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STRUCTURAL-KINEMATIC RELATIONSHIPS AT THE DEVELOPMENT OF SHEAR DISLOCATIONS AND THEIR IMPACT ON LOCALIZATION OF GAS-DYNAMIC PHENOMENA ON THE EXAMPLE OF KRASNOARMIYSKA MONOCLINE AT DONBAS

Purpose. The purpose of the paper is the reconstruction of the geodynamic development of the shear dislocation zone (shear stress fields) of the Krasnoarmiyska monocline (KM) of Donbas (Eastern Ukraine) and determining the relationships of their impact on the emergence of gas-dynamic phenomena (GDP) in coal sediments. **Methodology.** Methods of digital geological cartography, mining-geometric simulation, geological-structural analysis, and structural-geomorphological reconstruction are used for the analysis of structural-geological information. A complex of methods for statistical processing of data on the tectonic disturbance is used – estimation of the frequency of azimuth orientations by the roses-diagram method. Techniques of morphotectonic analysis of the coal bed (a mathematical technique for identifying the gradient structures) are applied. **Results.** A tectonic model of formation of pull-aparts in the mode of transtension on the territory of KM (on the example of "Dobropilska" mine) is proposed, which results in manifestations of GDP (in particular "wet blowers") in the form of a small kettle of subsidence in zones of en échelon overlapping of shears. The latter ones are formed under the action of the shear field of tectonic stresses (the axis of space shortening is (σ_1) due to the horizontal shear is oriented in azimuth 160–170° (340–350°), the axis of elongation is (σ_3) – 70–80° (250–260°). At this, the combination of fringing Y and T faultings in the conditions of transtension, most likely, provides gas permeability and water permeability of the zone. Structure-kinematic relationships of formation and development of shear dislocations of KM at Donbas are researched. **Scientific novelty.** The structural-kinematic relationships in the formation and development of shear dislocations of the Krasnoarmiiskyi district of Donbas and their impact on the formation of GDP zones were studied firstly. They are based on the developed digital model of the actual tectonic disturbance of the rock massif on the example of the mining allotments group of KM. It is established for the first time: a) subparallel disjunctives of the NE orientation (15–30°), regardless of morphology, are as the boundaries of parallelogram-like blocks, forming either scaly packets or packets of fault scarps (depending on the morphology of the faultings), limited in the strike by the fault planes of N-NE and SW fall; in the case of scaly packets in the orientation of the fall of the fault plane it is dominated by the E-SE direction, the faultings limiting the fault scarps are characterized by the opposite WN direction of the fall; b) faultings of SE orientation are morphologically represented by shear-thrusts, and with depth change not only the angle of incidence from 35° to 85°, but also the azimuth of strike (from 20–25° to 50°), forming a fanlike feathering of the main faulting in the plan; c) faultings of different morphology are represented not by a single fault plane, but by a series of disturbances on all stratigraphic horizons, which form a zone of faulting formation – a vertical "tectonic strip"; d) in the SE part of the mine "Pioner" a duplex of compression (transpression mode) was found, it is expressed by a folded system (F), up to 287 m wide and fragments of sloping, changing the strike of the Novoiverskyi thrusts; e) the zone of tension duplexes located in the chain, which have a characteristic broken-step configuration at the "Dobropilska" mine, to which "wet blowers" are connected with, develops due to local strike (transtension); f) paragenesis of deformations in the study area corresponds to the shear field of tectonic stresses with north-northwest direction of compression and east-northeast tension, in which fault-shear displacement occurs along with the disjunctive breaks. **Practical significance.** The established relationships of the impact of shear tectonics on the formation of GDP in coal beds are important both by clarifying the mechanism of tectonogenesis and the nature of pull-aparts formation (en echelon zones of tension), and by the possibility of using additional prognostic criteria for searching for accumulations of free methane and its sudden manifestations (GDP) in coal beds. The application of knowledge of these relationships at mining enterprises will allow reducing the costs for the struggle against dangerous GDP manifestations and predicting them reliably.

Key words: Krasnoarmiyska monoclinal; transtension; pull-apart; shear zone; GDP; blowers; paragenesis; fault-shear displacements; en échelon overlapping; Riedel shears.

Introduction

According to leading experts, the prospects for energy development in Ukraine in the coming years are mainly related to the development of gas-coal deposits. Coal reserves in the Ukrainian part of Donbas are about 56.7 billion tons, methane resources

in the coal rock strata, according to various estimates, range from 12 to 25 trillion m^3. About 95.4 % of domestic coal production is in Donbas. However, under the cutbacks to the funding of geological prospecting works and a situation of the modern development of coal deposits of Donbas, prospects of gas-coal sediments in connection with a possibility of methane mining (searches of accumulations of free methane in coal beds) or forecasting the areas of its localization and occurrence of gas-dynamic phenomena (GDP) requires the involvement of specialized modern less expensive research. It is unlikely that in the near future it will be possible to conduct geologic exploration in the amounts needed for a successful mining and geological forecast of both areas of methane accumulation and the emergence of GDP at operating mining enterprises. Objectively, the urgency of this problem reaches critical levels within the mining allotments of outburst-prone gas-coal massifs. That is why, in order to successfully make a mining and geological forecast of the above-mentioned issues based on the data of the already available information, a holistic view of the forming the carboniferous strata, its plicative and disjunctive structures involved in the accumulation of coal methane, their role in the emergence of GDP, it is advisable to apply the methods of geodynamic analysis, namely structural-tectonic reconstructions of geodynamic development of separate coal districts of Donbas (Eastern Ukraine).

The search for free methane accumulations and its unexpected shows (GDP) in coal beds should be based on exploratory conditions that can be used to identify and delineate the zones of accumulation of free hydrocarbon gases or dangerous zones of GDP in coal-bearing sediments. Prognostic criteria, which traditionally determine the zones of methane accumulation in coal beds (increased methane content of coal beds due to the optimal degree of coal metamorphism; depth; the complexity of tectonics and lithological composition of host rocks or improved filtration-capacity properties of the latter one) do not always allow us to assess the prospects of a local area regarding the presence or absence of coalbed methane accumulations without knowledge of the development of geodynamic events. That is, paleographic, paleofacial and other similar studies that reconstruct the primary parameters of the filtration-capacitive properties of rocks have no meaning and practical value without assessing the consequences of individual stages of tectonic development of the region.

Purpose

The purpose of the study is to determine the structural and kinematic patterns in the formation and development of shear dislocations of the Donbas KM based on the analysis of the actual location of "tectonic stripes" – Readel shears according to the data of the developed digital model of tectonic disturbance and to establish the main regularities of the shear tectonics impact on the formation of GDP in the coal deposits of KM.

Research methodology

For the analysis of structural-geological information and reconstructions of shear stress fields, authors used the methods of digital geological cartography, mining-geometric modeling, structural-geological analysis (diagnostic geometry of paragenesis of disjunctive structures – an analysis of structural pattern [Sylvester, 1988; Katza, et al., 2004; Tchalenko, 1970]), morphotectonic gradient analysis, statistical processing of factual data about: two thousand forty-eight (2048) tectonic disturbances (estimation of faultings frequency by a method of roses diagrams and range filtration), lithologic-facial inhomogeneities and caving zones which develop inheritedly on initially put weakened zones, on 7 coal beds (k_5 l_2^1, l_3, l_8, m_4, m_4^2, m_5^{1top}) within 4 mining allotments (mines: "Pioner", "Dobropilska", "Krasnonoarmiiska" and "Chervonolymanska") of KM. Individual techniques of morphotectonic analysis are used, which is to search the structural order of the relief of structural surfaces (coal bed), that reflects the regularities of the general tectonic structure, in which gradient structures are of special importance. They characterize the degree of contrast of changes in the immersion depth of the surface, as well as anomalies of the general structural plan.

