GEODYNAMICS & TECTONOPHYSICS
Published by the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences

TECTONOPHYSICS

2023 VOLUME 14 ISSUE 2 ARTICLE 0689

ISSN 2078-502X

DOI: 10.5800/GT-2023-14-2-0689

ANALYSIS OF THE FAULT-BLOCK STRUCTURE AND STRESS STATE OF THE SEDIMENTARY COVER IN GAS-CONDENSATE DEPOSITS: BASICS OF THE TECTONOPHYSICAL APPROACH

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ABSTRACT. Consideration is being given to the tectonophysical approach to the reconstruction of structure formation mechanisms and stress-strain state of rocks in hydrocarbon deposits localized in the platform cover, which has a complex structure in terms of rheological layering and disturbance by different-rank fractures. With the Kovykta gas condensate field, largest in Eastern Siberia, there were shown the main methods and ways of using modern achievements in tectonophysics for interpreting geological and geophysical information on the upper and lower parts of the sedimentary cover, unique in terms of volume and significance, that was obtained during geological exploration therein. Regularities of changes in the stress-strain state of rocks, found during the research, are combined into a tectonophysical model, which can be used as a base for other hydrocarbon deposits. The model is based on the concept of a zone-block structure of the platform cover, which is formed by a network of subvertical and subhorizontal fault zones that divide it into less faulted blocks. Disjunctive structures are highly fractured zones with concentration of relatively small low-amplitude faults, i.e. represent the early stages of faulting. The zone-block structure is formed mainly by tectonic or gravitational forces; in the first case, the stages and fracture characteristics are transformed onto the platform from the surrounding mobile belts, and in the second case they are determined by the presence of ductile rocks in the section capable of gravitational sliding. The graphic component of the tectonophysical model is 3D datasets that show the zone-block structure and stress state of rocks for the deposit with the degree of detail provided by key geophysical materials and, primarily, by seismic data. By modern GIS, this information can be quickly retrieved for any-size area of the studied rock mass and then used as a basis for solving production issues related to the development of deposits in fracture-pore reservoirs, or for analyzing general problems of their formation and dynamics.

KEYWORDS: tectonophysical approach; fault zone; stress field; zone-block structure; sedimentary cover; modeling; Kovykta gas condensate field

FUNDING: The generalization was performed on the materials as part of the 2021–2025 state assignment for the IEC SB RAS "Modern geodynamics, mechanism of lithosphere destruction and geologic hazards in the Central Asia" (scientific code FWEF-2021-0009). The work was conducted using equipment and infrastructure of the Centre for Geodynamics and Geochronology at the Institute of the IEC SB RAS (grant 075-15-2021-682).

RESEARCH ARTICLE

Received: May 25, 2022
Revised: August 10, 2022
Accepted: August 15, 2022

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FOR CITATION: Seminsky K.Zh., Burzunova Yu.P., Bornyakov S.A., Miroshnichenko A.I., Cheremnykh A.S., Seminsky A.K., Buddo I.V., Smirnov A.S., Gorlov I.V., 2023. Analysis of the Fault-Block Structure and Stress State of the Sedimentary Cover in Gas-Condensate Deposits: Basics of the Tectonophysical Approach. Geodynamics & Tectonophysics 14 (2), 0689. doi:10.5800/GT-2023-14-2-0689

1. INTRODUCTION

Understanding regularities of structure and stress state of the sedimentary cover is crucial for complex-structure hydrocarbon deposits' effective prospecting and exploration. The development of such hard-to-recover reserves has nowadays become one of the main priorities of oil and gas exploration in Russia [Kontorovich, Eder, 2015]. The key problem therewith is the selection of sites for failure-free drilling of exploration and production wells in rock massif which is characterized by heterogeneous stress-strain state due to the presence of significantly deformed substrate zones and abnormal reservoir pressures. The reliability of their mapping is becoming increasingly relevant in the context of exhaustion of world reserves of the reservoirs which are relatively simple in structure. In this regard, of particular importance are the methods of tectonophysics which make it possible to identify fault zones, to reconstruct the stress state of the rock massif, and to determine the mechanisms of its destruction under the action of tectonic and gravitational forces on the basis of the analysis of uniquely detailed geophysical data (primarily 3D seismic survey).

