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METHODOLOGY FOR DETERMINING RELATIVE LINEAR DEFORMATIONS IN A ROCK MASSIF OF THE SEDIMENTARY STRATA

Purpose. To develop a method for predicting fractured zones in a massif of sedimentary rocks formed due to the folding, by determining relative linear deformations that exceed those critical ones for discontinuity of rock massif.

Methodology. The task of identifying fractured zones is to determine areas in the rock massif where tensile deformations, under the action of tectonic processes, have exceeded the critical limit. The determination requires the map construction of the researched area with the help of trend analysis and a series of mathematical calculations, namely, finding the distance between the selected points of the direction and along the arc connecting them within the interpolating surface. The length of the last curve is found by integration. The coefficient of relative linear deformation is the result of dividing the found distances (the length of the arc by the length of the line).

Findings. A new methodology for predicting fractured zones in a massif of sedimentary rocks formed due to the folding is proposed. The methodology was developed based on an algorithm that involves calculating the relative linear deformations of the bed by constructing maps of local structures of the researched area and a series of mathematical calculations. Using the example of the "Chaikino" minefield, the authors present the concrete result of determining the relative linear deformations of the rock massif. An anticlinal local structure (the *2nd*-order structure) was identified within the minefield, the parameters of the structure were determined, and calculations were performed according to the appropriate algorithm. The obtained data indicate that the real values of relative linear deformations (1.011 and 1.034) significantly exceed the critical limit for sandstones (1.003–1.004). This indicates the discontinuity of rock massif and the presence of the fractured zone.

Originality. For the first time, the methodology has been developed that allows determining the relative linear deformations of rocks between any individual points within the researched area, based on the coordinates of the points' location in the plan and the hypsometric marking of the bed.

Practical value. The proposed methodology can be used to solve several geological problems directly related to the research and detection of fracturing, which was formed under the action of tectonic forces in the process of folding.

Keywords: *rocks, folding, structures, fractured zones*

Introduction. Fractured zones can act as both fluid conductors and accumulation sites for ore and non-ore minerals, making them important objects for the exploration and development of mineral deposits. Fractured zones are areas where rocks are penetrated by a system of cracks of various origins.

Accumulations of many minerals can be associated with fractured zones, if their formation is due to the circulation of fluids through existing cracks. Such zones are often places of concentration of various minerals due to the peculiarities of their formation and hydrothermal processes. Ore minerals, non-ore minerals, hydrocarbons, and rare earths are some of the types of minerals that can be associated with fractured zones.

Ore minerals are primarily gold and silver. Gold-bearing veins often occur in fractured zones, especially in areas connected to active tectonics and hydrothermal processes [1, 2]. Silver ores can be concentrated in fractured zones, especially in volcanic and hydrothermal systems [3, 4]. Native antimony and/or arsenic – native gold associations can be precipitated from hydrothermal fluids with low sulfur volatility [1, 5]. It can also be copper, lead, zinc – fields of these metals can form in hydrothermal systems associated with fractured zones [3, 6].

Non-metallic mineral resources. Fractured zones often serve as places for the deposition of quartz [7], which may be in the form of veins or large crystals. Fluorite is also often formed in fractured zones [8], especially in hydrothermal conditions.

Rare earth elements and rare metals such as tantalum, niobium, and lithium may be concentrated in fractured zones, especially in granite and other magmatic rocks [9, 10].

Fractured zones are usually a factor of increased water inflows, both in undisturbed rock massifs [11, 12] and in mining zones [13, 14].

In many cases, fractured zones can serve as channels for the migration and accumulation of hydrocarbons – oil and natural gas [15]. Hydrocarbon fields in such sediments have been identified in many regions of the world. For example, the "PY-1" gas field was discovered in the Indian sector of the Bay of Bengal, the reserves of which are almost 3.5 billion m^3 of natural gas and 185 thousand m^3 of condensate [16]. Purely fractured reservoirs are considered secondary ones for oil and gas exploration compared to the more common sedimentary reservoirs of sandstones and carbonates. Significant fractured reservoirs are located in Vietnam, Indonesia, Japan, Venezuela, Argentina, Russia, California, and China [15].

Works [17, 18] emphasize that fractured reservoirs, only in volcanic deposits, are widespread in more than 40 basins in 13 countries and have become important objects with large reserves for oil and gas development. In general, gas and oil deposits have been discovered, as well as oil in fractured intervals of magmatic rocks, occurring in more than 300 basins or blocks in greater numbers in more than 50 countries around the world [18, 19]. There are more than 200 oil fields in the world only in the fractured foundation [20]. This is especially true for regions where fracturing is associated with faults and other tectonic structures.

Tectonic processes in the earth's crust are the leading factor in the formation of the properties of rocks and the rock massif as a whole. One of the main consequences of tectonic processes is the occurrence of fracturing and the formation of fractured zones in rock massifs. Decompaction and fracturing

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of rocks due to the action of tectonic processes increase the permeability of dense rocks, promote the redistribution of water and gas, increasing the mobility of phases in the "water-gas" system of the rock massif, and the concentration of fluids – free methane and (or) water in the form of clusters.