Research results
The object of the research and the analysis of previously performed research

Of particular interest from the viewpoint of the prospects of gas-coal sedimentary deposits in connection with the possibility of methane production or forecasting areas of its localization and emergence of GDP in the Donetsk basin, are structures located in narrow strips on the border of Donetsk fold structure (DFS) with Bakhmutska and Kalmius-Toretska kettles (KTK). [Bogdanov, & Chernyakov, 2009; Privalov, et al., 2001]. For example, within the adjacent and above-fracture fault structures both blowers and natural gas explosions and numerous gas shows (the northern part of KM), closures of the southern side of the KTK and the northeastern part of Donbas (a section of the marginal part of the basin, Luhansk region), but also the zones of the northwestern strike, in which local gas fields are concentrated [Privalov, et al., 2011] (Fig. 1, *a*).

In doing so, despite the differences in the geostructural position of individual geological-industrial areas, in the mode of tectonic movements that affected the formation of different amplitude disjunctive tectonics (Fig. 1, *b-i*) in areas geographically located on the border of DFS, in a certain sense, these structures have similarities.

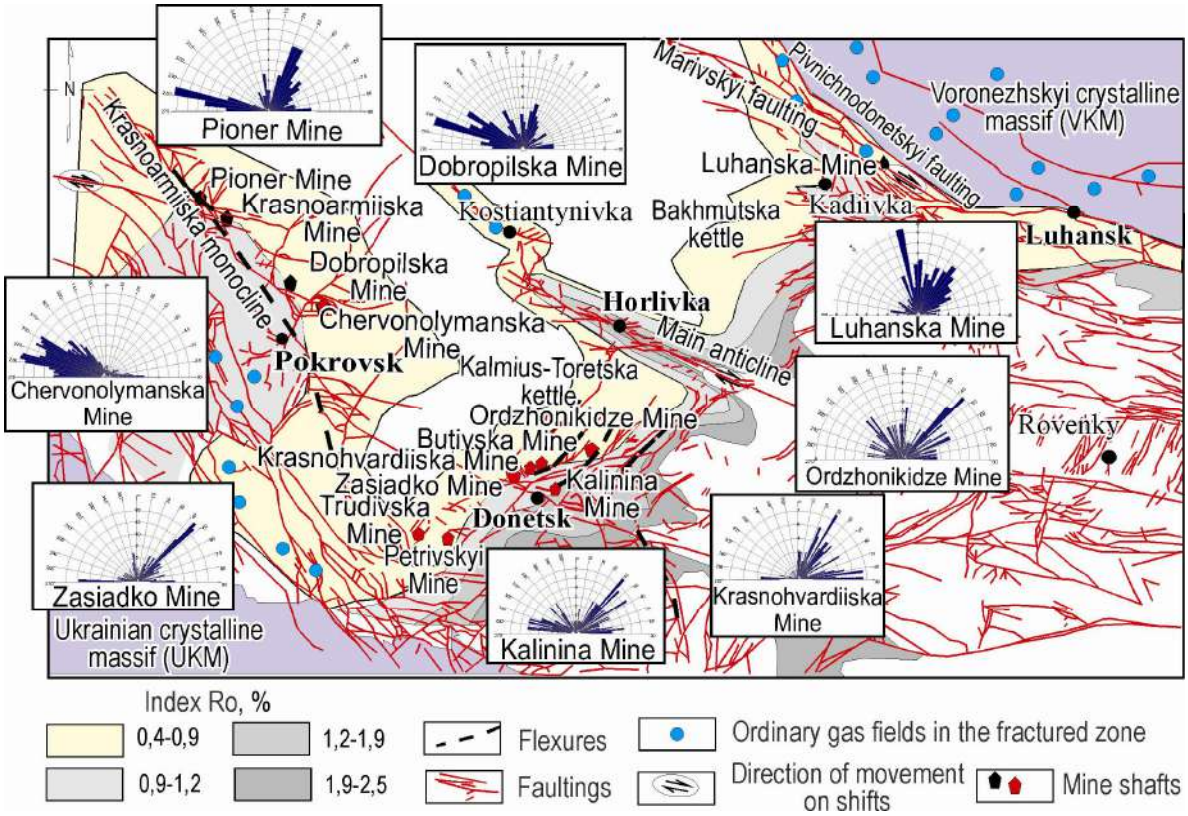

Fig. 1. Map-scheme of tectonic disturbance of separate geological-industrial districts of Donbas with detailing: ties of local gas deposits and cartograms of vitrinite reflection index (Ro, %) in isolines according to estimations [Privalov, et al., 2011] (*a*), roses-diagrams of strikes of medium and low-amplitude disjunctive tectonics (*b-i*) in areas (within the mining allotments of mining enterprises) geographically located on the border of DFS with Kalmius-Toretska and Bakhmutska kettles

Firstly, it is the vitrinite reflectance index (*Ro*) according to [Privalov, et al., 2011], as the most objective parameter of metamorphism, in the areas under consideration has equivalent low values – 0.4–0.8 % (coal rank D), for example, within the mining allotments of Chervonolymanska and Luhanska mines with a slight increase of 0.8–1.2 % (coal rank G, Zh) in the fields of "Dobropilska", "Bilozerska" mines, mines of the central part of the Kadiivskyi (formerly Stakhanivskyi) region (Fig. 1, *a*). Secondly, gas accumulations within the KM are situated to the horizons of sandstones l_7Sl_6, l_6Sl_5, l_5Sl_4, l_4Sl_3, l_2Sk_7, k_7Sk_5, open porosity in them varies from 10.58 to 4.68 %, permeability is in the range $(0.06–0.69)\cdot 10^{-15}$ m^2 (mD) [Privalov, et al., 2011]. The maximum documented gas content is of 14.0–27.8 m^3/t.c.m in the m_6^2, m_4^2, l_7, l_5, l_4, l_3, k_7, k_5 beds at the respective depths from 338 to 980 m. A similar situation is developing in the northeastern part of Donbas. Coals of Lysychansk district are weakly metamorphosed and represented by ranks D and G. The permeability of rocks that are not broken by cracks is very low, and even in sandstones, it is measured in thousandths of a millidarcy. The average values of the total porosity of argillites, aleurolites and sandstones are 12–14 % (long-flame coal) and 10–13 % in the strata containing gas coal.