As for the present paper, dealing mainly with the analysis of the fault zones, it should be noted that the 1970s' research, the results of which are published in "American Association of Petroleum Geologists Bulletin" [Wilcox et al., 1973; Harding, 1974; Harding, Lowel, 1979], provided a significant impetus to the development of scientific direction which can now be called tectonophysics of faults. Structural control over hydrocarbon deposits by fault zones led to the implementation of an in-depth study of their inner structure through the analysis of the formation mechanisms, including by physical modeling. The foundations have been laid for shear zone tectonics [Sylvester, 1984], i.e., there were determined the shear zone formation stages, irregularity of inner structure and 2nd-order fault paragenesis which was later applied to identify typical secondary fracture paragenes occurring near normal, reverse and thrust faults [Sherman et al., 1983; Seminsky, 1990, 2003]. The regularities of faulting obtained by specialists of the Irkutsk tectonophysical school [Sherman, 1977; Sherman et al., 1983, 1991, 1992, 1994; Seminsky, 1990] subsequently formed the basis of the study of hydrocarbon (HC) deposits in Western Siberia: mapping fault zones from the seismic survey data and their classification according to the degree of activation and stages of development of inner structure [Glukhmanchuk, Vasilevskiy, 1998, 2013]. In recent years, the methods of tectonophysics are widely used to identify the mechanisms of faulting in the sedimentary cover whose structure on the oil-bearing areas is studied in detail from the 3D seismic survey data [Koronovsky et al., 2009; Gogonenkov, Timurziev, 2012].

Therefore, there have appeared prerequisites for a new study of the HC deposit structure using tectonophysical approach. On one hand, it is related to the possibility of more detailed subsurface exploration due to intensive development of surveying technology and geophysical data conditioning on many licensed areas. On the other hand, tectonophysics, in terms of its main components, has reached the level at which the regularities and technologies obtained can be applied effectively in prospecting, exploration and exploitation of the complex-structure HC deposits.

This paper aims to present the main principles and stages of the integrated tectonophysical approach to identification of the fault-block structure and to reconstruction of the stress state of the sedimentary cover whose dislocation character should be taken into account in prospecting and exploitation of the HC deposits.

A full study on tectonophysics – a science about formation mechanisms of the crustal deformation structures [Gzovsky, 1975], – includes four main stages. These are: (1) mapping a system of structural elements (faults, folds and others) in the rock massif; (2) stress field reconstruction based on the analysis of their characteristics; (3) analogue or digital experiment on the reproduction of formation mechanism of the structure studied; (4) generation of the tectonophysical model of an object which can be used for theoretical generalizations or solution of their-related applied tasks.

As a consequence, the task of this study was to make some brief considerations of current tectonophysical research within each of the above-mentioned stages (kinds) of works by the example of the HC deposit which is complex in structure.

2. OBJECT OF RESEARCH

As the object of research, there was chosen the giant Kovykta gas-condensate field (GCF) located in East Siberia (Fig. 1, a). Complexity in the study of this deposit is due to the dislocation of rocks under the action of tectonic and gravitational forces. Tectonically, the studied area relates to the platform periphery of the fold-thrust belt, whose most dislocated part is situated southeast of that area. However, the already weak manifestation of tectonic fault structures is further complicated within the GCF by gravity deformations confined to the plastic salt-bearing layers.

This allows relating the Kovykta GCF to the complex-structure objects which are characterized by irregular distribution of productive deposits, abnormally low and abnormally high pressures in naturally fractured reservoirs, and brine outcrop or solution absorption during drilling. The above-mentioned complications are fully characteristic of the Kovykta licensed area [Vakhromeev et al., 2016; Gorlov et al., 2016; Ilyin et al., 2016; Smirnov et al., 2016; Buddo et al., 2016], an example of which provided here illustrates the main stages of tectonophysical approach to the identification of structure and stress state of the sedimentary cover (Fig. 1, a). The preliminary results of the application of this approach were presented earlier for the northeastern licensed area [Seminsky et al., 2018] and do not need their detailed description herein.

