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FOLDING AT INVERSION OF PALEORIFT SEDIMENTARY BASIN (ON THE EXAMPLE OF DNIEPER-DONETS AULAKOGEN)

The article focuses on the formation mechanisms of fold's diversity of sedimentary basin inversion. They are investigated on the example of structures of the Dnieper-Donets paleorift system. To achieve this aim we systematized structural and lithofacial data of the Dnieper-Donets basin and Donbas; used numerical modelling to establish the regularities of deformations within lithosphere and sedimentary cover in collisional compression setting. It is shown that the formation of main folding styles as discontinuous (intermittent), transitional and continuous (full) is accompanied by characteristic features of the cover. In this respect, we formulated the basic dependence principle of folding from lithofacial and lithogenic factors, which defined different mechanical properties of sedimentary cover complexes (the lithomechanics principle). Modelling results confirm prime significance of horizontal compressional conditions of basin's folds development. Moreover, the sedimentary basin plays the role of independent deformation attractor in the lithosphere. The main conclusion is that the transitional fold paragenesis of Donbas with crest-like Main anticline may be the result of particular strength's distribution, i.e. axial weak zone and competent layer of variable thickness with central minimum. Main anticline formation mechanism is complex. It includes vertical, axial-parallel viscous-plastical flow with distant bending. It is shown that intermittent folds (uplifts) of the Dnieper-Donets basin may be a result of sedimentary cover compression with a random combination of weakened and strengthened zones. On the contrary, full folding of East Donbas and the Karpinsky ridge corresponds to a bending mechanism of competent layer compression of constant thickness. For the first time we obtained the evidence for the folding inversion mechanisms within Dnieper-Donets aulagogen (including Main anticline), which was problematic for many years. Folding is directly related to peculiarities of sedimentary basin infilling within formulated principle of lithofacial mechanics. With necessary caution, the study offers the results of modelling and conclusions for explanations of fold development within intracontinental basins and marginal folded belts. Practical significance**.** Numerical modelling and elaborated principles of analysis may be used in reconstructions, numerical investigations of fold structures (uplift) within inverted basins, as well as in prognosis of ore, oil-and-gas deposits.

Key words: numerical modelling; sedimentary basin inversion; folding mechanisms; Dnieper-Donets aulacogen; Main anticline; lithofacial structure.

Introduction

Diverse inversional structures are formed by old rift basins composed of submerged platform regions. Common conditions of horizontal lithosphere compression may be regarded as causes of their formation [Lobkovsky, et al., 2004]. Concrete mechanisms of folding and elevation formation remain generally under discussion. The problem is not resolved by the modern paradigm of fold-and-thrust paragenesis because it is not universal and may be restrictedly applied to the basin structures as a particular case. More possible situation is when cover and basement deform together and are not dramatically separated by detachment. In general, problems of fold formation (within platforms or fold belts) may be effectively solved on a base of "out-of-faults" models. There is no a more mythologized conception in tectonics than "fault". Such an approach to basin folding analyses is presented in modern numerical investigations [Jarosinski et al., 2011], but processes are usually reproduced on the scale of the lithosphere. To satisfy requirements of basin structural analyses, models may include concrete established structural-material inhomogeneities of cover, which promotes localization of deformation and folding. The Dnieper-Donets paleorift (the Dnieper-Donets basin and Donbas with the Karpinsky ridge) [Gavrish, 1974; Chekunov, et al., 1992] may be considered as the most appropriate object for such consideration. It demonstrates the full spectrum of folding in V. V. Beloussov classification [Belousov, 1986], as possesses exceptional length and linearity. It is intermittent within the Dnieper-Donets basin, transitional – in Donbas, and to the east it becomes continuous, according to "geosyncline" type [Popov, 1963; Khain, 1977; Maidanovich & Radziwill, 1984; Volozh, et al., 1999; Saintot, et al., 2003; Стовба, 2008]. Donbas has a particularly significant position in this system and interpretation of inversional development. This defines a main task of this article which continues our earlier works on modelling tectonic evolution of the region [Gonchar, 2018, 2019].

Aim

The study is based on a position about structure genesis of Donbas in the common horizontal compression setting [Raznitsyn, 1973; Yudin, 2003; Patalakha, et al., 2004; Bartashchuk & Suyarko, 2020]. There is a crisis in points of view concerning the forming mechanism of Main anticline (MA). Its correct interpretation could become the key to understanding the tectonic process as a whole [Patalakha, et al., 2004]. According to V. V. Beloussov, MA is the brightest example of the type of crest-like transitional folds, as it possesses exclusive characteristics (the dominant position in structure, significant extent, constancy of distinguishing properties, ore control, etc.) [Popov, 1963; Nagorny, V. N., & Nagorny, Yu. N, 1976; Saintot, et al., 2003]. There are a number of hypotheses of the MA origin, namely: vertical basement movement[Tkachenko, 1976], crust underthrusting during closure of basin [Yudin, 2003], salt diapirism in common transtensional regime [Saintot et al., 2003], laminar flow in compression conditions [Patalakha, E. I. et al, 2004], gravitational ascent of the sedimentary material [Gordienko, V. V. et al, 2015]. As far as it is known, none these hypotheses has got its model confirmation. Modern situation of uncertainties seems to be due to the overestimation of the fold-and-thrust model possibilities which are considered as a modern paradigm of folding [Yudin, 2003]. According to geophysical data, it is not applied to structures of Donbas that saved autohton position [Stovba, 2008]. A necessary response of time may be a return to the classical interpretations of the folding mechanics as a manifestation of the competent layer bending, as well as simultaneous or superimposed flow, based on computer simulation. Due to the obvious complexity of the problem, the proposed attempt is rather a protomodelling one. It is designed to derive general principles of structure reproduction of inversion basin tectonics. In it, the origin of the folded spectrum agrees with the relevant (predicted) lithofacial filling of various depression segments from the geotectonic position, corresponding to the composition of rocks with mechanical (strength) section properties.

Methods of investigation

1. The comparative analysis of the main folding forms with features of lithofacial cover composition of the Dnieper-Donets basin and Donbas according to the published data [Popov, 1963; Maidanovich, Radziwill, 1984; Volozh, et al., 1999; Yudin, 2003; Stovba, 2008], as well as results of the author`s previous research [Gonchar, 2018, 2019].
2. Numerical modelling by finite element method in the conditions of elastic-viscoplastic medium, which reproduces the collisional compression deformation effects on the scale of the lithosphere and sedimentary basin (without mass forces). Plastic deformation is described on the basis of Coulomb criterion within the theory of a plastic flow (associated law) [Bugrov, 1974]; the study considers elastoviscous properties on a preplastical stage using relaxation modules [Fadeev, 1987].

Results

I. Features of folding structure and the lithofacial preconditions within Dnieper-Donets paleorift

Dnieper-Donets paleorift, with its extension beyond the East-European craton in the form of the Karpinsky ridge [Khain, 1977; Maidanovich, & Radziwill, 1984; Volozh, et al., 1999; Stovba, 2008] underwent repeated tectonic processes. The paleorift includes all basic folding types within the general morphological classification of V. V. Belousov [Belousov, 1986]: intermittent, characterizing the platform structures; continuous (full) with geosyncline affiliation; and transitional type is between them – within the basic part of Donbass and SE terminations of the Dnieper-Donets basin (Fig. 1). The transition complex consists of an axial ridge-shaped Main anticline framed by flat synclines and anticlines of the inversion initial stage. It does not include small folds of the NE and NW frame of Donbas, having late, imposed character [Raznitsyn, 1976; Bartashchuk & Suyarko, 2020]. Typical structures of the described sequence are shown in the sections (Fig. 2): the Dnieper-Donets basin folds, belonging to the intermittent type (A); the MA and surrounding in the jointing area of the SE Dnieper-Donets basin and NW Donbas (B); MA as a part of a transitional complex on a profile DOBRE (C); complete folding of East Donbas, where MA loses its dominant identity (D); and the complete vergent folding of the Karpinsky ridge (E).