It is significant that explosions and blowers of methane emissions recorded at different times, in the areas of mines (from west to east): "Bilytska", "Dobropilska", "Chervonolimanska" (KM); O. F. Zasiadko mine, O. O. Skochynskyi mine, M. I. Kalinin mine, "Chervona Zirka", K. I. Pochenkov mine, V. M. Bazhanov mine, "Krasnohvardiiska", H. K. Ordzhonikidze mine (Donetsko-Makiivskkyi district – DMD); "Luhanska", "Horetska", "Matroska" (Almazno-Marivskyi district) is situated to the zones of overfractured structures of deep faultings (Fig. 1, *a*). Of particular interest is the fact that in the blowers and outbursts of the listed mining allotments, a component composition of the gas with a high content of liquid hydrocarbons (such as condensate) was found. Shows of bitumen, heavy hydrocarbons (butane), hydrocarbon liquid (oil), aromatic hydrocarbons, and gas micro-deposits with a continuous inflow of free gas characteristic of gas fields were recorded. For example, at the O. G. Stakhanov mine (KM) from the cracks of outburst-prone sandstone $l_2Sl_2^1$ during the roadway driving at a depth of 986 m, the release of liquid hydrocarbons (oil) was documented [Kanin, et al., 2005]. Oil shows in the Central district of Donbas were observed at the "Komsomolets" mine when drilling a well from k_4 bed to the $k_4Sk_4^1$ sandstone [Karlov, et al., 1980],

where more than 500 liters of liquid hydrocarbons (gas condensate with a boiling point of 208 °C and a density of 0.8246 g/cm^3, a fractional composition close to diesel fuel). In the DMD, the release of gas condensate with a pungent odor of petroleum products in the blowers was recorded: O. F. Zasiadko mine and Shchehlivska-Hlyboka mine (blow gas emissions reached 43.2–51.8 thousand m^3/24-hour periods); mine "Oktyabrskyi Rudnyk" – emission of liquid hydrocarbons (condensate type) from sandstone m_3Sm_4, – there was a smell of petroleum products after outbursts of rock and gas in the workings); "Chaykino" mine (fractured limestone M_1SM_2 – oxidized oil) and V. M. Bazhanov mine (longwall, the roof of bed n_1 – an intensive emission of condensate with a density of 0.8414 g/cm^3 and a boiling point of 204 °C) [Antsiferov, et al., 2014]. The high content of butane C_4H_{10} (24.5 %) and helium (He) 2.2 % was found in the blowers of the mine "Bilytska" (KM). The high content of heavy hydrocarbons (C_2H_6, C_3H_8) and it was found in two areas of the western side of the KM: "Dobropilska-Kapitalna" areas and "Pivnichno-Rodynska" area. In the same areas in the sandstones of the suites C_2^7, C_2^6, C_2^5 the presence of bitumens was revealed, and while drilling the well a local area of gas deposits with a continuous inflow of free gas characteristic of gas fields was discovered.

All these data indicate a possible process of deep fluid inflow with the subsequent redistribution of hydrocarbon gases in the rock massif as a result of the action of a tectonic stress field through the formation of the so-called "structural window". It manifests itself in the form of spatial structures of tension and compression, which periodically occur, collapse, and replace each other. Thus, a necessary condition for the formation of migratory leakage is the presence of "structural windows" and structural traps and tectonic stress fields. Both the formation of tectonic inhomogeneities and "structural windows" are the result of their activity. The tectonic factor and the impact of shear fields of tectonic stresses in the rock massif on the formation of coal and gas outbursts and anomalous gas accumulations in the coal-bearing sediments of DMD or Western Donbas are substantiated and confirmed in many contemporary studies [Privalov, et al.,2011; Privalov, et al., 2012; Evdoshchuk, et al., 2013; Bezruchko, et al., 2018]. According to [Privalov, et al., 2011], the most intense methane emissions during coal mining in this area are usually associated with areas of active migration of hydrocarbons from traps of deep horizons.

In doing so, in modern research, the analysis of the impact of tectonic factors on the formation of methane blowers is usually reduced to the search for interdependent relationships in the system: metamorphism, depth, fracturing, the specificity of mining-geological conditions. According to statistics, 46 % of blowers are connected with disjunctives, 42 % of blowers are connected with plicatives, and 12 % are connected with plicative dislocations complicated by disjunctive disturbances [Bolshinskiy, 2003]. According to experts, blowers of geological origin are unevenly distributed over the bed area and represent differently oriented zones, which are associated with the orientation of tectonic faults and have a length of tens to several thousand meters in the strike and fall of coal beds. Zoning is observed not only within the minefields but also within the coal fields [Bolshinsky, et al, 2003]. Thus, traditionally, local methane emissions and their groups, in particular, blowers, are associated with the presence of plicative and disjunctive structures in the rock massif (thrusts, faults, anticlines, flexures), which play the role of either porous reservoirs or "accumulation traps". However, even here the sudden GDP or productivity of the debit of producing wells are selectively manifested, and their localization within the zones of rupture and folded disturbances is of a complex cellular nature. For example, within the KM mines, according to [Prykhodchenko, et al., 2019], methane-bearing anomalies are not associated with tectonic disturbances and are concentrated in syncline structures. There are also positive anomalies associated with local anticline structures. At the same time, the authors practically do not pay attention to the geometry of systems of tectonic inhomogeneities and conditions of their formation in researches. The experience of mining operations and previous studies have shown the connection of sudden emissions (GDP) and geological blowers to areas of low-amplitude tectonics [Zabygailo, et al., 1974], which in modern studies of the KM region are interpreted as "tectonic strips" of shear genesis [Dyachenko, 2014; Dyachenko, & Bezruchko, 2015]. Therefore, the locality of methane emission cannot be explained only by the presence of increased fracturing or its absence. Apparently, the main role belongs to the conditions of formation of tectonic forms in the tectonic stress field, which contributes to changes in the properties of methane reservoirs of coal deposits.

The structures of the northern part of the Pokrovskyi (formerly Krasnoarmiiskyi) geological-industrial area are of particular interest, in the context of studying the existing tectonic stress field in the gas-coal massif (currently) and its impact on the locality of gas emissions. Here zones of increased blowers emission in workings are usually situated to areas that are complicated by faults, erosions with the filling of the erosion cavity with sandstones, and where there is ambiguity in the connection with the blowers to a different fault and folded structures by amplitude, morphology, and genesis both in section and in the area of development.

Thus, the question of correlation in the localization of blowers in the area of Pokrovskyi district with certain systems of shear deformations that contributed to the formation of "structural windows", currently remains open.

Features of geostructural position and the geometry of the shear zone of the north-western part of the Krasnoarmiyska monocline (KM) of Donbas

Geo-structurally, the study area of the KM (see Fig. 1) is located in the southwestern part of the KTK. The structure is elongated in the north-western direction per 100 km on the strike with the strip width of coal-bearing sediments 18–20 km and is represented by a raising system, which is separated from each other by a very sloping, poor saddle.

The geological structure of this region is characterized by developed sedimentary rocks of the Middle and Upper Carbon, which are overlain by younger sedimentary rocks (Cenozoic, Triassic, Jurassic), the total thickness of which increases from south to north. Carboniferous sediments are an alternation of layers of coal, limestones, sandstones, argillites and aleurolites that are different by composition and thickness.

The relative smooth bedding of rocks is disturbed by tectonic faultings of different orientation and morphology. The first group of faultings (Fig. 2) is morphologically presented by thrusts of the near-meridional N–NW strike (Samarskyi, Krasnoarmiiskyi, Mertsalovskyi, the northern part of Dobropilskyi) and diagonal northeastern orientation (Selidovskyi, Tsentralnyi, the southern part of Dobropilskyi, set of Novo-Iverskyi faultings). The second one is numerous subparallel disjunctives of the fault morphology of the near-latitude N-NW strike (Chervonolymanskyi, Hlubokoiarskyi, Karpivskyi, Hrushivskyi, Fedorivskyi, Samoilivskyi, Hnilushynskyi) and diagonal NE orientation – fault No. 5, fault "B", Fig. 2, *b, c, e, g*).