The Kovykta licensed area lies in the central part of the deposit located in the eastern Angara-Lena tectonic step (south of the Siberian Platform). Neotectonically, the deposit belongs to the Angara-Lena plateau [Sankov et al., 2017], which changes in the southeastern direction to the

Cenozoic Predbaikalian trough and then to the structures of the Baikal Rift Zone (BRZ). To a first approximation, the study area is bounded on the east and south-southeast by the Khandinsky and Zhigalovsky faults, respectively (Fig. 1, a). The features of the manifestation of these and smaller faults in the southern Siberian platform and the fold patterns in the sedimentary cover are described by the predecessors [Zolotarev, 1967; Ryazanov, 1973; Zamaraev et al., 1976; Dubrovin, 1979; Zolotarev, Khrenov, 1979; Logachev, 1984; Malykh, 1985; Sizykh., 2001; Ufimtsev et al., 2005; Sankov et al., 2017]. The analysis of these works in combination with the focused research data [Seminsky et al., 2018] allows making a conclusion about an essential role of dislocations of sedimentary cover in migration and localization of hydrocarbons and, therefore, about the necessity of refining basic ideas of the gas-condensate deposit structure.

The crustal thickness near the Kovykta GCF is ≈40 km [Mats et al., 2001]. The depth to crystalline basement within the licensed area is about 2500 m (below the ground level). According to the structural-lithological features, in the structure of the sedimentary cover there have been distinguished three main salt complexes: subsalt, salt-bearing and postsalt. The subsalt complex is composed of the Vendian terrigenous rocks and Lower Cambrian carbonates. It is the main gas-bearing stratum of the region: in the Vendian Chora formation, there lies the Parfenov horizon with which the largest gas reserves are associated. The reservoir is composed of sandstones and is considered porous which generally corresponds to the monoclinal bedding of low-angle northwest- and north-dipping rocks [Seminsky et al., 2018]. The rocks of salt-bearing or salt complex are represented by intercalation of rock salt with dolomites, limestones and anhydrites. The upper complex (Angara and Litvintsev formations of the Cambrian) differs from the lower one in its structural-lithological features: it is characterized by much larger dislocation of the rocks interlayered with marls, sandstones and dolomites. The postsalt complex is composed of the Middle and Upper Cambrian terrigenous-carbonate deposits and Ordovician terrigenous rocks.