Within the clear formal classification framework there is a complex problem of establishing formation mechanisms of the entire folded structure spectrum, which is most acute in the situation with MA. Its distinctive features motivate researchers to deny external compression and confirm another folding mechanism. Thus, it has been believed that poorly deployed, flat synclines do not allow recognizing horizontal compression as the main cause of MA [Tkachenko, 1976; Gordienko et al., 2015]. As a consequence, the responsibility for its formation rested on the vertical foundation movements [Tkachenko, 1976], or on the advection of sediments due to gravitational instability [Gordienko et al., 2015]. However, deep sections do not allow any significant influence of the foundation movements (see Fig. 2, C).

The question on realization of gravitational instability is more complicated and is not considered in this article. Although it is possible to note that gravitational deposit unloading and compression in depot centres should be accompanied by simultaneous removal and their stretching along the sides of the depression that it is not observed. Other researchers do not agree vergents with the notion of considerable movement of a sedimentary cover above the basement (that is, with the concept of a cover thrusting) [Belichenko, et al., 1999] because of symmetrical structure and lack of MA. Compression, in their opinion, should be associated with the movements of the basement fault system coinciding with the fold axis. The MA marks an axial line of Donbas, and, according to many researchers, this is the reason for its formation. In [Saintot et al., 2003], the median position of MA is regarded as indication of its development along the rift axes. However, the transtensional conditions, offered by the authors, cannot be accepted to suit tectonophysical data [Belichenko, et al., 1999; Gonchar, 2019]. According to V. V. Gordienko, the anticline axial position is connected to the emerging compensating gravitational sliding of deposits on slopes [Gordienko, et al., 2015]. E. I. Patalakha was the first to present rheological meaning to the MA axial position, defining it as a marker of weakened thinned crustal “neck” (consequence of rifting). Having given a maximum deformation in compression, the researcher had specified a MA formation hypothesis by the concrete mechanism, i.e. a laminar flow [Patalakha, et al., 2004]. Some results of physical modelling data should also be noted. According to them, there is a large anticline folding in the central part of the compensated sedimentary basin due to the compression [Konstantinovskaya, et al., 2007]. However, it does not have MA properties in size and shape.

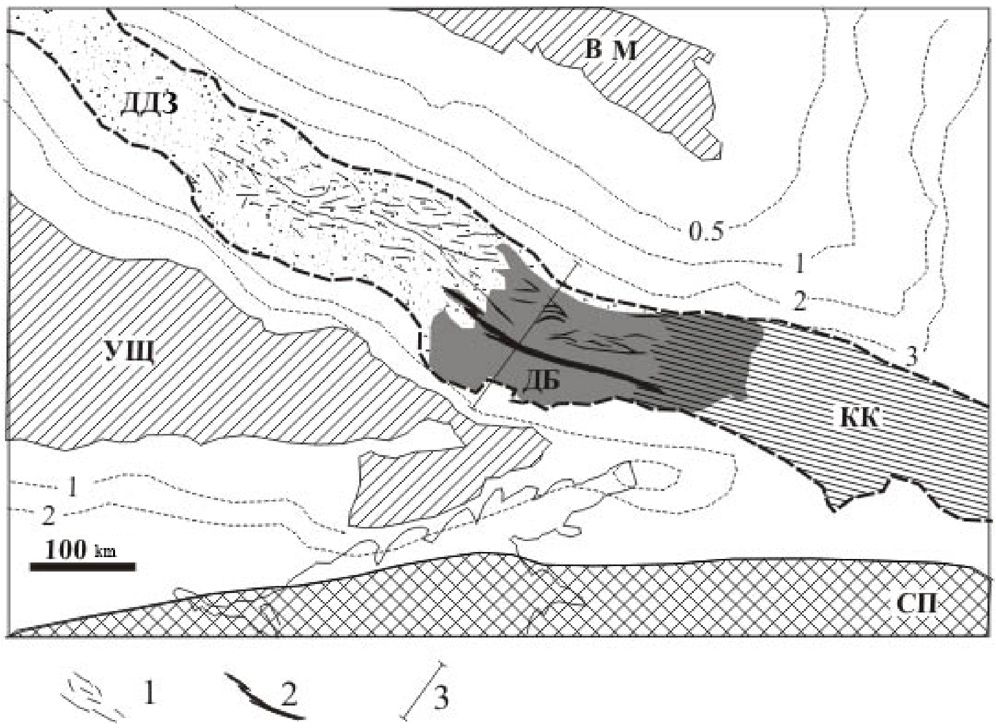

Fig. 1. The scheme of the East-European platform tectonical structure.

УЩ – Ukrainian shield; ВМ – Voronezh high; ДДЗ – the Dnieper-Donets basin; ДБ – Donbas; КК – Karpinsky ridge; СП – Scyphian plate. Isolines show Phanerozoic platform cover thickness: 1–2 – strikes of fold axes (1 – discontinuous folding, 2 – the Main anticline [Popov, 1963; Subbotin, et al., 1977; Stovba, 2008]), 3 – location of the DOBRE profile [Stovba, 2008].

Little attention is paid to the fact that the MA has also unequivocal longitudinal tectonic binding, practically coinciding with borders of the Donets coal basin. This was indicated by I. A. Majdanovich and A. J. Radziwill: “The Donets basin in the regional plan is the vast area of transition from the geosyncline parts of the Don-Dnieper depression to its platform part, and this intermediate position of Donbas defines its tectonic individuality …” [Maidanovich, Radziwill, 1984, p. 29]. Earlier, A. Ja. Dubinsky indicated that paralyc formation of the Donets zone could be considered as an area of exclusion of the flysch formation extended to the east [Dubinsky, 1982]. These definitions bring to the forefront of tectonic analysis the lithofacial factor of the Donbas folding genesis. These factors are of great importance, as they define the presence of coal that could influence the formation of structure transitive complex, i.e., lithofacial and lothogenic basin characteristics (Fig. 3A). The composition of the basin sedimentary filling could (and should) directly determine the deformation (strength) properties of the section. First of all, it could define the axial position of the deformation concentration (the MA site), due to the minimum strength of rocks. To confirm this, we can use a quantitative paleo-deep profile, built on the basis of history studies of SE of the Dnieper-Donets basin [Gonchar, 2018] (Fig. 3B, II).

Sedimentation depths increase in syn-, postrift basin is consistent, though it is variable in the vertical. It occurs from boards in the direction of slopes and further to the depression depocenter. Such a change in depths also means consecutive change in facies, i.e. from continental to coastal, from shallow sea to moderate and deep-water facies. Virtually the entire inner part of the sedimentary basin is projected in this model as an area filled with relatively deep-water deposits, with the exception of the upper layer, which corresponds to the stage of late Carboniferous sedimentary compensation. The expected change of rock composition according to this depth transformation is as follows: change of rocks with predominance of coarse-grained, sandstone and limestone in coastal and shallow facies rocks with significant specific weight or predominance of clay in the open sea and marked depths. The axial zone of the post-strip sedimentary basin is characterized by maximum sedimentation rates. It can a priori be recognized as an area with reduced lithogenetic changes in rocks compared to riparian areas. This lithofacial profile leads to a corresponding forecast of the rock strength of the postrift sedimentary basin, which enters the process of tectonic inversion (i.e. deformation). Coastal on-board areas and the upper part of the central sedimentation area form a layer of the increased thickness decreasing to the axial depocenter. These areas are characterized by the prevailing coastal-marine and continental sedimentation conditions.