It has been proven that even minimal tensile deformations, which exceeded the maximum permissible limit for discontinuity and lead to brittle fracture deformations, form filtration properties in low-porosity rocks with an absolute gas permeability of tens of millidarci, which corresponds to class IV of industrial collectors [21].

Therefore, the development of methods for predicting fractured zones in rock massifs is an urgent task toward solving many geological problems related to natural and technogenic processes of fracture formation – the search for oil deposits, traditional natural gas, and "sweet spots" in shale gas fields, the allocation of zones of increased water inflows, low-amplitude disturbance mapping, etc.

There are direct and indirect field-based research methods of fracturing, as well as analytical ones. Analytical methods are implemented based on the analysis of available geological and mining-geological data. Combined methods are also known, they are a compound of two or more others. The direct ones include the immediate ones. The immediate research of rock fracture in mining operations, in wells (and/or well cores/drill-hole cores), and outcrops are direct methods. Indirect methods are performed on several accompanying features and indirectly provide a qualitative and quantitative assessment of the rock massif's fracturing.

Most of the existing methods for studying fracturing are instrumental field and, mainly, geophysical. Geophysical exploration methods of wells (GEW) are more common for studying fracturing. The leading ones include caliper logging, thermometry, inclinometry, the spontaneous polarization method, and gamma-ray logging. Acoustic, neutron, and density logging methods are mostly used to determine porosity. On the one hand, they make it possible to assess fracturing, and on the other hand, under certain favorable conditions, to record the presence of secondary porosity. Usually, this task is performed by acoustic logging.

We should also mention the modern methods for the location of fractures offered by one of the world's leading companies, "Schlumberger". This is "Sonic Scanner" – 3D acoustic probing, FMI (azimuth electrical microimager), Quanta Geo (azimuth electromagnetic microimager), UBI (ultrasonic high-resolution microimager), OBMI (azimuth electromagnetic microimager) [22].

Applying many methods involves using expensive equipment, original company methods, and qualified personnel. Nevertheless, even all these techniques, taken separately, do not provide an opportunity to unambiguously locate fractures and assess the fracturing of reservoirs as a whole.

As mentioned above, combined methods consist of the complex application of various separate methods. It may be a combination of logging and analysis of field rock outcrops and well cores/drill-hole cores [23] or instrumental and analytical methods [24, 25].

Analytical methods include the processing, analyzing, and generalizing of existing geological and mining-geological data, which involves further implementation of relevant calculations [26, 27] or special modeling [28, 29].

An analytical technique for predictive assessment of the gas-bearing capacity of local anticlinal structures has been developed at the IGTM of the National Academy of Sciences of Ukraine [21]. This technique is intended for searching for zones of free methane accumulation in coal-bearing sediments. It is implemented based on geological exploration data and consists of calculating the quantitative indicators of filtration-capacitive properties that sandstones within the structure acquire during folding. Calculations are performed based on the thickness of the bed and the parameters of local structures – the amplitude, length, and width of the fold. The obtained data are assessed by comparing the correspondence of the obtained data to the conditions of the existence of gas traps and accumulations in the coal-rock massif.

The proposed [21] model assumes that the reservoir is formed by fracturing in the arched part of the anticlinal structure during its formation. This occurs under tension and deformation, which exceeds the maximum permissible limit for the given rock. As a result of tectonic processes, the bends of the rock strata are accompanied by interlayer sliding and fracturing. During the formation of an anticlinal fold, the bending of rock layers with their subsequent tension is observed. This process intensifies from the sole to the roof, which causes increased fracturing in the same direction. The lower part of the sandstone, at the same time, usually remains unaffected by fractures. Conversely, in the upper part of the bed, where the tensile deformations exceed the maximum permissible values for discontinuity, fractures develop, which significantly increase the permeability.

That is, the process of fold formation helps to increase the filtration characteristics of sandstone layers disturbed by fractures. Methane in these layers acquires mobility due to increased fracture permeability and can accumulate in the form of deposits. The screen of the deposit is a layer of this same sandstone, which is laid out up the rise and is unbroken by fractures, due to less bending, which makes it gas-impermeable, and the methane in the pores is practically immobile.

The method [21] allows us to determine the effective thickness of sandstone in the arched parts of local anticlinal folds, depending on the curvature of the fold. The radius of curvature of an anticlinal fold is determined by the values of its width and height. The model of formation of the effective thickness of sandstones in the arched part of the anticlinal structure is shown in Fig. 1.

The effective thickness is calculated as the difference between the total capacity of the sandstone and its critical capacity under the conditions of a concrete structure. The effective thickness is the thickness of the sandstone, or the thickness of the layer in the sandstone, which is characterized by improved reservoir properties and can potentially be favorable for the accumulation of free methane. The critical capacity is equal to the difference between the two radii of curvature of the fold, which determine the lengths of the arcs, which differ from each other by a critical value proportional to the maximum allowable tensile deformation for this rock.

