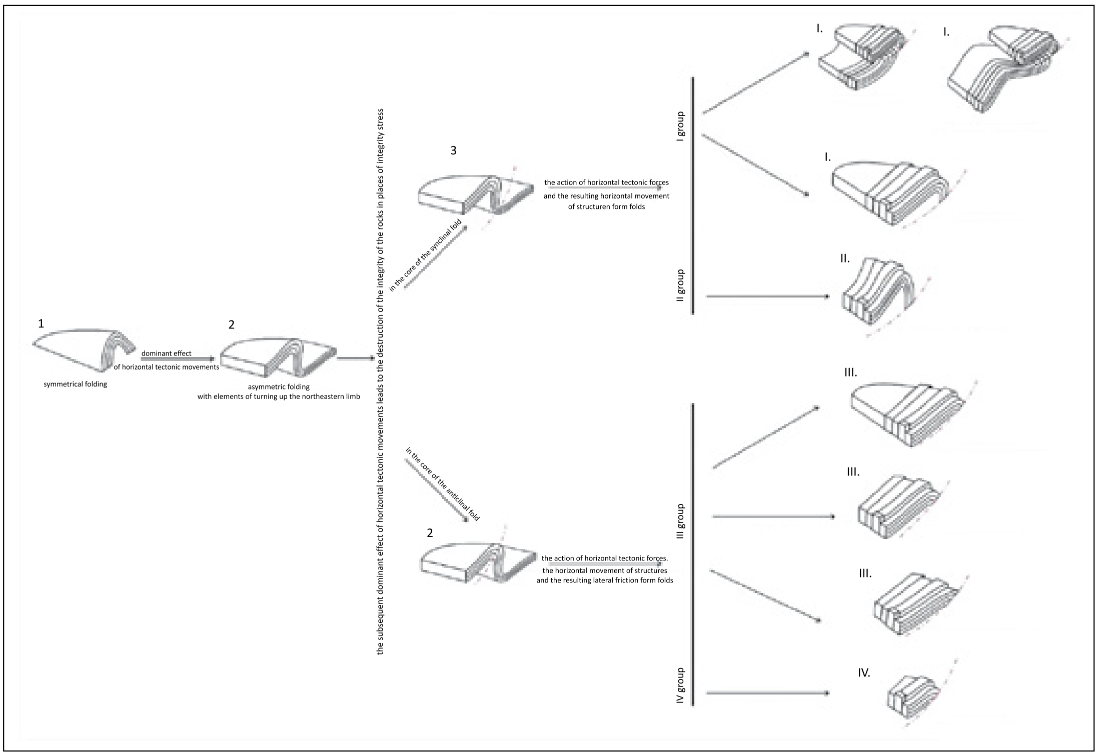

Figure 6. A model of the mechanism of complex formation in the Boryslav-Pokuttya zone

Rysunek 6. Model mechanizmu formowania kompleksu w strefie borysławsko-pokuckiej friction leads to the formation of "folds-periclines". The second type of folds in this group is "folds with crests", formed in contrast to the previous ones under the action of bilateral friction, resulting in the destruction of the periclinal parts. Folds with one preserved limb were formed similarly to the previous ones. It should be noted that in the formation of such types of folds in group III, a significant role was played by the process of pulling over some folds on others. The cross-section of the folds of group III has the form of pulled-over flakes on top of each other. During the formation of such folds, stresses were unloaded in the process of destruction of the initial anticline crest. Finally, the folds in group IV, have acquired their contemporary appearance under the action of three factors (tectonic movements of the horizontal direction, the pulling-over of some folds on others, and strong lateral friction). They are strongly clamped between tectonic faults, which act as stress concentrators transmitted into the core of the fold.

The current stress state of the folds in the Boryslav-Pokuttya zone is explained by the process of folding. The distribution of deformation in the bent layer is marked by stretching on the outer arc and compression on the inner arc. Between them, there is a "neutral surface" on which no tensile-compression deformation is observed. At the same time, at the moment of rupture of the rock continuity, an area of maximum compressions is formed in the fracture zone of overthrust. This leads to the compaction of rocks and an "impermeable zone" is formed along the overthrust plane. Thus, these tectonic disturbances always act as screens for possible oil and gas deposits.