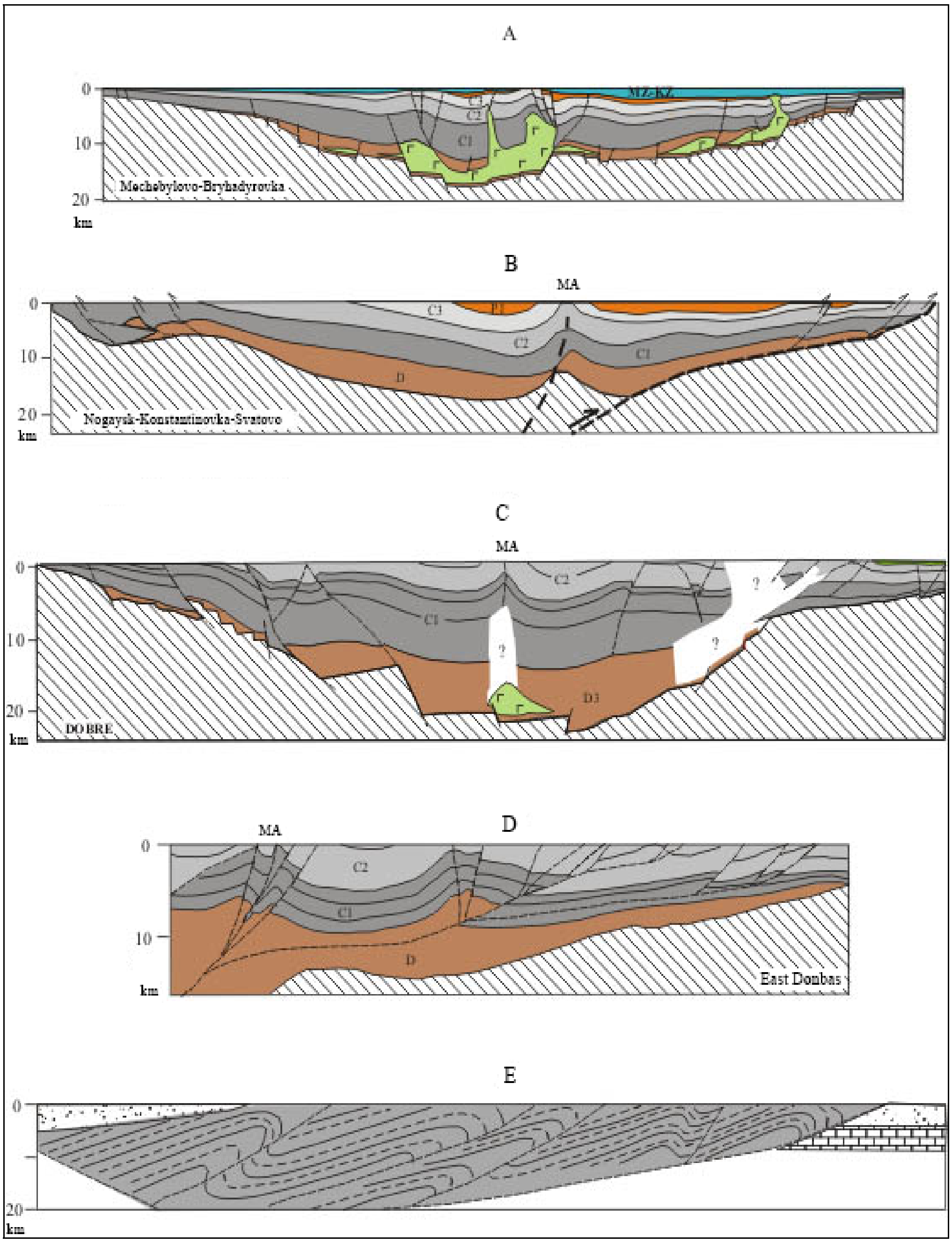

Fig. 2. Seismogeologycal cross-sections of the SE Dnieper-Donets basin (A) [Prospects for the development.., 2013], Donbas (B-D) [Yudin, 2003; Stovba, 2008] and the Karpinsky ridge (E) [Volozh, et al., 1999]:

Symbols: inclined hatch – basement, sign “г” – salt rocks.

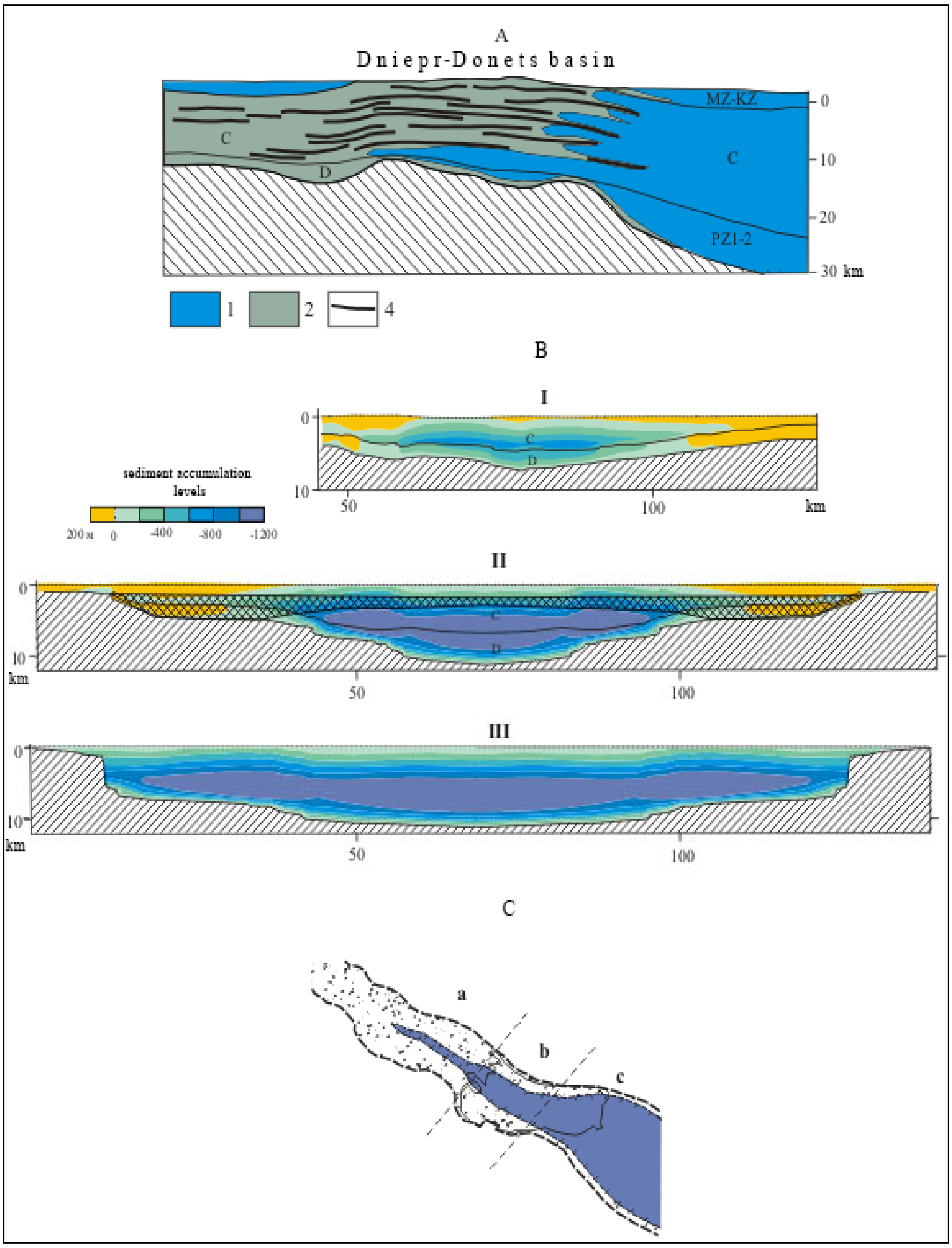

Fig. 3. Data concerning lithofacial structure of the Dnieper-Donets paleorift system:

A – averaged longitudinal profile of the Dnieper-Donets basin – Donbas – Karpinsky ridge transitional region (after [Maidanovic, Radziwill, 1986]); 1–3 – deposits: marine (1), coastal (2), coal (3). B – sedimentation depths models in central (I), south-east (II) parts of the Dnieper-Donets basin (after [Gonchar, 2018])) and hypothetical profile of deep sea trough of “geosyncline” zone (III). C – hypothetical scheme of the boundaries of the deep-sea marine path within the paleorift and the corresponding distribution of inversion folding types: a – intermittent; b – transitional; c – complete.

At depth, it is replaced by the central deep zone of less strong, weakened rocks. The reinforced layer as the upper border should have a limit of stable lithification (~ 3 km). V. S. Popov, emphasizing the dependence of the basic structural forms on an initial contour of a deflection, marked the general thickness reduction of coal deposits from the centre to periphery [Popov, 1969]. The researcher also indicated a decrease in the degree of coal metamorphism in the vaulted zone in comparison with the wings of the MA folds [Popov, 1963]. This feature, apparently, should be applied to other rocks. It is noticed that the sandstones are common in the area of low-grade coal metamorphism. They have mechanical strength, usually up to 200 kg/sm^2, but in the field of anthracites up to 600–2000 kg/sm^2. Later mapping data shows a sharp decrease in the grade of coal near the axis of the Gorlovka part of MA [Gordienko et al., 2015].

We come to the conclusion that the lithofacial changes, which occur both along the extension of the basin, and in a direction from boards to its axis, accompany change of characteristic folding forms. Thus, the emerging inversion structures are due to the appearance of the initial lithofacial inhomogeneities, inherent in a cover. Accordingly, the study formulated the basic assumption about the dependence of the folding process on the lithofacial and lithogenetic factors that determined the strength properties of the sedimentary stratum; the role of basement refers to the second plan, the role of "faults" refers to the third plan. In case of the Main anticline, strength model of the compensated sedimentary basin (Donbas and SE Dnieper-Donets basin) can be represented on the basis of two components of lithofacial content: 1) the central weakened zone (rocks of deep-water genesis); 2) the strengthened layer of variable thickness with a minimum in the centre and along the axis of the basin. It is a structure of the "arch bridge" type, connecting the two sides of the depression (Fig. 3B). The principal lithofacial sections of the cover can be represented on the basis of sedimentation depths models outside the coal-bearing Donbas transition region to NW (the Dnieper-Donets basin) and to SE (the Karpinsky ridge) (Fig. 3B, I). The typical cross-section of the Dnieper-Donets basin should be dominated by continental, coastal and shallow-water deposits. The lens of deep-water genesis rocks (up to 400-600 m) can be anticipated only in the central part. Contrary to it, the characteristic profile of the Karpinsky ridge is represented as a totally sea deep-water trough (Fig. 3B, III). Accordingly, it is possible to assume that intermittent (platform type) folding of the Dnieper-Donets basin is a result of lithomechanical "arbitrariness" in the cover. It presupposes lack of regularity in the rock composition and change of their properties that involves irregular strength variations. On the other hand, the typical "geosyncline" folding of the East Donbas and Karpinsky ridge displays extremely ordered strength characteristics, ideally alternations of competent and incompetent layers of constant thickness from a board to a board, provided by stable conditions of sea sedimentation.

Thus, if we ask the question concerning the main factor in the inversion process control by the lithofacial content within the entire Dnieper-Donetsk paleorift, we must first talk about the deep sea trough and the degree of its "implementation" in basin structures (Fig. 3C). Reduction of sea sedimentation influence both in space and time restricts the strength unification and this is probably gradual. The influence balance of "chaotic" continental-coastal and ordered marine sedimentation is formed within some transitional areas. The central Donetsk segment is the inversion reflection of such area.

II. Tectonic inversion models of sedimentary basin at compressional conditions

Specifics of deformation in lithospheric scale. A primary role should be given to lithospheric modelling of inversion. Because of insufficient detail, however, the lithospheric model is intended to reflect only the deformation effect (long-range) of the collision on the continental lithospheric plate containing the paleorift sedimentary basin (Fig. 4). The latter is considered to be heterogeneous in terms of properties. It contains a central weakened zone at the cover basement, which takes into account the substantiated presence of deep-water deposits in the lower part of the Donbas and SE of the Dnieper-Donets basin. The specified medium is elastic and viscoplastic. Simple exponential dependence of viscosity on temperature was used for the mantle. Effective viscosity of brittle-plastic transition was applied for a crust [Trubitsyn, 2012]. The lithosphere thickness under the basin was defined as a function of postrift cooling duration, equal to 95 million years (early Carboniferous– the beginning of the Middle Permian).

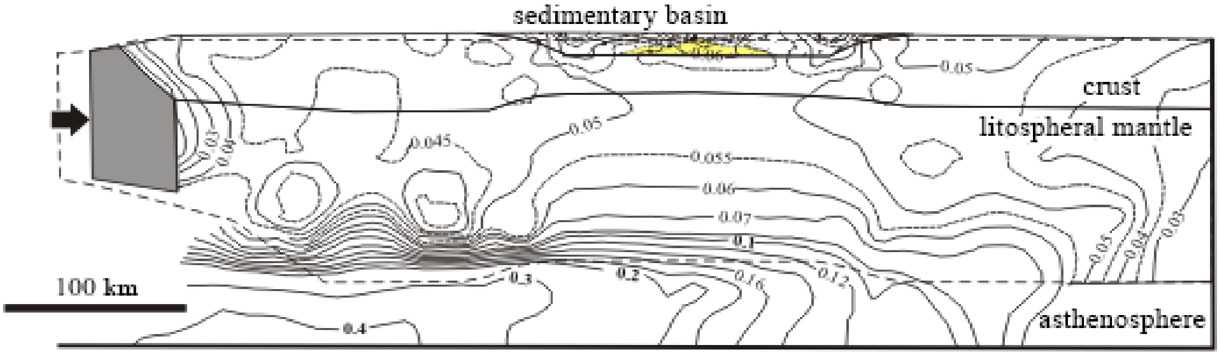

Fig. 4. Model of collisional deforming continental lithospheric plate, which contains paleorift basin.

Isolines mark distribution of equivalent deformation.

The depression cumulative effect should be considered as the main result [Gonchar, 2019]. It attracts and differentiates the deformation and does not require any additional conditions (e.g., crustal faults or detachment). Within the crust and lithospheric mantle, the deformation is distributed more or less evenly with a tendency to increase in the lower lithosphere. This corresponds to the condition of fixing the asthenosphere layer sole. Cover deformation is characterised by displaying three maxima at the top of the section. The average maximum caused by the presence of the weakened zone provides the manifestation conditions for MA and the central uplifts of the Dnieper-Donets basin. On-board equal deformation maxima also correspond to the general nature of the deformation distribution in the cross sections. This is especially true for the maximum deformation of the cover opposite to the collision direction, which corresponds to the increase in folding within the north-eastern flank of the postrift depressions (see Fig. 1).