An analysis of the structural pattern of medium-amplitude tectonic disturbance of coal beds (Fig. 2, *b, c, e, g*) within the mining allotments of mines: "Pioner", "Krasnoarmiiska", "Dobropilska" and "Chervonolymanska" allows us to state the following:

– subparallel medium-amplitude disjunctives mainly of NE orientation (azimuth is 15–30°) regardless of morphology (faults or thrusts) are coaxial to the azimuthal orientation of the Central and southern part of Dobropilskyi thrusts and are boundaries of parallelogram-like blocks, forming either scaly packets or packets of fault scarps (depending on the morphology of the faultings), limited in the strike by the fault planes of N–NE and SW fall;

– in the case of scaly packets in the orientation of the fault plane fall, the E–SE direction dominates, the faultings limiting the fault scarps are characterized by the opposite W–NW direction of fall;

– medium-amplitude faultings of different morphology are represented not by a single fault plane, but by a series of disturbances on all stratigraphic horizons that form a vertical tectonic strip (Fig. 2, *b, c, e, g*);

– medium-amplitude faultings of NE orientation are localized in the zones adjacent to high-amplitude thrusts of N–NE strike (Krasnoarmiiskyi, the northern part of Dobropilskyi thrusts). In this case, the medium-amplitude thrusts of the above orientation are characteristic exclusively for the northernmost part of the analyzed area (mine "Pioner"). With distance in a south-easterly direction, in the central part of the block, closed between the high-amplitude thrusts of the N-NW strike, the medium-amplitude thrust structures disappear (Krasnoarmiiska mine) and give place to fault ones ("Dobropilska" mine). The absence of faultings in the NE orientation is recorded in the south-eastern part of the analyzed area (a mining allotment of the "Chervonolymanska" mine);

– faultings of NE orientation are morphologically represented by shear-thrusts, they change with the depth not only the angle of incidence (from 35° to 85°, that is, they are flatten out when approaching the surface towards the lowered wing) but also the azimuth of strike (from 20–25° to 50°), forming a fanlike feathering of the main faulting in the plan. Their azimuth orientation corresponds to the orientation of a wide (up to 270 m) zone of plicative dislocations on the eastern wing of the mining allotment at the mine "Pioner" (Figs. 2, *7–7*);

– in the northernmost part of the analyzed area (mine "Pioner") near-fracture anticline structures of NE orientation in the lying wings, which are flatten out to a surface of thrusts (Figs. 2*, 1–1, 2–2, 3–3, 4–4*), received a significant development;

– medium-amplitude subparallel faultings of near-latitude W-NW orientation (azimuth is 270–290°) of fault morphology of mainly steep fall (the incidence angle is 65–90°) are fixed on all digital models of tectonic disturbance of the analyzed mining allotments (Fig. 2);

– of particular interest are the steeply dipping faultings of the fault morphology of N–NW orientation (Mertsalivskyi, Hlubokoiarskyi faults), the azimuth of strike is 330–350°, which have a large crushing zone, they are often replaced by sandstone and, in fact, represented by expansion (Fig. 2);

– against the general background of faulting formation, low-amplitude tectonics is developed quite locally, it is concentrated in tectonic strips oriented coaxially with medium-amplitude faultings of different morphology. In this case, it is located in the volumes of fault or scaly-thrust packets, the boundaries of which are faultings of the NE orientation;

– the joint angle between the tectonic strips in NW and NE orientation in the general approximation is about 60°, and the faultings of the near-latitude and N–NE strikes are connected at an angle of about 85°;

– low-amplitude faultings are numerous, they are concentrated in the system of subvertical en-echelon-like locating and connecting "tectonic strips", rather evenly distributed over the area and projectively coincide in the section;

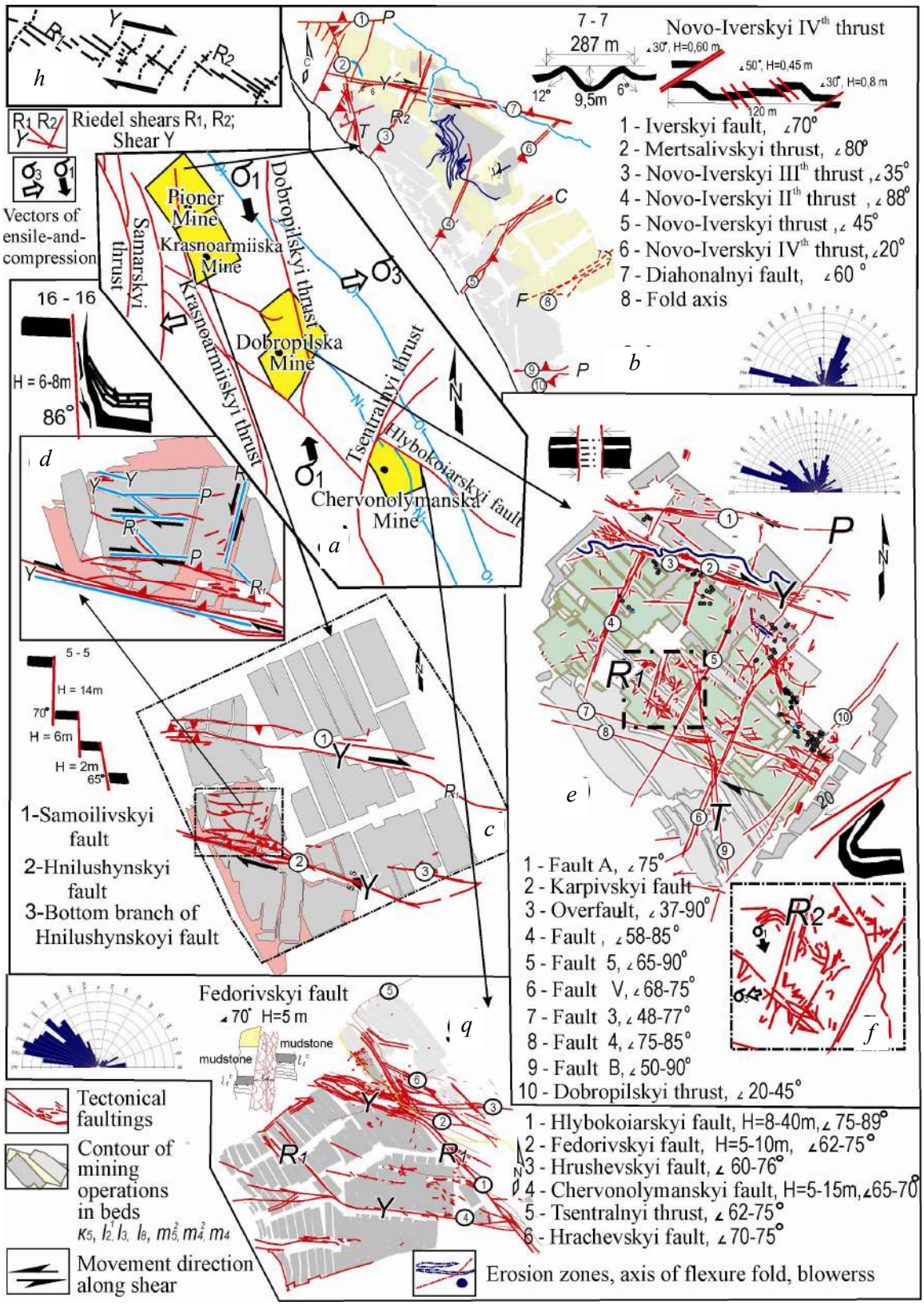

Fig. 2. Scheme of mines at the Krasnoarmiyskyi geological-industrial district (a). Digital mining-geometric models of tectonic disturbance of coal beds within the mining allotments of mines: Pioner (b), Sviato-Pokrovska (Krasnoarmiyska) (c), Dobropilska (e), Chervonolymanska (g) with detailing of roses-diagrams, shears R_1, R_2, Y, P, tension cracks T in the contour of the dextral shear zone, fragments of tectonic strips within sections (d, f) and sketches result of tectonic modeling in Riedel's experiments [Riedel, 1929] (h)