The method allows for finding the effective thickness of the rock bed, as the difference between the total thickness of the bed and the calculated critical thickness. And also to determine the coefficient of relative linear deformation. Sandstone layers are considered to be gas-bearing if the sandstone thickness is greater than the critical one, and the relative linear de-

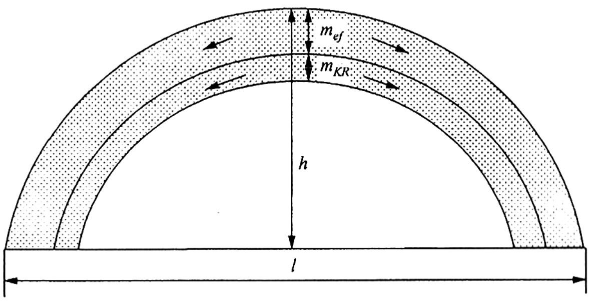

Fig. 1. The model for the formation of the effective thickness of sandstone in an anticlinal structure [21]:

m_{ef} – the effective thickness of the sandstone layer (fractured layers); m – the thickness of the sandstone layer; m_{KR} – the critical thickness of the sandstone layer, not affected by fractures; h – amplitude (height) of the fold; l – the width of the fold

formation coefficient exceeds the value of 0.003–0.004 [21]. This mechanism became the theoretical basis for the creation of a normative document – an industry standard of the Ministry of Coal Industry of Ukraine [10.1.05411357.004:2005. Accumulation of free methane in an undisturbed carbon deposit. Methodology for predicting zones and determining their parameters: Regulatory Document Coal Industry of Ukraine. Standard], for predicting accumulations of free gas – methane, formed by local anticlinal structures in a coal rock massif undisturbed by mining operations.

The experience of the practical application of this method fully proved its effectiveness and confirmed the existence of a mechanism by which the formation of fracturing occurs due to the difference in the degree of deformation of individual rock layers (upper and lower) [21, 30], and the greater the bed thickness crumpled into a fold, more significant this deformation is. That is when the formation of an effective thickness (a reservoir with improved properties) occurs in the upper layers of the bed (in the roof), in which the tensile deformations have exceeded the critical ones for breaking continuity.

However, it is worth noting that this model has certain disadvantages. First, it assumes that the surface and layers of sandstone, geometrically, in space, are part of the arc of a regular circle. The second disadvantage for mathematical calculations is also the ratio of the height and amplitude of the fold – the height of the fold must be much smaller than the length of the fold axis. Depending on this ratio, the obtained calculated values can be distorted with a significant increase in the height of the structure. Thirdly, the method is suitable for determining relative linear deformations only for closed structures – classical and the *2nd* order, so-called "local folds". Structures of this kind (of the *2nd* order) include folds that complicate the monoclinal occurrence of rocks and are distinguished by the deviation of the hypsometry of the layers from the approximating surface. In the case of positive structures, they are classified as structural noses, structural ledges, structural terraces, and flexures. Meanwhile, solving several geological problems requires determining the relative deformations of rocks and predicting the fracturing of the rock mass not only for existing closed structures but also in areas where they are absent.

The formation of fracturing occurs under conditions when the stress in the rock massifs exceeds the ultimate strength of rocks and causes a discontinuity. The condition for discontinuity of the rock massif and the formation of fracturing is the presence of deformations of the massif that exceed the critical limit. It is known that the maximum allowable tensile deformations in a coal-bearing strata are 0.003–0.004 for sandstones, 0.004–0.006 for siltstones, 0.006–0.008 for mudstones, and 0.002–0.003 for coal beds [21]. According to the values of linear deformations, which are greater than the critical values, the deformations of the rock layers are considered to be those that cause a discontinuity of the rock massif and form a fractured zone. Thus, the task of predicting fractured zones is to determine the relative linear deformations that exceed the critical limit for the corresponding rock layers and cause decompaction and development of fractures.

The purpose of the work is to develop a method for predicting fractured zones in a rock massif formed due to the formation of folding by determining the critical relative deformations for discontinuity of rocks.

The object of research is the processes of formation of fractured zones, in particular in the coal-rock massif within the "Chaikino" minefield of the Donets-Makiivskyi geological and industrial district.

Methodology. In conditions of low-dipping rocks, low-amplitude uplifts, and deepenings are lost against the background of monoclinal rock immersion and are not indicated on hypsometric plans and structural maps, since the angle of regional inclination of rocks mostly exceeds the angle of dip of wings of low-amplitude structures. To detect small local structures that complicate the regional inclination of the rocks, as well as for visual and accurate determination of the bends and flexures of bends, it is necessary to get rid of the influence of the regional inclination and the predominant strike of rocks. This task can be solved by decomposing the structural map into a regional slope map and a map of local structures.

A local structure is a part in a layer of sedimentary rocks, mostly isometric in plan, that has absolute marks higher (positive) or lower (negative) than the average value (or approximating surface). In a broad sense, the approximation is zooming, the simplification of real complex dependencies, and the replacement of unknown functions with known ones. When solving geological problems, it is usually about finding a monoclinal surface, which determines the regional bedding of rock strata.

It is known that most of the parameters of the rock strata bedding vary significantly by area, but it is often difficult to establish the nature of this variability due to the presence of numerous local random fluctuations. This task can be solved by applying the trend analysis method.

The use of trend analysis makes it possible to obtain two geological maps: 1) regional constituents, which reflect trends in the behavior of the feature throughout the mapped territory, and 2) local constituents, which characterize random fluctuations that insignificantly affect systematic variability.