Cover deformation. Experiments on deformation of the sedimentary basin cover allowed us to work out the basic schemes of formation of intermittent, transitional (with axial ridge anticline) and complete folding. (Fig. 5). Equal final displacement of the left side wall was used for isosceles (depth – up to 10 km, length – 200 km), but different in properties models. The starting point is a model with homogeneous strength properties (Fig. 5, I). A generally uniform rise of the cover is formed as a result of compression. There is a symmetrical distribution of the deformation maxima at a depth near the slopes of the depression. In addition, relative elevations are formed above the maxima along the edges of the inversion orogen. These structures can be considered as prototypes of intermittent folding. Despite its simplicity it is possible to see similarity on some deep seismic sections [Brun, & Nalpas, 1996]. This result is close to the one obtained in [Jarosinski, et al., 2009] for the initial stage of inversional process.

Introduction of the central weakened zone to the model completely reformats the inversion picture. There is a median uplift and an axial maximum of deformation at depth (model II in Fig. 5). At the same time there are no on-board maximum deformations at the cover base as in the first model. The cover edge zones over boards of the depressions are characterised by a minimum deformation and, accordingly, the rise within them is not formed. Apparently, the reason for this is the integral strengthening of the section, which contributes to the foundation rocks. This effect also distinguishes real sections of the Dnieper-Donets basin where folds are developed only in the field of maximum depression (see Fig. 2A).

The obtained data suggest that the intermittent folding (namely, the isolated uplifts of different scale and form) can be associated with the effects of localization, increasing deformation in a cover, caused by peculiarities of composition and structure. “The necessary” weakened zone location can explain the patterns observed in an arrangement of cover rise. For example, the axial strength minimum is suitable to substantiate the reasons for a series of median risings within the Dnieper-Donets basin; it is suitable for the explanation of the MA formation mechanism which will be later described. Another regularity that needs to be clarified is the attraction of the intermittent folding within the NE basin board (see Fig. 1). Basal weakened layer stretched from the centre to a right board can help to approach such a rise distribution in the model (Fig. 5, III).

The study presents a model with random distribution of deformation properties of the cover. It is a final step in the series reproducing folded structures of intermittent type (Fig. 5, IV). However, as in the previous case, it has a weakened basal layer in the opposite part of the basin. The Poisson’s value is a set varying within 0.15–0.45, the Yung`s modulus is $0.3–0.9·10^{10}$ kg/m^2, the viscosity is $1·10^{18}–1·10^{20}$ Poise. The corresponding deformation field gains a complex distribution character (of chaotic nature) of maxima and minima that affect the resulting rise location. In general, they tend to places of the increased deformation, but the area of slopes remains “forbidden” for them. This model seems to be the most suitable for reproducing the fold developed in the main part of the Dnieper-Donets basin. According to the anticipated sedimentation conditions (Fig. 3B), it must correspond to the weakly differentiated rock accumulation of continental, coastal and shallow genesis.

Manifestation of transitional type in SE part of the Dnieper-Donets basin and within Donbas folds should mean further change of sedimentation conditions with a separate zone of stable lithofacial regime. But introduction of only the axial weakened zone is inadequate in relation to the transitional fold morphology of Donbas (MA and its frames). In order to involve the bending mechanism, the strengthened (competent) layer of variable thickness is entered into a homogeneous cover. Its aim is more exact reproduction (more than 2000 m at boards and a minimum in the centre composing 110 m). Its set of properties as a whole corresponds to the parameters of crustal rocks, except for Poisson ratio varying in a range of the maximums values (0.495–0.498) which provides practical incompressibility. Presence of the competent layer with gradual reduction of thickness provides the minimum central strength. The reduction of the basin in this case leads to the localization of deformation and more intense uplift in the depression axial zone. The anticline fold acquires a distinct crest-like character, corresponding to the image of MA. In addition, it is possible to notice signs of bending of the competent layer on each side, specified by vectors of active descending movements. The obtained result gives fundamental answers to the question on probable mechanisms of both axial crest-like fold and its complete structural paragenesis (adjoining flat synclines and anticlines).

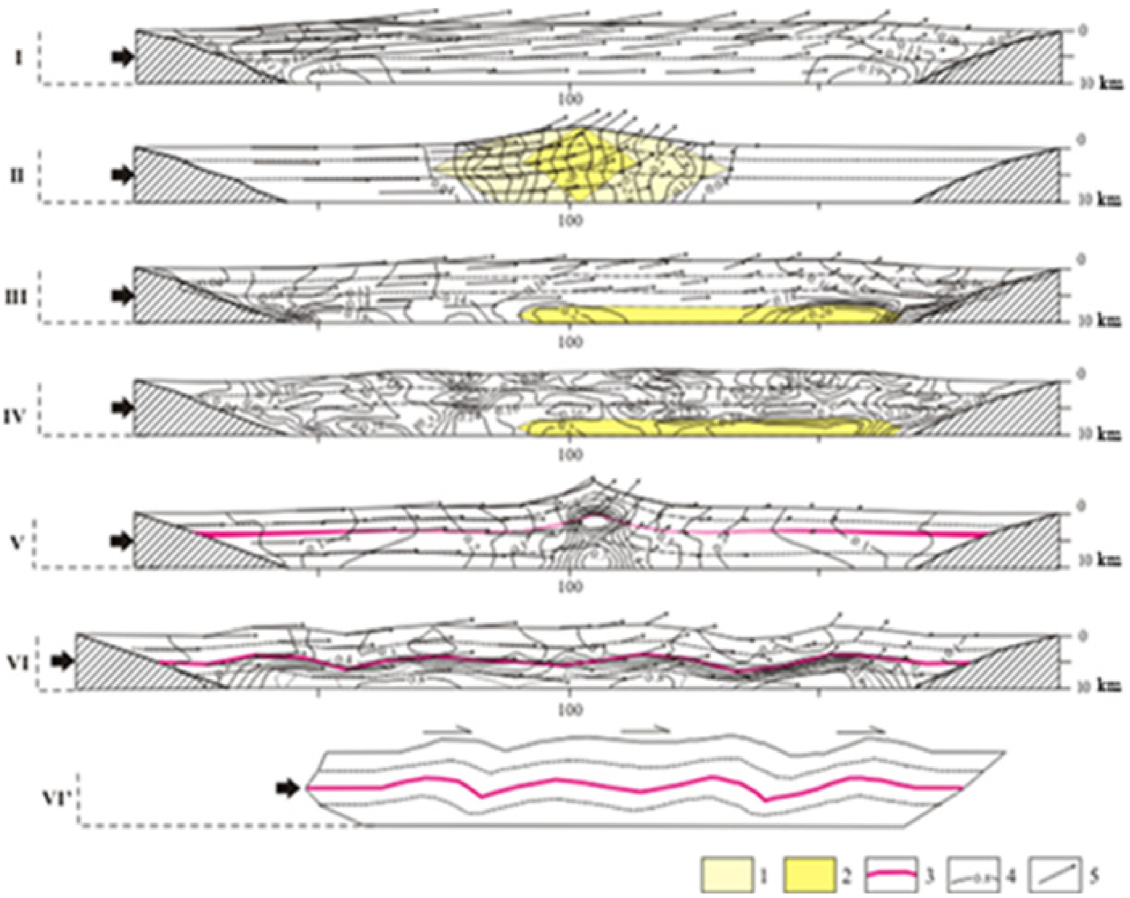

Fig. 5. Deformation distribution, displacement vectors in the horizontal compression models of the sedimentary basins with different structure:

I – homogeneous cover; II – with presence of weakened zones in the central part; III – with basal weakened layer; IV – with casual fluctuations of deformational properties of a cover (Poisson value, Yung modulus, viscosity); V – with presence competent layer of variable thickness (minimum in the centre); VI – model, which generates full folding in presence of competent layer with constant thickness; VI' – adduction of folding to asymmetric (vergent) type under imposing of no-coaxial horizontal flow. 1–2 – reduced strength zones; 3 – competent layer.