– in the south-eastern part of the mining allotment at the mine "Pioner" a duplex of compression (transpression mode) was formed, expressed by a folded system (F), up to 287 m wide and fragments of sloping, changing strikes Novoiverskyi thrusts (Fig. 2, *b*);

Summarizing the above and based on the generally accepted concept of the formation of thrust and fault structures it can noted: the first are formed in a situation of local compression, the second ones – in a situation of local tension – systems of faultings had to be formed in different geodynamic conditions, obviously, it does not correspond to reality. According to [Pavlov, et al., 2009] "Spatial relationships of all selected systems of faultings indicate that they are the same age or about the same age". As a result of using kinematic analysis of crack-faulting structures, the authors concluded that the structures "could be laid as shears". Considering the above, the above-described systems of disjunctive dislocations refer to the shear association of structures with certain systems of shear deformations and the internal structure of shear duplexes. That is, the analysis of the actual material and interpretation of numerical data obtained at different times suggests that the faultings of the analyzed geostructural unit were formed in the situation of shear stress field (horizontal position of the main kinematic axis of compression – tension (σ_1- σ_3), the position of the axis of intermediate stress σ_2 is vertical).

To analyze the relationship of tectonic disturbance and reconstruction of shear stress fields we used data on seven coal beds (k_5 l_2^1, l_3, l_8, m_4, m_4^2, m_5^{1top}) within four mining allotments (mines "Pioner", "Dobropilska", "Krasnoarmiyska" and "Chervonolymanska"). Statistical processing of actual data concerning two thousand forty-eight (2048) tectonic disturbances, caving zones, and lithologic-facial inhomogeneities which develop inheritedly on initially put weakened zones was carried out.

The analysis of the structural pattern and the maximums of orientations of the faultings on the rose-diagrams (Fig. 2) allowed us to identify two systems of fractures: synthetic right R_1-shears (azimuth of strike is 300–310°, maximum corresponds to 300–304°) and antithetic left R_2-shears (azimuth of the strike is 12–28°, the maximum corresponds to 22–24°), which are symmetrical about the axis of compression (σ_1) parallel to which the tension cracks (T) develop. (Fig. 2, *f*). Tension cracks occupy the position of the bisector of the angle formed by the connected Riedel shears R_1 and R_2, with the average value of the joint angle 66° (minimum value is 60°, the maximum one is 78°), azimuth of the strike for tension cracks varies in the range of 340–350°. Characteristically, that the systems of connected fractures – Riedel shears R_1 and R_2 (Fig. 2, *h*) were obtained as a result of tectonic modeling in Riedel's experiments [Riedel, 1929] and on the scheme of interpretation of natural structural-geological data in mine workings (Fig. 2, *d, f, g*) are almost identical.

Shears R_1 are diagonal and form the acute angle α with the axis of the shear zone (Y) in the direction of displacement, which varies from 5° to 20–30° (values of 15–20° are mostly found), are synthetic ones, i.e. the direction of movement along the faultings corresponds to the direction of movement of the main shear zone. Shears R_2 are transverse ones and, accordingly, antithetic, i.e. the shear of fracture wings is directed opposite to the direction of movement of the main shear zone. The latter is forming an angle β with the axis of the shear zone, which can vary from 65–70° to 80°. The magnitude of the angles α and β is due to the internal friction that arises in the process of the shear deformation. As the total shear deformation increases, the Riedel shears undergo some rotation, so the values of the angles, as a rule, tend to increase. Antithetic shears due to their transversality toward the general orientation of the movement, are partially curved, gaining a Z-shaped shape in plan within the boundary sections of the deformed strip due to the edge effect with increasing strip size in the direction of the shear axis. It is this feature (curvature) that explains the range variance in the azimuthal orientations of Ridel's antithetic shears and, accordingly, the variation in the values of the magnitude of the joint angle of R_1 and R_2 shears.

Since there are no absolutely linear systems in the shearzone, fracture zones are often disrupted, shifted relative to each other, and the crushing zones of disturbances and weakened rocks are accompanied by various deformation defects, so the tracks of "tecktonic strips" in the study area are represented by numerous separate fault planes which are disrupted, split into several branches, and their stratigraphic amplitudes and dip azimuth are characterized by high variability both along the strike, and in section.

Studies showed that: faultings formed in the situation of shear stress field, the axis of space shortening (σ_1) due to the horizontal shift is oriented in azimuth 160–170° (340–350°), the axis of elongation (σ_3) is 70–80° (250-260°); systems of synthetic right (R_1) and antithetic left (R_2) Riedel shears connected at an angle of 60–78° (average value is 66°), symmetrical about the compression axis (σ_1) and having orientations of 300–310° and 12–28° (respectively); tension cracks (T), parallel to the compression axis (σ_1) – bisector of the angle formed by the connected R_1 and R_2 shears, oriented in azimuth 340–350°; synthetic shifts (Y) – the main dextral shear zone – are expressed by the orientation of steeply dipping faultings (morphologically faults) W–E strike (azimuth 280–290°); secondary synthetic shifts (P) in orientation are close to the latitudinal (270°). Interpretation of structural and geological data of the analyzed mines allows us to state that there is a clear complementarity of the fracture network within all mining allotments, i.e. the correspondence in the orientations of the violations formed in the contour of the dextral shear zone (Fig. 2).

It should also be noted that the "tectonic strips" R_1 and R_2 are located quite regularly. Antithetic shears (R_2) are separated from each other by a distance that

for large "tectonic strips" with a width of the disturbed zone from 50 m to 100 m is 1600–2500 m, for smaller ones (with a zone width up to 50 m) is 800–1100 m (Fig. 2, *e, f*). The distance between the synthetic shears (R_1) varies between 400–600 m.

On the faultings of the north-eastern orientation sinistral shift displacements with a characteristic turn of the wings are recorded (Fig. 2, *c*), on the faultings of the north-western orientation we observe dextral shift displacements, which is characteristic of the dextral shift zone. The antithetic left Riedel shears (R_2) are expressed more clearly than the synthetic right shears (R_1) and they are coaxial to the strike of steeply dipping faults No. 5, "B" and the fragment of Dobropilskyi thrust, in the lying wing of which the analyzed coal beds were worked out. Moreover, the horizontal displacement of the feathering faultings along the Mertsalovskyi thrust within the coal bed l_8 of the mine "Pioner" was almost 150 m (Fig. 2, *b*). The revealed regularity is confirmed by the actual orientation of the slickenlines on the fault planes, which were recorded during the mapping of faultings in the mine workings. That is, along with fault and fault-shear displacements dextral shear displacements on sublatitudinal faultings and sinistral shear displacements on submeridional ones were documented [Pavlov, et al., 2009]. The manifestation of tectonic processes in the mode of horizontal shift is indicated by a number of lithological features. These are, first of all, coal replacement zones controlled by fracture compaction zones, and it testifies to the fact that the zones of disturbances were drained by the channels of ancient watercourses.