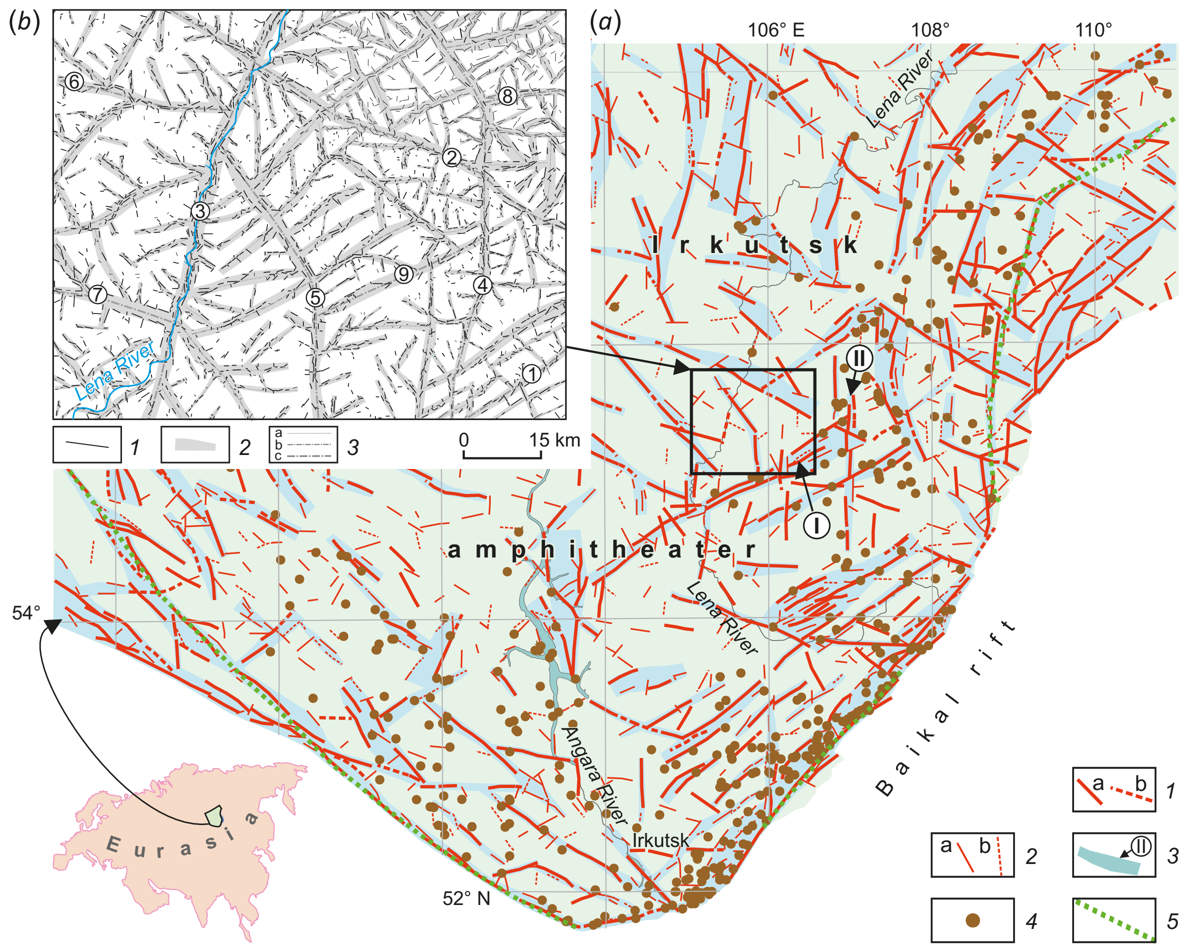

Fig. 1. Different-rank fault zones of the Irkutsk amphitheater identified on the basis of relief lineament analysis.
(*a*) – scheme of fault zones in the south of the Irkutsk amphitheater: *1–2* – large (*1*) and small (*2*) fractures, clearly (a) and less clearly (b) defined; *3* – fault zones, incl. Zhigalovskaya (I) and Khandinskaya (II); *4* – earthquake epicenters according to the catalog published by the Baikal Branch of the RAS Geophysical Survey; *5* – marginal suture of the platform.
(*b*) – scheme of fault zones of the Kovykta license area: *1* – relief lineaments; *2* – fault zones at an early stage of development of the internal structure; *3* – axes of zones of the 3rd (a), 2nd (b) or 1st (c) scale ranks. The numbers in circles are the numbers of zones of the 1st order.

The differences in bed cross-section and in the structure of the subsalt, lower salt-bearing, upper salt-bearing and postsalt complexes of the Kovykta GCF predetermined the features of methodological approaches to the study of their structure. As a result, they are considered separately when describing the results obtained.

3. ZONE-BLOCK STRUCTURE OF THE SEDIMENTARY COVER

3.1. The tectonophysical prerequisites for study

In accordance with modern ideas of tectonic divisibility of the lithosphere as a whole and of the earth's crust in particular, their main structural elements are mobile zones and relatively stable blocks revealed [Sadovsky et al., 1987; Seminsky, 2008]. Such zone-block structure (ZBS) occurs at different hierarchical levels of the organization of substance with faults in their wide tectonophysical sense acting as interblock zones in the crustal scale. According to [Sherman et al., 1983; Seminsky, 2003], this notion involves not only a narrow strip of tectonites of the main fault (1st-order fault) but also a much wider zone of the 2nd-order structures which occurred at three main stages of faulting (Fig. 2, a).

At the early disjunctive stage (Fig. 2, a, I), there occurs a wide zone of relatively small advanced fractures, often called highly fractured or potential basement-fault zone etc. in the geological practice. At the late disjunctive stage (Fig. 2, a, II), the fault has a clearly defined zone of propagation of advancing fractures represented by small segments of the main fault between which there are intensively disturbed fracture conjugation zones. At the disjunctive stage of complete decomposition (Fig. 2, a, III), the fault is represented by a single main fault and feather fractures.