Anticlinal and synclinal folds, small in wingspan, in turn, caused the development of fracturing in coal beds and rocks. The parts of the crests of folds are the most affected by fracturing. On ordinary hypsometric maps, or plans of mining operations, anticlinal and synclinal folds of beds are visible, but the shapes of local structures are not fixed. They can be visually formalized if you build a map of the bed's projection on the approximating surface.

A conventional coordinate grid with coordinates X and Y is plotted to the mine plan. For each well, the values of the coordinates X, Y, and the actual, absolute depth (mark) of the bottom of the marking horizon, (usually a coal bed) Z, are tabulated.

To calculate the approximating surface, a first-order polynomial trend model was used, which has the form

$$z(x, y) = A + Bx + Cy.$$

And the second-order

$$z(x, y) = A + Bx + Cy + Dx^2 + Exy + Fy^2.$$

The construction of two maps using different approximating surfaces is caused by the need to find the surface closest to the marking horizon.

To predict and find places favorable for methane accumulation in fractured rocks, positive structures with absolute marks above the approximating surface are highlighted on local structure maps.

Often, there is not a single closed positive local structure in the areas under research. From the viewpoint of classic oil and gas fields, such structures are considered unpromising for hydrocarbon accumulation; however, in coal and gas fields, the inflection zones of local anticlinal structures are of some interest. In such zones, the development of fracturing in coal beds and rocks is noted, which contributes to the accumulation of methane in these zones.

Thus, at the first stage, the array of data is prepared according to the hypsometric plan of the coal bed in the form of a set of marks – x, y, z, where x and y are the coordinates of a point on the plan (the location of the well within the minefield). Z is a vertical mark in space, that is, it is the depth of the bed bottom/floor of rocks, in this case, a coal bed. Further research was carried out by constructing a map of local structures of the 1st order using trend analysis. The map is constructed by the method of interpolation based on the deviation of the actual hypsometric marks of the coal bed from the corresponding marks of the approximating surface.

Based on the constructed map of local structures, a promising anticlinal structure was highlighted and cross-section lines were drawn on it, along which deformations will be assessed in the future, both in terms of strike and dip of the coal bed. Next, an equation was established that describes the vertical plane passing through the selected points. The next step was the construction of a multidimensional interpolating polynomial based on the array of primary data. By solving the system of two equations (the equation of the vertical cutting plane and the equation of the interpolating surface closest to the real surface), the equation of the curve is found, which is the intersection of the vertical cutting plane and the surface closest to the real one. It is a curve that connects selected reference points within the interpolating surface in the vertical plane.

The next step is to calculate the length of the curve between the selected reference points by integrating the equation that was the solution of the system of equations. The limits of integration are the coordinates of reference points. Next, based on the corresponding coordinates, the distance between the selected points along a straight line is found. At the last stage, the coefficient of linear deformation is calculated by dividing the specified arc length by the length of the straight line segment connecting the selected points.

The research area's geological structure. The "Chaikino" mine is located in the Donets-Makiivsk geological and industrial district.

The Donets-Makiivsk geological and industrial district is located south of the Main anticline and is within the Donetsk region. In the northeast, the district borders Chystiakovo-Snizhniansk, in the south – Amvrosiivsk and Yuzhno-Donbask, in the northwest – Pokrovsk geological and industrial districts. The northern boundary coincides with the minus 1,600 m mark of the upper working bed n_1^1. The total area of the district is 3,170 km^2.

The district's geological structure includes sediments of Carboniferous, Neogene, and Quaternary ages. Mesozoic sediments are limited in distribution in the western part of the district.

Carboniferous sediments are represented by the Bashkir and Moscovian stages of the Middle Carboniferous (suites C_2^1–C_2^7), Kasimiv and Gzhel stages of the Upper Carboniferous (suites C_3^1–C_3^3). They are mainly characterized by a siltstone-argillite composition with a subordinate content of sandstones, limestones, and coal.

The carbon content in the upper part decreases sharply. The industrial coal-bearing capacity is confined to the medium (C_2^1–C_2^7) suites and partially to the upper Carboniferous suites C_3^1, which contain 147 coal beds and interlayers, of which 53 reach working capacity. The most stable layers are: h_3, h_7, h_8, h_{10}, h_3, k_8, l_1, l_3, l_4, l_8^1, m_3, n_1, which retain working capacity over most of the area. The structure of beds is mostly complex. According to the degree of metamorphism, the coal of the district is represented by the entire gamut – from weakly metamorphosed long-flame coal to anthracite.

In the western part of the district, coal sediments are unconformably overlain by Triassic sandstones, quartzites, conglomerates up to 185 m thick, and Upper Cretaceous sands, spongolites, and chalk. The thickness of Upper Cretaceous sediments ranges from 10 to 80 m.

In the north and west of the district, Mesozoic and Paleozoic sediments unconformably overlain with Paleogene and Neogene sands, sandstones, and clays with a total thickness of 20–50 m.

On the territory of the district, Quaternary sediments are developed everywhere. Lithologically, they are represented by clays, loams, sands, and gravels. The total thickness of Quaternary sediments is on average 10–20 m.

In tectonic terms, the district is located at the southern closure of the Kalmius-Toretsk Basin. The western part of the district is characterized by a calm bedding of rocks with small ruptures. The central and especially the eastern part has a complex tectonic structure. Carboniferous rocks dip northwest, at an angle of 12–18°. The main strike of plicative dislocations is sub-latitudinal sub-meridional.