Features of "wet blowers" in the area of the "Dobropilska"mine and patterns of their location in the pull-apart structures

Studies [Diachenko, 2014] in the area of the "Dobropilska" mine showed that twelve cases of methane blowers show were recorded in the workings on coal beds l_3 and l_2^1, which are dependent not only on low-amplitude disturbances but also to areas of high water shows in the mine workings. It should be noted that the intense inflow of water was observed in almost all beds developed (eighty-two cases) at different depths of development, both in the southern and northern longwalls. For example, in the eastern wing: at the bed l_2^1 there were 1, 2 southern longwalls (horizon is –300 and –350 m) 3, 4 northern longwalls (horizon is –400 and –450 m) 3, 4 northern longwalls; at bed l_3 there were 1, 2 southern longwalls (horizon is –300 and –350 m), 4th northern longwall (adjacency to the reverse fault No. 1). The intensity of blower- and water shows is uneven and has a characteristic feature: almost all cases are concentrated in the diagonal step-like zone of the north-western strike (Fig. 3, *a*) in the eastern part of the mining allotment. This zone diagonally crosses the study area from the south-east to the north-west, in the area of which the low-amplitude faultings are the most developed and they are interpreted as tension cracks (T) and faultings parallel to the main shear zone (Y). This is a set of faultings of tension and shear, to which hydro- and blower activation is confined to (Fig. 3, *c*).

The conducted analysis of the structural pattern of tectonic faultings and, in general, the paragenesis of deformations, which corresponds to the shear field of tectonic stresses (horizontal position of the main kinematic plane of tension-compression) with the north-northwest direction of compression and east-northeast tension, in which the fault-shear displacements along the faultings occur allowed suggesting that in the eastern part of the mining allotment shallow depressions (small subsidence kettles) of strike-slip type pull-apart (Fig. 3, *b*). The latter are represented by parallelogram-like depressions, in which the boundaries of diagonal orientations are represented by oblique shifts and the submeridional boundary by tension joints and faults. According to [Novikova, & Privalov, 2008], these pairs of rupture or plastic shears and faults develop due to local crust tension, and the chains of adjacent duplexes have a characteristic broken or stepped configuration.

A separate issue is the model of the formation of pull-apart complexes. Structures of strike-slip tension (sedimentary troughs of subsidence) can be formed either as "pure" pull-aparts on the bends of large shears or as depressions of strike-slip subsidence in areas of en echelon shears overlapping. Probably, geodynamic events in the study area developed according to the transtensional scenario, leading to the formation of a system of echelon-like pull-apart structures. At the same time, the combination of fringing Y and T faultings in the conditions of transtension, most likely, provides not only gas permeability of the zone (blowers activation) but also water permeability. According to [Rudnev 2009], powerful "wet blowers" in Donbas, gas condensate and oil shows are confined to the Lysychansk region, where tectonics is the most complex in the entire basin (the northern zone of small size folds is connected with the largest North Donetsk thrust, which is a marginal deep fault). At the same time, the formation reconstruction analysis of the Lysychansk anticline (LA) on the border with the North Donetsk thrust allowed to identify the structural paragenesis of strike-slip compression zones (transpression) and the presence of pop-up structures formed in compression zones along large shifts, as well as alternation of compression and tension structures [Diachenko N. & Diachenko A., 2019].

That is, "wet blowers" take place both in the zones of pull-apart (KM) and in the areas of oblique pop-ups (LA). The complex mosaic of transpression and transtension zones within the main shear zone in which shear duplexes of local compression – extension are formed, plays an important role in many geological processes. This role is fundamental when it comes to the structure of coal-rock massifs and spatial control of various manifestations of dangerous GDP and processes in the carboniferous strata.

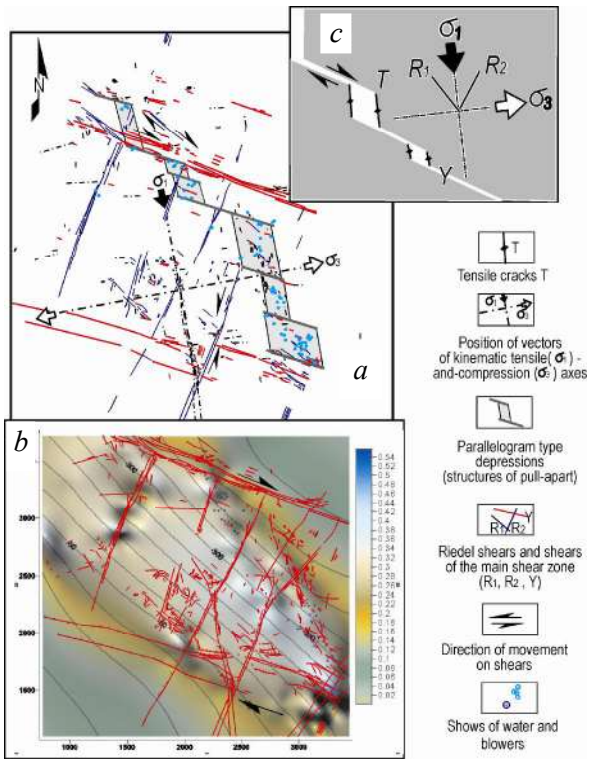

Fig. 3. The results of range filtering of orientations of tectonic faultings formed in the contour of the shear zone under the conditions of dextral shear activation in the mode of transtension are supplemented with: the rose-diagram of the orientations encounter (*a*); the result of morphotectonic analysis of bed l_3 (*b*); and the scheme of forming the structures of the pull-apart: the subsidence beams (*c*)

Compression duplexes are tectonic formations represented by a system of break surfaces that overlap each other on the principle of laying tile and are accompanied by reverse faults, thrusts, and flexural bends, and at deep horizons merge with the main thrust.

Tensile duplexes include strike-slip pull-apart structures (stretched to the sides of the shear- expansion). The latter are parallelogram-like depressions, in which the boundary of diagonal orientations is represented by oblique shears, and the submeridional boundary is represented by separation and faults, which have a characteristic stepped configuration.

That is, returning to the purpose of these researches, while identifying the relationships of shear zones impact on GDP formation in coal sediments it is necessary, first of all, to identify zones of above-rapture structures of deep faults, shear duplexes of compression and tension, and their formation.

The use of morphotectonic analysis in this work, which is to search the structural ordering of the relief of structural surfaces to some extent reflects the relationships of the general tectonic structure of the sedimentary cover, in which the gradient structures characterizing the degree of contrast of changes in the depth of subsidence of the surface as well as anomalies of the general structural plan are of particular importance, which made it possible to identify small subsidence depressions in the relief of the coal bed l_2^1. The result of identifying the gradient structures (Fig. 3, *b*) with a characteristic system of isohyps bends (differences in relief fragmentation) in the zone of the stepped structure indicates the contrast of changes in the depth of immersion of the surface under consideration.

Interpretation of structural and geological data of the analyzed mines allows us to state that there is a clear complementarity of the fault network within all mining allotments, i.e. the correspondence of the orientations of the disturbances formed in the contour of the dextral shear zone (Fig. 2). At the same time, the zone of tensile duplexes located in the chain, which have a characteristic broken-step configuration at the "Dobropilska" mine (Fig. 3), to which hydro- and blowers activation is confined, and in the area of which tension cracks and faultings (parallel to the main shift zone) are most developed, develops due to local strike (transtension), which is consistent with the known echelon-like "pull-apart" schemes that determine the "selectivity" of hydro- and blowers activation. The latter is associated with the decompression of rocks in the pull-apart area, where there is an increase in piezometric pressures due to displacement and migration of water from deep compression-stress horizons in a heterogeneous layer, as well as the existence of pressure waves arising from water percolation [Bulat, et al., 2007] into the pores after the methane emission.