Hatching lines – positions of initial horizontals, thick lines – uplifts.

The model should be endowed with the properties of the section of deep-water trough basin (Fig. 3, B, III). Its aim is to reproduce continuous folding of the geosynclinal type, in accordance with the interrelation principle of the section lithofacial features with the structure arising during the inversion deformation. The stable character of sedimentation within all trough valleys should be reflected by the deformation model, which is close in essence to the mechanical stratigraphy principle. The change in the strength properties of the main rock complexes is taken into account only vertically. For this case, the basic model of inversion in our approach is as follows: a competent layer with a constant thickness of 100 m is introduced in a layer with low strength properties. Lateral compression of such a basin at the initial stage leads to a sequence bend (Fig. 5, VI), in which both anticlines and synclines are equally developed. The latter are active structures, as indicated by downward shear vectors. Accordingly, a specific distribution of deformation with the maxima located at the bottom of the section is visible. It distinguishes the type of folding both from uplifts in the intermittent type models and from the paragenesis of folded-sliding scales, where synclines are passive formations. Evolving in the conditions of horizontal non-coaxial currents characteristic of folded areas (compression and simultaneous horizontal shift [Gonchar, 2000]), the full folding also acquires the vergence characteristic of the Eastern Donbas and Karpinsky ridge structures.

Scientific novelty

Geodynamics and facies (conclusions concerning modelling inversional folding principles). The obtained modelling results and conclusions with the necessary caution can be offered as a basis for explaining the origin of the main folding morphological types according to V. V. Belousov [Belousov, 1986], connecting them with the lithofacial features of a basin cover with a corresponding geotectonic position. We raised the topic of using lithofacial data analysis in geodynamic research, following the basin modelling of the Dnieper-Donets basin and Donbas [Gonchar, 2018]. In questions of inversion deformation of various genesis and tectonic position basins, sedimentary facies should be shown so as they define mechanical rock properties. This provision, obviously, is very rarely used in practice in the study and basin fold reproduction. The problem of folding is rather complex, and there is no clear solution to it yet. The concept of fold-and-thrust paragenesis is within the modern paradigm. It is based on mechanisms of interaction of sheet and ramp (all subtleties of representtations are collected under the aegis of reconstruction techniques of the balanced cross section). The paradigm uses the concept of mechanical stratigraphy to allocate displacement surfaces and thrust sheets. In this work, we use two-dimensional analysis of deformation properties of sedimentary basin structures. It involves taking into account their lateral changes regardless of stratigraphic binding (see Fig. 2A). .

Thus, not stratigraphic but the *lithofacial mechanics* of the paleorift basin is the basis of inversion structure model analysis. Complexity of the further development of this concept is that much less attention is paid to the reflection of the lithofacial filling of the depression sections than to their stratigraphic description. The stratigraphic boundaries may not coincide with the lithofacial ones, especially within the transitional and intermittent folding zones. Folding in this approach is realized either in the form of a classical bend of the competent layer present in the section, or due to the viscoplastic flow (large coherent deformations) of the medium. Bending is realized at the earliest deformation stages and in the future can influence deformation redistribution; it is distinguished by synclines as active structures. The flow is localized within the deformation maxima and its influence (in the conditions of cover horizontal compression) leads to the formation of the uplifts separated by passive synclines. Numerical experiment showed that bending and flow can develop in close interaction

Formation mechanism of the Main anticline of Donbas. Summing up, it is necessary to return to the topic of experimental testing hypotheses of the Main anticline origin. Some theories, apparently, have already become a history, as, for example, basement block movements [Tkachenko, 1976]. Other theories can be still subjected to the experimental research. They include basin crust underthrusting [Yudin, 2003], salt diapirism [Saintot, et al., 2003] or gravitational pump of sediments [Gordienko, et al., 2015]. Now, based on the model of transitional folding formation (Fig. 5, V), it is possible to confirm E. I. Patalaha's idea about the main anticline as laminar (plane-parallel) flow folds, which developed under horizontal compression of the crust [Patalaha and et al., 2004]. In general, the formation mechanism of the whole paragenesis of the Main Anticline is complex. It includes both the axial flow and classical bending of the competent layer. The study clarified E. Patalakha's position on the reason of a laminar flow: it is caused not by the axial weakening of paleorift crust, but by the cover strength features. Accordingly, the maximum deformation along the MA axis observed in the sections [see Belichenko et al., 1999; Stovba, 2008] is explained not as a manifestation of fault tectonics, but as an effect of viscoplastic flow associated with folding.

To bring the obtained folded forms directly to the structures of Donbass, we have developed a model with some specification of the initial parameters (Fig. 6). In particular, the thickness variation of the reinforced layer was significantly adjusted with a minimum reduced to 15 m in the centre. However, by contrast, the values at the edges were increased. The small axial weakened area, which is more pliable than the cover, is below the minimum layer. At the initial stage of compression, the maximum deformation is mostly localized along the layer, slightly covering the bottom of the section in the axial part. The Main anticline with accompanying lateral hollow synclines and anticlines are formed as a result of shifting the wall by 32 km and significant compression of the cover. Comparison of contours of the latest model with profile DOBRE [Stovba, 2008] shows that their compliance seems to be satisfactory for the first attempt. Essential divergences appear in a southern half of the profile where real layer lifting is larger. It is also necessary to note a small inclination of a real fold axis to NE (small vergence which however varies from section to section (see Fig. 1). This is explained by the limited formulation of the problem, which did not take into account a number of factors, including the impact of lithospheric processes. In addition, the deformation deficit in the model leaves room for the manifestation of later (posthertz) inversion motions.

Lithospheric modelling tasks. Although the performed protomoding does not fully solve the problem of inversion tectonics, it indicates the direction of further research. Full modelling is associated with technical difficulties as it should be executed with necessary details for the basin, but in the scale of the lithosphere. Relatively recent works (for example, [Jarosinski et al., 2011]) still operate with homogeneous properties of the basin map, so the results are too general. At the lithosphere level, a number of effects beyond the considered basin models are revealed. There are processes of deformation distributions within the lithosphere, in particular, a warp of boards of the Dnieper-Donets basin and Donbass [Gonchar, 2019]. It is still unclear how such a warp will be combined with the Main anticline formation, and whether these processes are simultaneous or sequential. Clarification also requires a contribution to the mechanisms of later, superimposed deformations.

As all geophysical profiles show (Fig. 2), in the basis of folded Donbas, there are signs of neither essential (necessary for accommodation of considerable deformations), nor minimal thrust movements; the layers crumpled into folds lie on practically undeformed deposits that have preserved the features of the rifting depression.. In the very structure of folded strata, this is reflected in the absence of systemic vergence, folds are essentially symmetrical. In other words, the autochthonous structure of Donbass, which lies on its own foundation, is obvious [Patalaha et al., 2004]. Another thing is the folded structures of the NE and NW terminations of Donbas, but these areas are subject to separate consideration proceeding based on their specific tectonic position (marginal, interfaced to regional deflections, fold-and-thrust structures [Raznitsyn, 1976; Patalakha, et al., 2004; Bartashchuk, & Suyarko, 2020]). One can agree with the constructions of V. V. Yudin, who presents the presumed crustal thrust in the depth profile. The movements along the thrust explain the origin of the vergent folds and cover thrust of NE Donbas [Yudin, 2003] (see Fig. 1, B).