From the sub-latitudinal structures, the Riasnianska syncline and the Zuievska anticline stand out, and from the submeridional ones – the Vetkivska, Chaikinska, Kalynivska, Yasynivska anticlines, and the Makiivska syncline. Of the disjunctive faults, thrusts are mainly developed in the area, and very rarely – faults/discharges. Thrusts are divided into four distinct groups. Group 1 includes sub-latitudinal thrusts with a northeast and southwest dip, these are Mushketovskyi thrusts with an amplitude of up to 750 m and Pozdovzhnii thrust with an amplitude of up to 250 m.

The *2nd* group of thrusts includes the sub-meridional northwest-dipping ones – Frantsuzkyi with an amplitude of up to 622 m, Kalininskyi with an amplitude of up to 350 m, and Tymoshenko with an amplitude of up to 380 m. The *3rd* group of thrusts with a northeast strike and a southeast dip are represented by the Pervomaiskyi one with an amplitude of up to 220 m and the Frantsuzkyi thrust with an amplitude of up to 180 m. The arc-shaped Italiiskyi and Dulinskyi thrusts with amplitudes of up to 150 m belong to the *4th* group.

The area's hydrogeological conditions are complex. The aquifers are confined to limestones, sandstones, and sands of the Carboniferous, Jurassic, Upper Cretaceous, Paleogene, and Quaternary ages. Water inflows vary from 0.1 to 16.6 thousand m^3/day and average 3.0–3.1 thousand m^3/day. According to the gas regime, most mines in the district belong to the supercategorical. The methane content of the mines ranges from 10 to 36 m^3/t.

The "Chaikino" minefield is located in the northeastern part of the southern wing of the Kalmius-Toretsk basin, in the hanging wing of the Frantsuzkyi thrust, between the Kalininskyi and Chaikinskyi flexural folds.

Carboniferous sediments on the minefield belong to suite C_2^5–C_2^7. They are composed of sandstones, mudstones, and siltstones containing beds of limestone and coal. Carboniferous rocks are overlain by Paleogene and Quaternary sediments. Paleogene sediments are located in separate small areas. Quaternary sediments are spread throughout the minefield. Their capacity ranges from 1.5 to 15.0 m. The main working coal bed is m_3. The hypsometric plan of coal bed m_3 is shown in Fig. 2.

The coal depth within the minefield ranges from 650 to 1,150 m. The general sublatitudinal strike of rocks is complicated by the above-mentioned flexures and the Chaikinsk syncline fold located in the southern part of the field. The angles

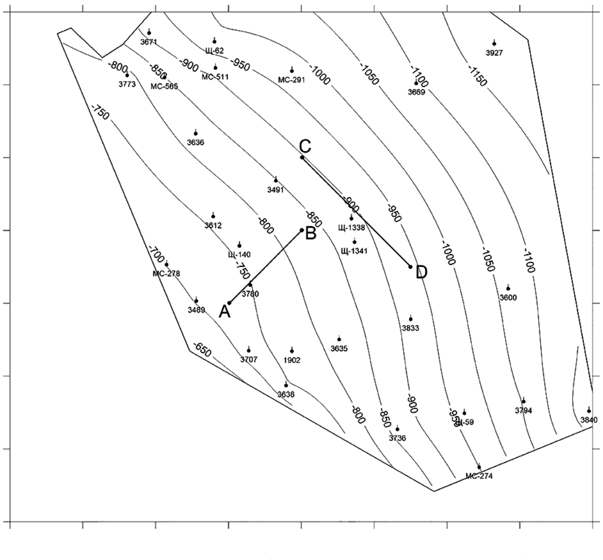

Fig. 2. Hypsometric plan of the m_3 coal bed on the "Chaikino" minefield

of rock dip are 8–15°, in places where it is more complicated up to 20°.

The Chaikinsk syncline is a gentle (3–5°) fold dipping in the northeast direction at an angle of 2–3°. The northern part of the minefield is occupied by a slope (2–3°), a wide brachianticline, which stretches from the southwest to the northeast.

The Butovskyi thrust is dissected by Novo-Chaikinsk No. 1, which divides the minefield in the latitudinal direction approximately along the axis of the Chaikinsk syncline. In the western direction, the Novo-Chaikinsk thrust No. 1 gradually fades away. The displacement amplitude in the central part is 10–17 m, the fracture zone is 10 m. In the south and southeast direction, the thrust amplitude increases to 30–70 m, and at depth, it merges with the Frantsuzkyi thrust. The dip of the Novo-Chaikinsk thrust No. 1 is southeast at an angle of 10–15°.

In the west of the minefield, at an acute angle, the Novo-Chaikinsk thrust No. 2 joins to the above-mentioned thrust. The dip is south, at an angle of 15–20°. The displacement amplitude is 7–10 m, and the width of the fracture zone is about 10 m.

In the northwest of the minefield, its natural boundary is created by the Bezimennyi thrust, which apparently adjoins the Hryhorivsk thrust. The amplitude of the Bezimennyi thrust is up to 46 m. Its dip is northwest at an angle of 14–25°.