The revealed relationship agrees with the theory of activation of convective flows in tensile zones, which from the viewpoint of thermomechanical equilibrium disturbance are characterized by increased permeability for diffuse-filtration deep underflows of water-gas fluids and gas jets [Zankevich, & Shafranskaya, 2009] and the formation of thermally anomalous regions. In particular, the formation of a thermally anomalous region to the north of the city Pokrovsk (Krasnoarmiisk), including the research site, at the intersection of the Mariupol-Kursk lineament, zone of Volnovakha-Lozova faultings and the transverse deep faulting in the zone of local tension, where increased heat fluxes are recorded, noted in [Privalov, 1998, Privalov, et al., 2007].

Originality

For the first time, a study of structural-kinematic relationships in the formation and development of shear dislocations of the Krasnoarmiiska monocline of Donbas and their impact on the formation of GDP zones was carried out. It based on the developed digital model of the actual tectonic disturbance of the rock mass on the example of a group of mining allotments at mines "Pioner". "Sviato-Pokrovska" (till 1999 "Krasnoarmiiska-Zakhidna"), "Chervonolymanska" and

"Dobropilska" with the use of modern means of information processing and its visualization. It is established for the first time: 1. Subparallel disjunctives of the NE orientation (15–30°), regardless of morphology, are as the boundaries of parallelogram-like blocks, forming either scaly packets or packets of fault scarps (depending on the morphology of the faultings), limited by the strike of the fault planes of N–NE and SW fall; in the case of scaly packets in the orientation of the fall of the fault plane it is dominated by the E–SE direction; the faultings limiting the fault scarps are characterized by the opposite WN direction of the fall; 2. Faultings of SE orientation are morphologically represented by shear-thrusts and with depth change, not only the angle of incidence from 35° to 85° but also the azimuth of strike (from 20–25° to 50°), forming a fanlike feathering of the main faulting in the plan. Their azimuthal orientation corresponds to the orientation of a wide (up to 270 m) zone of plicative dislocations on the eastern wing of the mining allotment at the "Pioner" mine; in the northernmost part of the analyzed area ("Pioner" mine), the discontinuous anticlinal structures of the NE orientation in the lying wings, which flatten out to the surface of the thrusts, have developed significantly. 3. Medium-amplitude faultings of NE orientation are localized in the zones adjacent to high-amplitude thrusts of N–NE strike (Krasnoarmiiskyi, the northern part of Dobropilska). In this case, the medium-amplitude thrusts of the above orientation are typical for the northernmost part of the analyzed area (mine "Pioner"). With the distance to the south-eastern direction, in the central part of the block (between the high-amplitude thrusts of the W–SW strike), the medium-amplitude thrust structures give place to faults ("Dobropilska" mine); in the south-eastern part of the analyzed area ("Chervonolymanska" mine), there are no NE faultings of orientation at all. 4. Breaks of various morphology are represented not by a single fault plane but by a series of disturbances on all stratigraphic horizons, which create a zone of the faulting formation – a vertical "tectonic strip". 5. In the south-eastern part of the mining allotment ("Pioner" mine), a duplex of compression (transpression mode) was found, it is expressed by a folded system (F), up to 287 m wide and fragments of sloping, changing the strike of the Novoiverskyi thrusts. 6. The zone of tension duplexes located in the chain, having a characteristic broken-step configuration at the "Dobropilska" mine, to which "wet blowers" are confined, and in the area of which the tensile cracks and faultings parallel to the main shear zone are most developed, develops due to local extension (transtension). It was proved for the first time that the paragenesis of deformations in the study area corresponds to the shear field of tectonic stresses (horizontal position of the main kinematic plane of compression-tension) with north-northwest direction of compression and east-northeast tension, in which fault-hear displacements occur.

Practical value

The established relationships of the impact of shear tectonics on the formation of GDP in coal beds are important both by clarifying the mechanism of tectonogenesis and the nature of "structural windows" formation in the form of en echelon zones of tension, and by the possibility of using additional prognostic criteria for searching for accumulations of free methane and its sudden manifestations (GDP) in coal beds. Since traditionally accepted criteria (increased methane content due to the optimal degree of coal metamorphism; occurrence depth; improved filtration-capacity properties of host rocks do not always allow assessing the prospects of a local area regarding the presence/absence of coalbed methane accumulations and its sudden manifestations without understanding the development of geodynamic events. Therefore, it is necessary, first of all, to focus research on the assessment of the stages of tectonic development of individual structural units of the region from the modern viewpoint. The application of knowledge of the relationships identified in the study at mining enterprises will reduce the cost for the struggle against dangerous GDP during the operation of the gas field, and reliably predict these phenomena.

Conclusions

The problem of hard-to-predict natural hazards of geological, hydrogeological, and geomechanical nature and related material and human losses in modern coal mining are characteristic in many mining enterprises of Donbas. Among the most dangerous factors of underground coal mining traditionally include GDP. For the effective choice of methods of their forecasting and prevention, it is necessary to consider the regularities of their localization. Sudden outbursts of coal and gas, blowers of geological origin are unevenly distributed over the seam area and represent differently oriented zones that are associated with both the orientation of tectonic faults and plicative structures and have a length of tens to several thousand meters along the strike and fall of coal beds. At the same time, the locality of GDP cannot be explained only by the presence of increased fracturing or its absence. Obviously, the leading role belongs to the conditions of the formation of tectonic forms in the tectonic stress field, which contributes to the change in the properties of reservoirs of gas-coal fields.

That is why the reconstruction of the geodynamic development of the shear dislocation zone (reconstruction of shear stress fields) of the KM and the identification of regularities of its impact on the formation of GDP in coal deposits is an important and urgent research task. The presented results of geometrization and the mechanism of tectonic disturbance within the KM allowed identifying spatially related geostructural