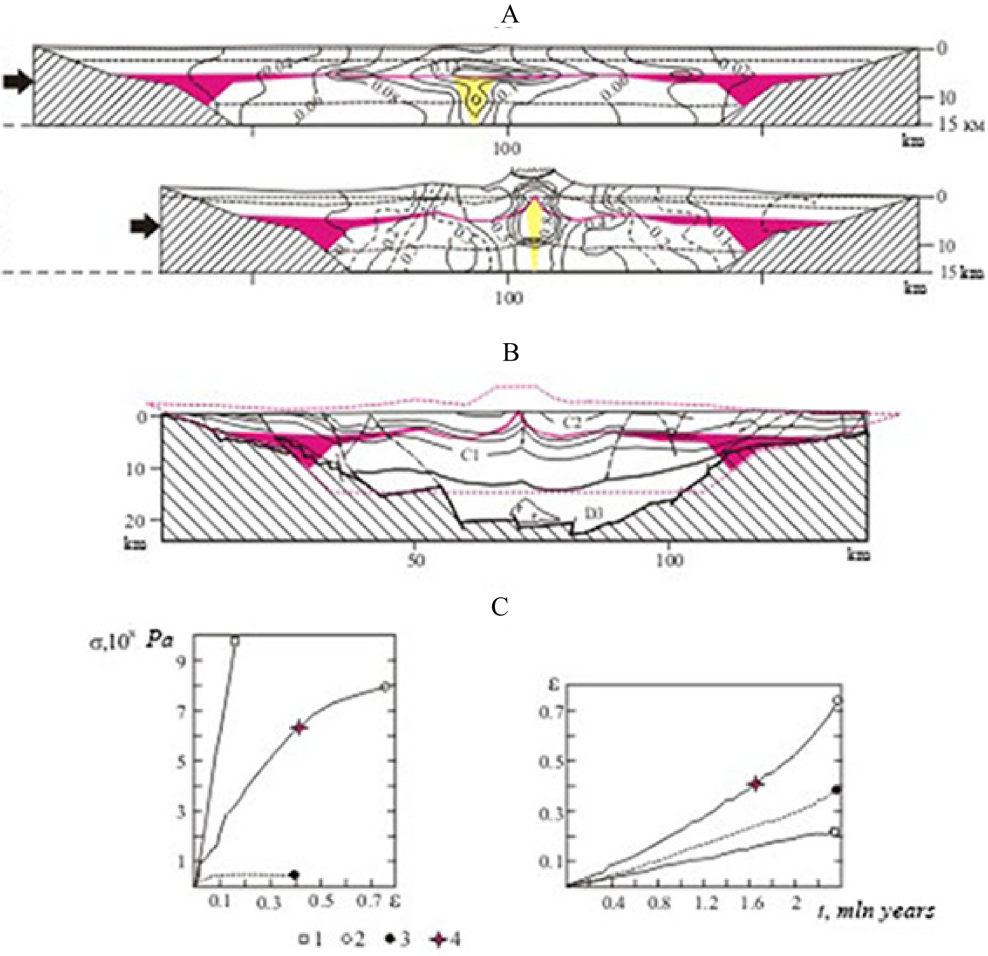

Fig. 6. Two studies of a model of the Donbas Main anticline (A); comparison of contours of model with profile DOBRE [Stovba, 2008] (B); curves of deformation development in different points of the model (C):

1–2 – competent layer in bedding fold and crest-like fold, respectively; 3 – medium surrounding; 4 – the point of beginning crest-like anticline.

Practical importance

The correct understanding of folding mechanisms and, moreover, possibility of numerical research (reproduction) of folds has practical value when working out the models connected with the processes of mineral deposition. This work showed (for example, the Main anticline) that modern numerical modelling is able to bring the received fold forms closer to those observed in nature. According to the principle of lithofacial mechanics, quite definite strength characteristics of a cross section are laid into this mode that unifies structural and material criteria of the prognosis. Profile differentiation of strength allows operating rheological rock properties more definitely, anticipating, in particular, places of advancing destruction and, accordingly, free space for ore-, and hydrocarbon accumulation.

References

Bartashchuk, O, & Suyarko, V. (2020). Geodynamics of formation of the transition zone between the Dnieper-Donets basin and the Donbas foldbelt. Tectonic style of inversion deformations. *Geodynamics. 29*(2), 51–65. https://doi.org/10.23939/jgd2020.02.051

Belichenko P. V., Gintov O. B., Gordienko V. V., Korchemagin V. A., Panov B. S., Pavlov I. A., & Usenko O. V. (1999). The main stages in the development of the Olkhovatsko-Volintsevo anticline of the Donbass in connection with its ore content (according to tectonophysical, geothermal and gravimetric data). *Geophysical Journal*, 21(2). (in Russian). https://scholar.google.com.ua/scholar_host?q=info:4AGxrCEra24J:scholar.google.com/&output=viewport&pg=69&hl=uk&as_sdt=0,5Belousov V. V. Structural geology. M.: Publishing House of Moscow. un-t, 1986. 248 p.

Belousov, V. V. (1986). Structural geology. M.: Publishing House of Moscow University, 248 p.

Bugrov, A. K. (1974). On the solution of a mixed problem of the theory of elasticity and the theory of plasticity of soils. Foundations, foundations and soil mechanics. No. 6, 21–23 (in Russian).

Brun, J. P., & Nalpas, T. (1996). Graben inversion in nature and experiments. *Tectonics*, *15*(3), 677-687. https://doi.org/10.1029/95TC03853

Chekunov, A. V., Garvish, V. K., Kutas, R. I., & Ryabchun, L. I. (1992). Dnieper-Donets palaeorift. *Tectonophysics, 208*(1–3), 257–272. https://doi.org/10.1016/0040-1951(92)90348-A

Dubinsky, A. Ya. (1982). On the ratios of the paralytic and flyschoid formations of the Carboniferous of the Donetsk-Borievksinsk fold system. *Soviet Geology*, (11), 94. (in Russian).

Fadeev A. B. (1987). The Finite Element Method in Geomechanics. Moscow: Nedra, 221 p. (in Russian).

Gavrish, V. K. (1974). Deep faults, geotectonic development and oil and gas potential of riftogens. Kyiv: Naukova Dumka, 160 p. (in Russian).

Gonchar, V. V. (2000). Finite and progressive deformations in non-coaxial flow: an application in structural analysis. Izv. universities. *Geology and exploration*. No. 6, 30–34 (in Russian).

Gonchar, V. V. (2018). Formation and sedimentary filling of the Dnieper- Donets depression (geodynamics and facies) in the light of new data of paleotectonic modeling. *Geofizicheskiy Zhurnal*, *40*(2), 67–94 (in Russian). https://doi.org/10.24028/gzh.0203-3100.v40i2.2018.128931

Gonchar, V. V. (2019). Tectonic inversion of the Dnieper-Donets depression and the Donbas (models and reconstructions). *Geofizicheskiy Zhurnal*, *41*(5), 47–86 (in Russian). https://doi.org/10.24028/gzh.0203-3100.v41i5.2019.184444

Gordienko, V. V., Gordienko, I. V., Zavhorodnya, O. V., Logvinov, I. M., & Tarasov, V. N. (2015). Donbass (geophysics, deep processes). Kyiv: Logos, 123 p. (in Russian). https://drive.google.com/file/d/1QrCyDa_JU065oJlJS748Mzdok8UJkNAt/view

Jarosinski, M., Beekman, F., Matenco, L., & Cloetingh, S. A. P. L. (2011). Mechanics of basin inversion: Finite element modelling of the Pannonian Basin System. *Tectonophysics*, *502*(1-2), 121–145. https://doi.org/10.1016/j.tecto.2009.09.015

Khain, V. E. (1977). *Regional geotectonics. Extra-Alpine Europe and West Asia*. Moscow: Nedra, 335 p. (in Russian).