The structure of the m_3 coal bed is complex. Within the entire minefield, the bed has a persistent working capacity from 1.45 to 1.90 m. In most cases, its upper coal bench has a thickness from 0.04 to 0.14 m. It is separated by a rock interlayer with a thickness of 0.03–0.09 m from the main lower coal bench. The thickness of the lower coal bench/pack may vary slightly from 1.40 to 1.65 m. In the south, within the limits of the minefield, bed m_3 has a three-pack structure.

Coal bed m_3 belongs to ZH grade. The yield of volatile substances is 27.6–34.4 %. Both of its coal benches are low-ash (4.3–7.3 %). Sulfur content does not exceed 3 %. The bed is composed of a strongly restored genetic type of coal.

The roof of the bed is composed of argillite, thickness of 7–19 m, and at the bottom there are rocks of different compositions – from the beginning, it is siltstone-clay with a thickness of 0.5–5.0 m, sometimes up to 15–20 m, and below – sandstone with a thickness of 1.2 to 29.0 m.

The methane content of m_3 coal bed varies within fairly wide limits, namely, from 14.7 to 27.4 m^3/t.g.m. The zone of methane gases extends to depths from 230 to 300 m. In the zones of geological disturbances, gas-dynamic phenomena were recorded, namely blowers and emissions of coal and gas. In other areas, in conditions of calm bedding, gas manifestations are normal.

There is an outburst zone along the axis of the Chaikinsk syncline.

Results and their discussion. As a result of the completed constructions, one anticlinal structure and one synclinal structure were highlighted on the map of local structures of the *1st* order for m_3 bed (Fig. 3).

The positive local structure is located in the central part of the minefield. The axis of the fold is elongated in the northeast direction. The length is 2.5 km, and the width of the fold is 2.25 km. The amplitude of the fold is 55 m. The maximum marks of the structure are in the area of wells Sh-1338 and Sh-1341. The structure has a dome shape.

A negative saddle-shaped structure is distinguished in the section of the minefield, which extends through the entire researched area from the northwest to the southeast. In the peripheral parts of the structure, the marks reach -60 m (in the area of wells No. 3671, Sh-62 in the northwest, and 3840 in the southeast). In the central part of the minefield, the structure marks decrease and reach –5– –10 m (wells Nos. 3638 and 1902). The length of the structure is 4.5 km, and the width is up to 1.6 km.

On the map of local structures of the *2nd* order (Fig. 4), a positive structure extending from the northwest to the southeast is found.

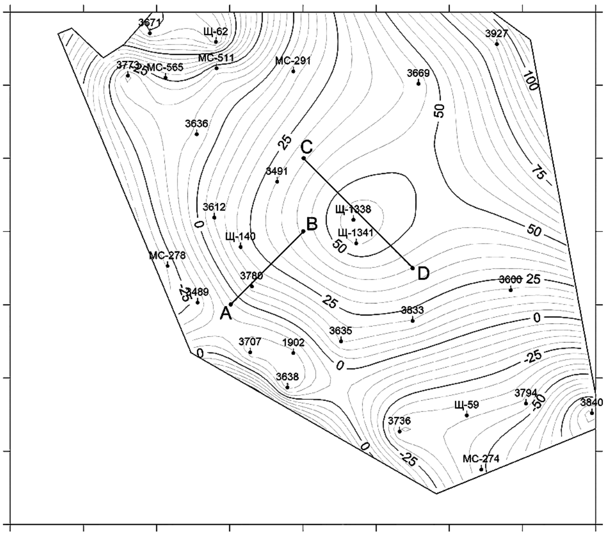

Fig. 3. Local structures of the 1st order for m_3 bed on the Chaykino minefield section

Along the entire length of the structure, the amplitude is 20–25 m. In the area of wells Sh-1338 and Sh-1341, the amplitude of the structure increases to 40–45 m, and in the area of well No. 773, the structure marks reach +50 m. The map shows two negative local structures that are parallel to the positive. The first one is located in the area of wells Nos. 3489, 3707, 3736. The minimum marks of the structure are -40 m. The second local structure of the synclinal type is located in the area of wells Sh-62, Nos. 3669, 3927. The axis of the fold dips in the northwest direction. Minimum marks reach -45 m.

One promising positive structure stands out in the minefield, from the viewpoint of fracturing and increased gas bearing capacity. The axis of the bend passes in the area of wells Sh-1338, Sh-1341. The width of the fold is 1,850 m, the height is 40 m.

The computer algebra system Wolfram Mathematica was used to calculate the length of the curve formed at the intersection of the surface, which is constructed according to the markings of the bottom of the coal bed and the vertical plane passing through the local structure.