elements that develop kinematically consistent and interconnected with a characteristic internal structure and the corresponding regime of the dextral shear zone by structural paragenesis, lateral and vertical structural zonation. Analysis of the structural pattern and maximums of the encounter of orientations of small and medium-amplitude faultings on the roses-diagrams allowed to identify seven systems of disjunctives: synthetic right (R_1) and antithetic left (R_2) Riedel shears, which are symmetrical about the compression axis (σ_1) and have an orientation of 300–310° and 12–28° (respectively); tension cracks (T), which are parallel to the compression axis (σ_1) and oriented on azimuth 340–350°; synthetic shifts (Y) – the main shear zone – are expressed by the orientation of steeply dipping faultings (morphologically faults) along the strike of 280–290°; secondary synthetic shifts (P) are close to the latitudinal ones (270°) in orientation. This paragenesis of deformations in the studied area corresponds to the shear field of tectonic stresses (the axis of space shortening (σ_1) due to horizontal shear is oriented in azimuth 160–170° (340–350°), the axis of elongation (σ_3) is 70–80° (250–260) with a north-northwest direction of compression and east-northeast of tension, in which the shear-thrust displacements occur along the faultings. It is established that subparallel disjunctives of NE orientation (15–30°), regardless of morphology are as boundaries of parallelogram-like blocks, forming either scaly packets or packets of fault scarps (depending on the morphology of the faulting); they are limited in the strike by fault planes N–NE and SW fall; in the case of scaly packets in the orientation of the dip of fault planes are dominated by the W-SW direction, the faultings limiting the fault scarps are characterized by the opposite WN direction of fall. It is found that the faultings of SE orientation are morphologically represented by shear-thrusts, and with depth change not only the angle of incidence from 35° to 85°, but also the azimuth of the strike (from 20–25° to 50°), forming a fanlike feathering of the main faulting in the plan, the azimuthal orientation of which corresponds to the orientation of a wide (up to 270 m) zone of plicative dislocations on the eastern wing of the mining allotment at the ("Pioner" mine; in the northernmost part of the analyzed area ("Pioneer" mine); the near-faulting anticlinal structures of the NE orientation in the lying wings, which flatten out to the thrust surface, have developed significantly. In the south-eastern part of the mining allotment of the "Pioner" mine, a compression duplex (transpression mode) was found. It is expressed by a folded system (F), up to 287 m wide and fragments of sloping, changing the strike of the Novoiverskyi thrusts. A tectonic model of the formation of "structural windows" (the zone of tensile duplex chains with a characteristic broken-step configuration at the "Dobropilska" mine) in the transtension mode is proposed, which causes the GDP show ("wet blowers") in the areas of KM in the form of pull-apart of small subsidence kettles, which are formed under the action of a shear field of tectonic stresses was proposed. It is established that numerous emissions of coal and rocks and bowers, which were recorded in the areas of mines (from west to east): "Bilytska", "Dobropilska", "Chervonolymanska", O. F. Zasiadko, O. O. Skochynskyi, M. I. Kalinin, "Chervona Zirka", K. I. Pochenkov, V. M. Bazhanov, "Chaikino", "Luhanska", "Horetska", "Matroska" had a component gas composition with a high content of liquid hydrocarbons (such as condensate). Shows of heavy hydrocarbons (butane), hydrocarbon liquid (oil), aromatic hydrocarbons and bitumens were also recorded in these mines, despite the differences in the geostructural position of individual geological-industrial areas located on the border of the DSS.

This indicates the possibility of deep fluids influx with the subsequent redistribution of hydrocarbon gases in the rock mass as a result of the shear field of tectonic stresses in the zones of over-fault structures of deep faults. The obtained results allowed taking into account not only the problems of KM tectogenesis, but also to ask a number of questions related to increasing the accuracy for the effective choosing of forecasting methods of GDP.

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СТРУКТУРНО-КІНЕМАТИЧНІ ЗАКОНОМІРНОСТІ РОЗВИТКУ ЗСУВНИХ ДИСЛОКАЦІЙ ТА ЇХ ВПЛИВ НА ЛОКАЛІЗАЦІЮ ГАЗОДИНАМІЧНИХ ЯВИЩ НА ПРИКЛАДІ КРАСНОАРМІЙСЬКОЇ МОНОКЛІНАЛІ ДОНБАСУ

Мета. Метою роботи є реконструкція геодинамічного розвитку зсувної дислокаційної зони (зсувних полів напружень) Красноармійської моноклінали (КМ) Донбасу (Східна Україна) та виявлення закономірностей її впливу на виникнення газодинамічних явищ (ГДЯ) у вугільних відкладах. **Методика.** Для аналізу структурно-геологічної інформації застосовано методи цифрової геологічної картографії, гірничо-геометричного моделювання, геолого-структурного аналізу та структурно-геоморфологічного реконструювання. Використано комплекс методів статистичного оброблення даних про тектонічну порушеність – оцінювання частоти зустрічі азимутних орієнтувань методом роз-діаграм. Застосовано прийоми морфотектонічного аналізу вугільного пласта (математичний прийом виділення градієнтних структур). **Результати.** Запропоновано тектонічну модель формування пул-апартів у режимі транстенсії на теренах КМ (на прикладі шахти "Добропільська"), що зумовлює прояви ГДЯ (зокрема "мокрі суфляри") у вигляді малих улоговин просідання у зонах кулісного перекриття зсувів. Останні сформовані під дією зсувного поля тектонічних напружень (вісь укорочення простору (σ_1) внаслідок горизонтального зсуву орієнтована за азимутом 160–170° (340–350°), вісь подовження (σ_3) – 70–80° (250–260°). Поєднання облямовувальних Y та T розривів в умовах транстенсії, швидше за все, забезпечує газопроникність та водопроникність зони. Досліджено структурно-кінематичні закономірності формування та розвитку зсувних дислокацій КМ Донбасу. **Наукова новизна.** Вперше на основі розробленої цифрової моделі фактичної тектонічної порушеності масиву гірських порід на прикладі групи гірничих відведень шахт КМ досліджено структурно-кінематичні закономірності формування та розвитку зсувних дислокацій Красноармійського району Донбасу та їх вплив на формування зон ГДЯ. Вперше встановлено, що: а) субпаралельні диз'юнктиви ПнС орієнтування (15–30°) незалежно від морфології слугують межами паралелограмоподібних блоків, утворюючи або лускаті пакети, або пакети скидних уступів (залежно від морфології розриву), обмежені за простяганням скидовими зміщувачами Пн-ПнС та ПдЗ падіння; в разі лускатих пакетів у орієнтуванні падіння зміщувачів домінує С-ПдС напрямок, розриви, що обмежують скидні уступи, характеризуються зустрічним ЗПн напрямком падіння; б) розриви ПдС орієнтування, морфологічно представлені зсуво-насуваами та з глибиною змінюють не тільки кут падіння з 35° до 85°, але й азимут простягання (з 20–25° до 50°), утворюючи в плані віялове оперення основного розриву; в) розриви різної морфології представлені не поодиноким зміщувачем, а серією порушень на всіх стратиграфічних горизонтах, які формують зону розривоутворення - вертикальну "тектоносмугу"; г) у ПнС частині шахти "Піонер" виявлено дуплекс-стиснення (режим транспресії), виражений складчастою системою (F), ширина яких до 287 м, і фрагментами пологих Новоіверських насувів, що змінюють простягання; д) зона розташованих ланцюгом дуплексів розтягу, що мають характерну ламано-ступінчасту конфігурацію на шахті "Добропільська", до якої приурочені "мокрі суфляри", розвивається завдяки локальному розтягу (транстенсії); е) парагенез деформацій на досліджуваній території відповідає зсувному полю тектонічних напруг із північ-північно-західним напрямком стиснення і схід-північно-східним - розтягування, в якому по розривах відбуваються скидо-зсувні зміщення. **Практична значущість.** Встановлені закономірності впливу зсувної тектоніки на формування ГДЯ у вугільних пластах важливі не тільки уточненням механізму тектоногенезу та природи формування пул-апартів (кулісоподібних зон розтягу), але і можливістю використання додаткових прогностичних критеріїв пошуків скупчень вільного метану та його раптових проявів (ГДЯ) у вугільних пластах. Застосування на гірничовидобувних підприємствах цих закономірностей дасть змогу зменшити витрати на боротьбу з небезпечними проявами ГДЯ та надійно їх прогнозувати.

Ключові слова: Красноармійська монокліналь; транстенсія; пул-апарт; зсувна зона; ГДЯ; суфляри; парагенез; скидо-зсувні зміщення; кулісне перекриття; сколи Ріделя.

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