Konstantinovskaya, E. A., Harris, L. B., Poulin, J., & Ivanov, G. M. (2007). Transfer zones and fault reactivation in inverted rift basins: Insights from physical modelling. *Tectonophysics*, *441*(1-4), 1-26. https://doi.org/10.1016/j.tecto.2007.06.002

Lobkovsky, L. I., Nikishin, A. M., & Khain, V. E. (2004). Current problems of geotectonics and geodynamics. Moscow. Nauchnyi mir, 612 p. (in Russian). https://www.elibrary.ru/item.asp?id=19475639

Maidanovich I. A., & Radziwill A. Ya. (1984). Tectonic singularities of coal basins of the Ukraine. Kyiv: Naukova Dumka, 120 p. (in Russian).

Nagorny, V. N., & Nagorny, Yu. N. (1976). Features of tectonic development of the Donetsk basin in the early Permian time. In: *Tectonics of coal basins and deposits of the USSR* . Moscow: Nauka 93–98 (in Russian).

Prospects for the development of shale gas and shale oil resources of the Eastern oil and gas region of Ukraine. Unconventional sources of hydrocarbons of Ukraine. Book V. Kyiv: 2013. 240 p. (in Ukrainian).

Patalakha, E. I., Senchenkov, I. K., & Trofimenko, G. L. (2004). The problems of tectonic-geodynamic evolution of the southwestern forelands of the East European Craton and its orogenic bordering. Kyiv: EKMO, 233 p. (in Russian).

Popov, V. S. (1963). Donets Basin: Tectonics. In *Geology of coal deposits and oil shales of the USSR* Vol. 1, 103–151. Moscow: GONTI (in Russian).

Raznitsyn, V. A. (1976). Tectonic zoning and genesis of the structures of the northern zone of fine folding of the Donets Basin. *Geotectonics*. No. 1, 57–73 (in Russian).

Saintot, A., Stephenson, R., Stovba, S., & Maystrenko, Y. (2003). Structures associated with inversion of the Donbas Foldbelt (Ukraine and Russia). *Tectonophysics*, *373*(1–4), 181–207. https://doi.org/10.1016/S0040-1951(03)00290-7

Spiegel, C., Sachsenhofer, R. F., Privalov, V. A., Zhykalyak, M. V., & Panova, E. A. (2004). Thermotectonic evolution of the Ukrainian Donbas Foldbelt: evidence from zircon and apatite fission track data. *Tectonophysics*, *383*(3–4), 193–215. https://doi.org/10.1016/j.tecto.2004.03.007

Stovba, S. N. (2008). Geodynamic evolution of the Dnieper-Donets Basin and Donbass: Doctor’s thesis. Kiev, 495 p. (in Ukrainian). http://www.disslib.org/heodynamichna-evoljutsia-dniprovsko-donetskoyi-zapadyny-ta-donbasu.html

Subbotin, S. I., Sollogub, V. B., & Chekunov, A. V. (1976). The structure and evolution of the earth's crust of Ukraine and the adjacent regions of Tethys in the light of new data and ideas. *Geofizicheskiy sbornik,* 70, 13–45 (in Russian).

Tkachenko, V. F. (1976). Time of occurrence and mechanism of formation of folding in the Donets Basin. *Sovetskaya geologia*. No. 9, 98–107 (in Russian).

Yudin, V. V. (2003). *Geodynamics of the South Donbass*. Kiev, 292 p. (in Russian). https://www.researchgate.net/profile/Viktor-Yudin/publication/259041291_217_Geodinamika_Uznogo_Donbassa_Monografia/links/00b49529cb583d9b6d000000/217-Geodinamika-Uznogo-Donbassa-Monografia.pdf

Volozh, Yu. A., Antipov, M. P., Leonov, Yu. G., Morozov, A. F., & Yurov, Yu. A. (1999). The structure of the Karpinsky Ridge. *Geotectonics,* No. 1, 28–43. (in Russian).

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СКЛАДКОУТВОРЕННЯ ПРИ ІНВЕРСІЇ ПАЛЕОРИФТОВОГО ОСАДОВОГО БАСЕЙНУ (НА ПРИКЛАДІ ДНІПРОВСЬКО-ДОНЕЦЬКОГО АВЛАКОГЕНУ)

Досліджено механізми становлення різноманітних складчастих форм інверсії осадового басейну на прикладі та з урахуванням особливостей будови Дніпровсько-Донецької палеорифтової системи. З цією метою систематизовано дані про структури і літофаціальне наповнення ДДЗ-Донбасу, застосовано числове моделювання деформацій континентальної літосфери і чохла басейну в умовах колізійного стиснення. Показано, що прояв основних форм складчастості – переривчастої, перехідної, повної – супроводжується характерними літофаціальними особливостями чохла; відповідно до цього сформульовано базове припущення про залежність процесу складкоутворення від літофаціального і літогенетичного факторів, що визначили властивості міцності осадової товщі, яка вступає у стадію деформаційної інверсії (принцип літофаціальної механіки). Загалом моделюванням підтверджено вирішальне значення умов горизонтального стиснення в становленні складчастих структур; відзначено роль осадового басейну як самодостатнього атрактора деформацій в масштабі літосфери. Встановлено, що перехідний складчастий парагенезис Донбасу – гребнеподібна Головна антикліналь і прилеглі положисті структури – може бути наслідком неоднорідностей міцності особливого роду: осьової ослабленої зони в чохлі й високоміцного (компетентного) шару з осьовим мінімумом потужності; сам механізм формування парагенезису Головної антикліналі визначається як комплексний, що включає вертикальну в’язкопластичну течію уздовж осі басейну і вигин на видаленні. Показано, що переривчасті складки (підняття) ДДЗ можна трактувати як результат стискання чохла з довільним сполученням ослаблених і зміцнених порід; натомість повна складчастість Східного Донбасу і кряжа Карпінського зв’язується з вигином компетентного шару постійної потужності. **Наукова новизна.** Вперше отримано модельне підтвердження механізмів формування складчастих структур первиного (основного) етапу інверсії ДДЗ і Донбасу (зокрема Головної антикліналі), які тривалий час являли собою проблему в регіональних тектонічних дослідженнях і реконструкціях. Складкоутворення безпосередньо пов’язане з особливостями осадового наповнення западин у межах сформульованого принципу літофаціальної механіки. Результати моделювання і висновки з необхідною обережністю можна запропонувати як основу для пояснення походження основних типів складчастості в межах як внутрішньоконтинентальних осадових басейнів, так і крайових складчастих поясів. **Практичне значення.** Виконано числове моделювання, розроблені принципи аналізу можуть бути використані в реконструкціях, кількісному дослідженні розвитку складчастих структур (підняттів) інверсованих басейнів, зокрема під час вивчення і прогнозування зв’язаних з ними покладів корисних копалин.

Ключові слова: тектонічна інверсія; палеорифтовий осадовий басейн; механізми складкоутворення; Дніпровсько-Донецький авлакоген; Головна антикліналь; літофаціальна будова; чисельне моделювання.

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