Analyzing the current stress state of the structures of the Boryslav-Pokuttya zone, it can be concluded that local maxima of stresses are confined to highly disturbed areas. The rest of the territory of the Boryslav-Pokuttya zone is characterized by a smooth decrease in stresses from the frontal part of the zone to its periphery. Simultaneously, hydrocarbon deposits are distributed throughout the area of the Boryslav-Pokuttya zone and are confined to areas marked by different stresses. There is some gradation between the size of reserves and the nature of the tension of the structural form to which the oil and gas field is confined. That is, the unstressed structures of Group III contain large and medium (up to small) deposits; the low-stressed structures of Group I contain mainly medium and small deposits; the stressed structures of Group II contain small deposits; the highly stressed structures of Group IV contain very small deposits. At the same time, there is also a tendency to reduce oil and gas production from wells as the stresses in the structures containing oil and gas deposits increase.

Thus, areas characterized by the development of high stresses are characterized not only by small reserves of oil and gas but also by insignificant production of hydrocarbons from productive horizons. This leads to a sharp increase in the cost of oil and causes the economic inexpediency of further work. In other words, the prospects of such areas are weak, and conducting prospecting and exploration work using modern methods and technologies is not rational.

The conducted research also found that deposits and unproductive structures do not differ in morphological features and quantitative indicators. Therefore, it is impossible to distinguish them by these features among the forecast ones.

The sequential statistical analysis and the determined informativity coefficients confirm that the nature of the oil and gas content of the structure depends on the extent to which the structure is complicated by tectonic disturbances. This paper proposes a graphical method for determining the conditions of screening by tectonic disturbances.

Determination of the conditions for tectonic screening of traps should be carried out when planning prospecting drilling on the structure. The execution of such activities will enable establishing the presence of a trap and determining its height, assessing the prospective resources of the relevant predictive productive horizons, determining the most optimal location of prospecting and exploration wells, and adjusting the drilling depths of prospecting and exploration wells.

Conclusions

As a result of the qualitative description of the plicative structures of the Boryslav-Pokuttya zone, it is observed that all structures exhibit linearity, asymmetry, and disjunctive disturbance. The quantitative description of these structures using structural-tectonic, linear-geometric, and angular indicators allowed us to establish that each of the isolated morphological varieties of structures is characterized solely by specific quantitative indicators. At the same time, there is a clear differentiation of structures among themselves based on features such as the intensity coefficient of structure formation (m/km^2), the density of tectonic disturbances (km/km^2), rock stress (MPa), the angle of inclination of the axial surface (degrees). Indicators such as amplitude, area, volume, and linear dimensions of the structure can be the same for certain (adjacent) groups of structures.

To represent the qualitative and quantitative indicators of the tectonic structures of the Boryslav-Pokuttya zone, a classification was developed. The classification was based on the extent to which the structures are disturbed by tectonic movements in the process of folding and the nature of changes in quantitative indicators. Such research in preparation for prospecting and exploratory drilling allows us to model the morphology of a new object. For this purpose, quantitative indicators are used, which can be determined from the structural map and the nature of the ratio between them. At the same time, it was established that the use of the method of analogies for the Boryslav-Pokuttya zone, at least in the construction of structural maps, is not appropriate. This is because adjacent folds do not always have the same morphology.

The selected morphological varieties of structural forms in the Boryslav-Pokuttya zone are formed in the process of folding. They are determined by the place of destruction of the rock continuity (in the core of the anticlinal or the core of the synclinal fold). The formation of groups I and II of the developed classification occurred during the destruction of rocks in the core of the synclinal fold. The determining factor in the formation of folds of group I was horizontal movements. Horizontal movements and lateral friction were involved in the formation of folds of group II. The formation of folds of groups III and IV occurred during the destruction of the rock integrity in the core of the anticlinal fold. The determining factor in their formation, in addition to tangential movements that cause the pulling-over of some folds on others, is also played by lateral friction (one-sided or two-sided).

It is established that isolated traps in lowered tectonic blocks can exist under the following conditions:

- when the vertical amplitude of the displacement of the blocks in the plane of tectonic disturbance exceeds the thickness of the productive part;
- when the horizontal amplitude of the displacement in the plane of tectonic disturbance is equal to or greater than half the width of the fold in the raised block;
- when the rocks in both blocks have the same dipping angles (the same inclination of the limbs) and due to the disturbance of the reservoir rocks come into contact with impermeable rocks.

Different combinations of the above-mentioned conditions are also possible, leading to either the existence of a tectonically isolated trap in the lowered block or its absence (this should be considered on a case-by-case basis). Given the complex block structure of the Boryslav-Pokuttya zone, when justifying the prospects of oil and gas content, we recommend determining the conditions for tectonic screening of traps and using surface methods of geological research. At the same time, the areas of maximum stress concentration in the oil and gas-bearing relation are weakly promising. Conducting prospecting and exploration works on them using modern methods and technologies is not appropriate.

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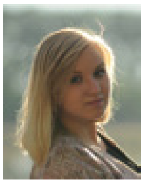

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