The fault which underwent all three stages of inner structure formation is characterized by three-membered transverse zonation (Fig. 2, c). In its sides, there are the following successive subzones: Stage 1 peripheral subzone of paragenetically related jointing; Stage II highly fractured subzone of the 2nd order; Stage III subzone of the main fault. In case if faulting is a still ongoing process, the zone can

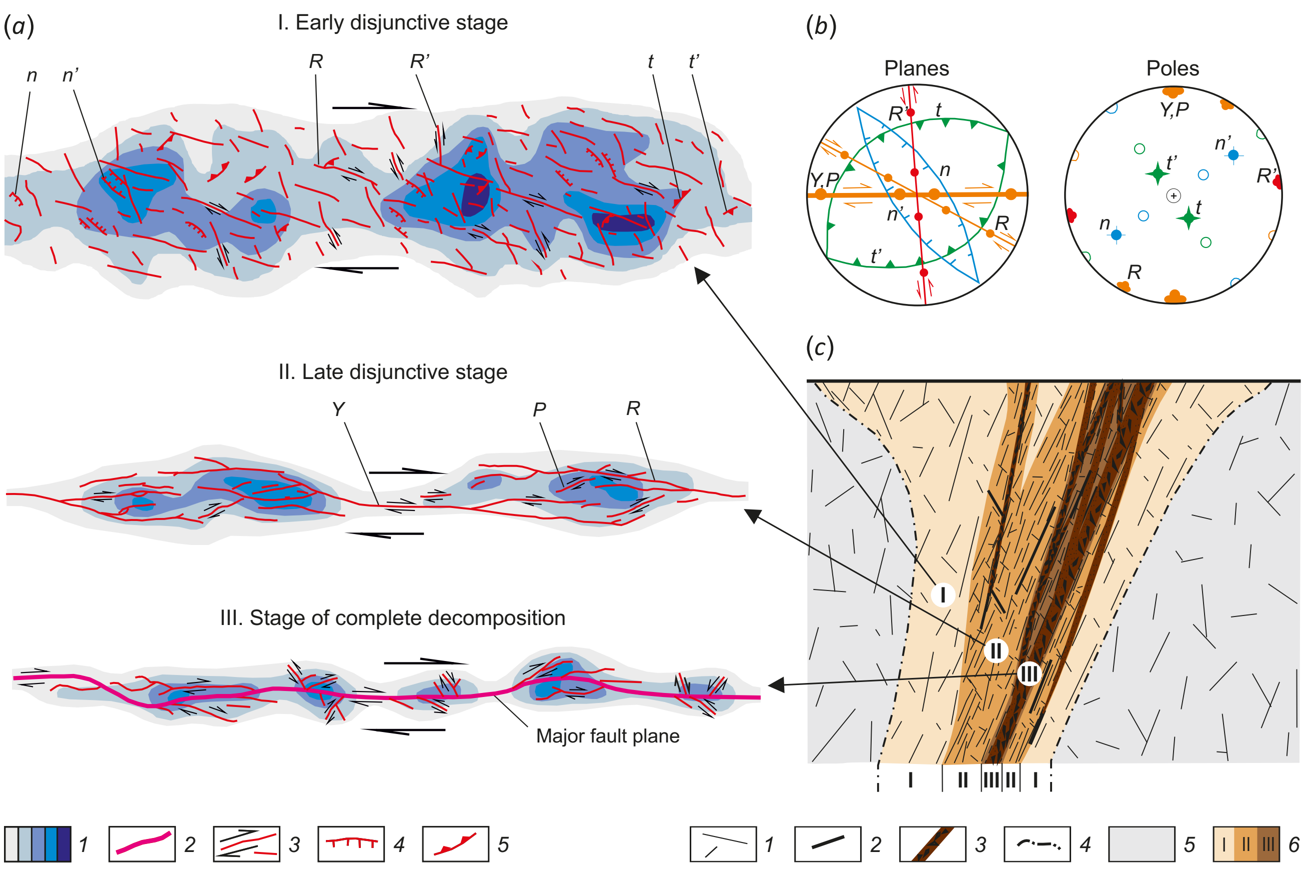

Fig. 2. The structure of the fault zone (by the example of the right-lateral strike-slip fault). (*a*) – structure of the fault zone at three main stages of development: *1* – areas with a different number of fractures per square unit; *2* – main fault plane (fracture of the 1st order); *3–5* – strike-slip faults (*3*), normal faults (*4*) and thrusts (*5*) of the 2nd order. Latin letters are different-type fractures of the 2nd order (*n'*, *n*, *R'*, *R*, *t'*, *t*, *P*) and the main fault plane of the 1st order (Y).
(*b*) – standard parageneses (patterns) of 2nd order fractures for the strike-slip zone, presented on circular diagrams by planes and poles. Orange indicates right-lateral strike-slip faults, red – left-lateral strike-slip faults, blue – normal faults, and green stands for thrusts. Unfilled circles are poles of conjugated fracture systems.
(*c*) – transverse fault zonation model (with the fault undergone all three stages of fracturing): *1* – jointing; *2* – large joint; *3* – fault plane filled with tectonites; *4* – outer boundary of the fault zone; *5* – slightly disturbed rock mass; *6* – main elements of the internal structure of the fault zone, formed at different stages of fracturing.