Wolfram Mathematica is a computer algebra system from Wolfram Research Company. This is a computer program or program package that allows you to perform a wide variety of mathematical operations and transform algebraic expressions

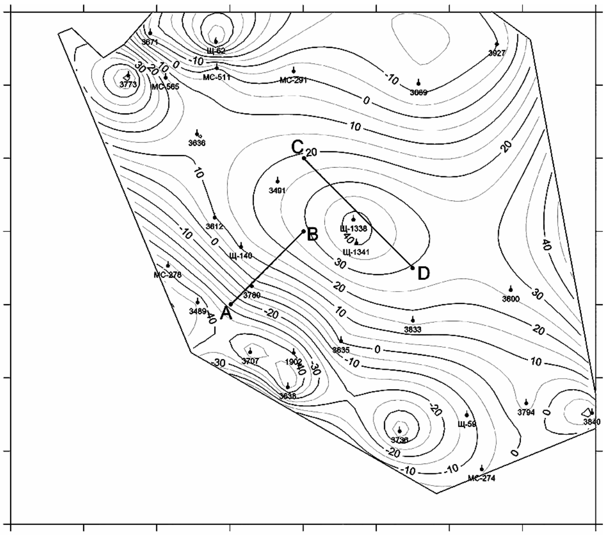

Fig. 4. Local structures of the 2nd order for m_3 on the "Chaikino" minefield section

given in numerical and symbolic (variables, functions, polynomials, matrices, etc.) forms. Modern systems have functions from almost all branches of modern mathematics, support interactive visualization, and one or more programming languages, and often allow combining algorithms, mathematical formulas, text, graphics, diagrams, or animations with sound, as well as calculation results in a single file.

Based on the constructed map of local structures of the 1^{st} order, a prospective anticlinal structure was highlighted and intersecting lines were drawn on it, along which deformations will be assessed, both in terms of dip – A–B, and strike – C–D (Fig. 3).

In line with the proposed algorithm, the first step was to establish an equation describing the vertical plane that passes through the line whose length needs to be calculated. The equation of a vertical plane passing through two points in three-dimensional space has the form $Ax + By + Cz + D = 0$. However, since the plane is vertical and passes through points with different x and y coordinates, but no z constraint, the key point is that it will be parallel to the z-axis. This means that in the equation of the plane, the coefficient at z is 0, simplifying the equation to the form

$$Ax + By + D = 0.$$

To find the specific coefficients of A, B, and D for our plane, we can use the coordinates of the start and end points of the segment that the cutting plane passes through. For this, we only need their x and y coordinates, since the plane is vertical and does not change in z. Since the plane passes through both points, the coordinates of each point must satisfy the equation of the plane. This allows us to construct a system of equations to find A, B, and D. However, we will have one equation for two points and three unknowns, which usually requires additional information for a unique solution. In the case of a vertical plane, we can take advantage of the fact that one of the coefficients (C in this case) is 0, and we only need to determine the ratio between A and B, as well as the value of D. Given that we only need the form of the equation of the plane, and not its exact position, we can use a vector directed from one point to another for determining the normal to the plane. This normal will indicate the direction of A and B for our plane.

In this way, it was obtained that the equation for the vertical plane passing through the points A (x = 1,500, y = 1,500) and B (x = 2,500, y =2,500) has the form

$$x - y = 0.$$

And for the plane passing through points C (x = 2,000, y = = 2,500) and D (x = 2,750, y = 1,750), has the form

$$x + y - 4500 = 0.$$

The next step is the construction of a multidimensional interpolating polynomial, for which the Interpolating Polynomial method was used, in which the first argument is the array of x, y coordinates of the wells and the z coordinate (the mark of the coal bed bottom in each of the wells), and the second argument was that the calculation must be performed in dependence on variables x, y.

The equation of the curve obtained as a result of the intersection of the obtained interpolating polynomial and the vertical cutting plane is the result of solving the system of two equations describing the indicated surfaces (Figs. 5, 6).

The last step is to calculate the curve length between the points the x coordinates give. For this, the NIntegrate method was used, which gives a numerical approximation of the integral

$$\int_{x_{\min}}^{x_{\max}} f dx.$$

The function has the form: $\sqrt{xt^2 + yt^2 + zt^2}$, where xt is equal to 1, yt is the derivative of the expression of the equation for the vertical cutting surface through xt, and zt is obtained as a solution of the system of equations for the interpolating polynomial and the vertical cutting plane.

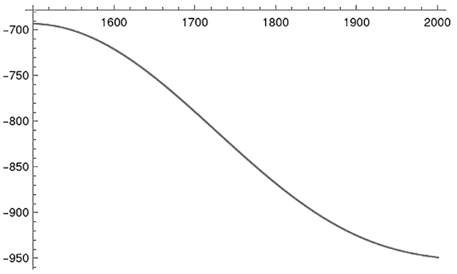

Fig. 5. The intersection curve of the vertical secant and the interpolating surface along the A–B line

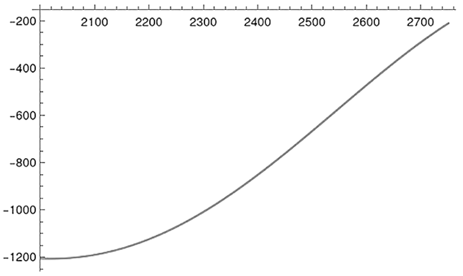

Fig. 6. The intersection curve of the vertical secant and the interpolating surface along the C–D line

Thus, we find that the curve length between points A–B is 760.41 m.

To calculate the distance between the start and end points of a straight line segment, the Euclidean distance formula was used, which has the form

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}.$$

The distance in a straight line between points A and B is 752.03 m. The curve length between points C–D is 1,504.25 m, the distance in a straight line is 1,454.97 m. By dividing the corresponding determined lengths of the curves by the lengths of the straight line segments that connect the selected points (A–B and C–D) we obtain the required coefficients of relative linear deformations. It is equal to 1.011 in dip, and 1.034 in strike, which significantly exceeds the critical tensile limit for all rocks of the coal-bearing stratum – argillites, siltstones, and sandstones. This indicates a discontinuity of rock massif and the presence of a fractured zone within the researched section of the minefield.

Based on the obtained coefficients of relative linear deformations, it is possible to calculate the coefficient of relative volumetric deformation of rocks within the compacted part of the structure. It is calculated as a product of corresponding linear coefficients and in this case, it is equal to 1.045.

Based on calculated data on the volumetric deformation of rocks and their reservoir properties, it is also possible to obtain the value of the fracture porosity coefficient, absolute gas permeability, and effective porosity coefficient by calculation according to the method [21].

The most powerful sandstone within the minefield, which can potentially accumulate gas, is sandstone $m_4Sm_4^1$, with a thickness of 37 m, an open porosity coefficient of 5–10 %, and an effective porosity coefficient of up to 2.5 %. For sandstone with such filtration-capacity parameters and volume compaction with a coefficient of 1.045, the calculated value of fracture porosity can be up to 4 %. According to the methodology [21], the absolute permeability coefficient will be equal to 340 mD (10–15 m^2).

The coefficient of effective porosity in the decompressed zone is determined as the sum of the coefficient of effective porosity in the undisturbed zone and the calculated fracture porosity. That is, the effective porosity in the zone of greatest decompaction can reach a maximum of 6.5 %.

Thus, the sandstone $m_4Sm_4^1$ within the researched local structure, according to its properties acquired in the process of folding, can be a potential coalbed methane reservoir.

Conclusions. A new method for predicting fractured zones in a massif of sedimentary rocks formed due to the folding is proposed. The methodology has been developed based on an algorithm that involves calculating relative linear deformations of the bed by constructing maps of local structures for the researched area and a series of mathematical calculations.

An anticlinal local structure (the 2nd-order structure) was identified within the "Chaikino" minefield of the Donets-Makiiv geological and industrial district, the parameters of the structure were determined, and calculations were performed according to the appropriate algorithm.

The concrete result of determining the relative linear deformations of the rock massif is given on the example of the "Chaikino" minefield. The calculated values of the relative linear deformations along the dip of the coal bed were 1.011, along the strike – 1.034, and the relative volumetric deformation coefficient – 1.045.

The obtained data indicate a significant excess of the real values of the relative linear deformations above the critical limit for all rocks of the coal-bearing strata – argillites, siltstones, and sandstones. This indicates a discontinuity of rock massif during tectonic stresses and the formation of secondary folding and the presence of a fractured zone within the researched area.

The proposed method can be used to solve several geological problems directly related to the research and detection of fracturing, which was formed under the action of tectonic forces in the process of folding.

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Методика визначення відносних лінійних деформацій породного масиву осадової товщі

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Мета. Розробка методу прогнозування тріщинуватих зон у масиві осадових гірських порід, утворених за рахунок формування складчастості, шляхом визначення відносних лінійних деформацій, що перевищують критичні для порушення суцільності порід.

Методика. Завдання виділення тріщинуватих зон полягає у визначенні ділянок у масиві гірських порід, де деформації розтягання, під дією тектонічних процесів, перевищили критичну межу. Визначення потребує побудови карт досліджуваної ділянки за допомогою тренд-аналізу й низки математичних розрахунків, а саме знаходження відстані між обраними точками напряму та за дугою, що їх з'їднує в межах інтерполюючої поверхні. Довжина останньої кривої знаходиться шляхом інтегрування. Коефіцієнт відносної лінійної деформації є результатом ділення знайдених відстаней (довжини дуги на довжину прямої).

Результати. Запропонована нова методика прогнозування тріщинуватих зон у масиві осадових гірських порід, утворених за рахунок формування складчастості. Методика розроблена на базі алгоритму, що передбачає розрахунок відносних лінійних деформацій пласта шляхом побудови карт локальних структур досліджуваної ділянки й низки математичних розрахунків. На прикладі поля шахти «Чайкіно» наведено конкретний результат визначення відносних лінійних деформацій породного масиву. У межах шахтного поля виділена антиклінальна локальна структура (структура 2-го порядку), визначені параметри структури й виконані розрахунки за відповідним алгоритмом. Отримані дані свідчать про значне перевищення реальних значень відносних лінійних деформацій (1.011 і 1.034) критичної межі для пісковиків (1.003–1.004). Це свідчить про порушення суцільності масиву гірських порід і наявність тріщинуватої зони.

Наукова новизна. Уперше розроблена методика, що уможливлює визначення відносних лінійних деформацій гірських порід між будь-якими окремими точками в межах досліджуваної ділянки, за координатами розташування точок у плані та гіпсометричною позначкою пласта.

Практична значимість. Запропонована методика може слугувати для вирішення цілої низки геологічних завдань, що безпосередньо пов'язані з дослідженням і виявленням тріщинуватості, яка була сформована під дією тектонічних сил у процесі складкоутворення.

Ключові слова: *гірські породи, складчастість, структури, зони тріщинуватості*

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