only be represented by two (I and II) or one (I) subzones. The latter situation is typical for the platform sedimentary cover where the intensity of tectonic effect is usually insufficient for the main basement-fault formation. Therefore, most of the zone-block structure of the sedimentary cover, hosting the hydrocarbon deposits, should be represented by slightly disturbed blocks bounded by the early-stage fault zones. Their structure consists of relatively small faults, fractures and the folds because the plastic component is a significant part of the total shear deformation [Seminsky, 2003].

3.2. The upper sedimentary section

Under these conditions, the mapping of ZBS of the hydrocarbon deposits becomes a non-trivial task whose solution is complicated by poorly exposed rocks. As a consequence, the identification of fault zones in the upper section is usually based on the **relief lineament analysis** because the origin of straight elements of relief morphology (rectilinear or slightly curved scarps, river valley segments etc.) is mainly due to tectonic faulting. Some subjectivity in identification of lineaments can be leveled by using a series of relief maps and schemes for the study area. On one hand, they are based on digital models generated with high-resolution satellite images (SRTM and ASTER GDEM2), on the other hand – on the maps and orthoplans of detailed areas obtained using unmanned aerial vehicles.

The result of the lineament analysis of the Irkutsk amphitheater area was a scheme of fault zones (see Fig. 1, a) obtained using the SRTM digital elevation model. Most of the structures that were identified in the sedimentary cover represent an early or late disjunctive stage of faulting, except for the Zhigalovsky fault and some other large faults near the marginal suture of the platform. Besides identification of fault zones, SRTM images were also used for mapping summit surface and contouring local uplifts [Logachev, 1984]. One of these uplifts, near the eastern boundary of the Kovykta licensed area, was identified and described by V.A. Sankov [Seminsky et al., 2018], which is of significant importance to determine genesis of the fractures and folds because such uplifts may cause gravitational sliding of plastic rocks towards the topographic low.

A scheme of lineaments of the Kovykta area (see Fig. 1, b) was obtained through the relief analysis using Aster GDEM2 digital model with an areal resolution of ≈15 m. Even if not all the lineaments identified are equated with tectonic fractures, their high-density zones can with high probability be related to faults. Many of them coincide with river valleys emphasizing weak crustal segments. The scheme obtained gives a clear understanding of the zone-block structure of the sedimentary cover, with almost an enclosed network of early-stage fault zones characterized by hierarchical subordination. The widest and longest 1st rank zones correspond to the structures that were identified for the Irkutsk amphitheater as a whole [Zolotarev, 1967; Zamaraev et al., 1976; Logachev, 1983, 1984; Zolotarev, Khrenov, 1981; Khrenov, 1982; Malykh et al., 1987; Migursky, Staroseltsev, 1989; Sankov et al., 2017] (see Fig. 1). The width and length of smaller fault zones allow dividing them into two-scale ranks, with zone orientations, as well as with those of larger faults, generally tending to the four systems, i.e., northeastern, northwestern, submeridional and sublatitudinal.

Besides the lineament analysis, mapping of fault zones in the upper sedimentary cover of the hydrocarbon deposits may also involve **seismic and electrical exploration of shallow depths and the ways of identification of permeable areas on the basis of gas surveys of different types**. However, the interpretation of the results obtained is complicated by the influence of numerous neotectionic factors, the main of which are a consequence of the impact of groundwater, different-type exogenous processes, and atmospheric loads. The disjunctive-structure identification survey becomes more effective if the interpretation of results is based on tectonophysical regularities of the fault zone structure (Fig. 2, c).

Thus, the three-member zonality of fault zones implies a different degree of the substrate disturbance within single subzones and, as a consequence, a different permeability of fluids and gases which is reflected in the field of electrical resistivity and intensity of gas emission from rock massif. To date, the most formalized is the method of tectonophysical interpretation of the electric sounding data, developed based on the example of shallow-depth tomography [Seminsky, Bobrov, 2009, 2018; Seminsky et al., 2016] and near-field time-domain electromagnetic sounding [Seminsky et al., 2019]. In the publications cited above it is shown that the use of tectonophysical approach allows contouring the fault zones and identify the features of their inner structure.

Of particular importance for hydrocarbon deposits is the application of such approach to the interpretation of the gas survey data and, primarily, the survey data for radon. This radioactive gas, due to inertness, is suitable for making measurements, marks the faults [Schery et al., 1982; King et al., 1996; Ioannides et al., 2003; Utkin et al., 2006; Seminsky, Bobrov, 2009; Lombardi, Voltattorni, 2010; Seminsky, Demberel, 2013], and adjoins a column of such gases as hydrogen, methane, nitrogen and carbon dioxide, migrating from deep horizons [Etiope, Martinelli, 2002; Shuleikin, 2018]. The procedure of identification of the three-member zonality of disjunctives from the gas survey data is not formalized yet, though its very existence was stated during the oil well drilling in West Siberia [Volpin et al., 2018]. This was the basis to change the field development plan – from commonly used uniform (in the context of water-injection and exploration well drilling locations) to that taking account of inner structure of fault zones. Thus, an effective plan for the recovery of reserves was that in which the water-injection wells are located in slightly disturbed blocks, and the exploratory wells – in subzone II (Fig. 2, c) as the most permeable for fluids and gases.

At the Kovykta GCF, the proposed approach was used to verify the location of fault zones identified through the relief lineament analysis. By the example of the northeastern part of the licensed area where the electrical and gas surveys were conducted, it was shown [Seminsky et al., 2019] that Fig. 1, b, generally reflects the zone-block structure of the upper sedimentary cover.

The field geological and structural or morphotectonic methods, in relation to a poor exposure of the rocks in the platform cover and non-contrasting relief in many platform regions, are secondary for mapping fault zones. Although the observations are fragmentary, they play an important role in the determination of such zone parameters as dip and strike, degree of the Neogene-Quaternary activity, and others. In the presence of a scheme of the zone-block structure drawn from the lineament analysis data (see Fig. 1, b), these characteristics obtained for one outcrop can be extrapolated to the whole spatially related zone. Each observation like that improves the information nature of ZBS.

3.3. Lower sedimentary section

The main methods of mapping the zone-block structure in deep-seated parts of sedimentary complexes are large-scale 3D electric and seismic sounding surveys conducted at the HC deposits [Rybalchenko et al., 2020; Buddo et al., 2021]. The block boundaries represented by main faults are defined clearly on the geoelectrical or seismic sections by the displacement of marking horizons, line-ups etc. [Mushin et al., 2001; Baudon, Cartwright, 2008; Bull et al., 2009; Jackson, Rotevatn, 2013; Rønning et al., 2014; Reeve et al., 2015; Iacopini et al., 2016; Hu et al., 2021; and others]. However, the total amplitude of early-stage faults, dominant in the sedimentary cover, is distributed along a wide zone of small-fault propagation which almost does not allow identifying the marking-layer displacements in the sections.

For the electrical survey data, a clue to a way out of this situation can be found in fluid-conducting fault zones. In the field of electrical resistivity (ER), they are distinguished through low-resistivity segments, which were identified for the deep-seated parts of the sedimentary cover on the Kovykta area [Seminsky et al., 2018]. Thus, on the maps of electrical conductivity of some horizons of the salt-bearing and subsalt complexes, there are high-conductivity areas characterized by a linearly elongated shape and a systematic arrangement in plan. The largest of them are traced along several or all horizons studied, providing almost an enclosed network. It is therefore reasonable to assume that the zones considered herein are of faulting origin and thus represent the main component of the zone-block structure of the lower platform cover.

For the seismic survey data, the main way of identifying amplitudeless-fault concentration zones was to apply the attribution analysis of a 3D seismic dataset [Interpreter's Guide..., 2007]. The main operations recommended for identifying fractures and other linear anomalies of the

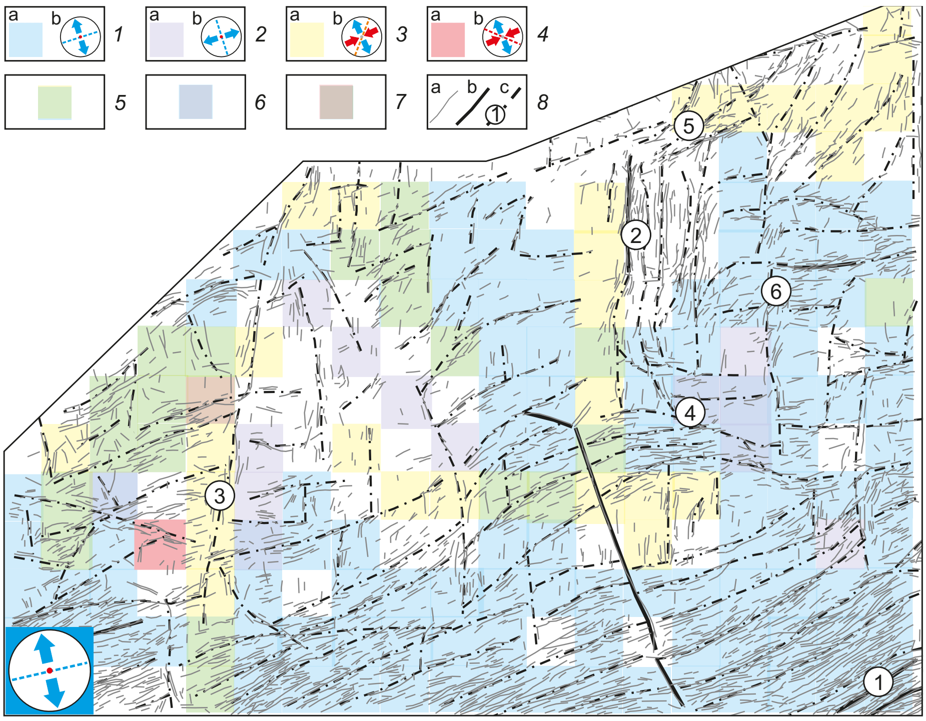

Fig. 3. Stress-strain state of rocks of the subsalt complex for the stage of NW–SE extension of the sedimentary cover of the Kovykta area (see stress tensor at the bottom left).
1–7 – different types of local-rank dynamic settings: NW–SE extension (*1*), NE–SW extension (*2*), right-lateral shear (*3*), left-lateral shear (*4*), superposition of NW–SE extension and right-lateral shear (*5*), superposition of NW–SE extension and NE–SW extension (*6*), superposition of NW–SE extension and right-lateral and left-lateral shears (*7*): a – areas of occurrence of this setting within the site, б – its corresponding stress tensor; *8* – faulting structures: a – fractures identified from a 3D seismic dataset, б – major faults, в – axes of fault concentration zones (early-stage fault zones), with the largest of which numbered.

wave pattern are "Ant-tracking" and "Variance" [Pedersen et al., 2002; Silva et al., 2005; Aarre et al., 2012; Basir et al., 2013; Khair et al., 2012]. Their joint use for the Kovykta area made it possible to obtain a three-dimensional dataset on the planes which represent faulting structures. Fig. 3 and 4, a show the networks of faults identified from a 3D seismic dataset on the subsalt complex hosting most of the productive deposits of the Kovykta GCF. There are clearly defined linearly elongated segments of concentration of subparallel and en-échelon fractures representing the fault zones. The extensive fractures, indicative of the late-stage faulting, occur only in some the zones, whereas most of the fractures are characterized by the early-stage inner structure development. The largest of the mapped zones (1, 3, 6 and others) are fully or fragmentarily visible on the scheme of faulting structures of the Kovykta area obtained for the upper section through the lineament analysis (see Fig. 1, b). The spaces surrounded by fault zones – the blocks – are characterized by a sparser network of faults which generally do not provide clearly defined systems.

3.4. Concluding points

The tectonophysical approach applied to the interpretation of various geological-geophysical data types reveals the zone-block divisibility of the sedimentary cover at the Kovykta GCF: slightly disturbed blocks contact with each other along wide zones of high-density faults, most of which are not major ones. Large zones disturb the entire cover

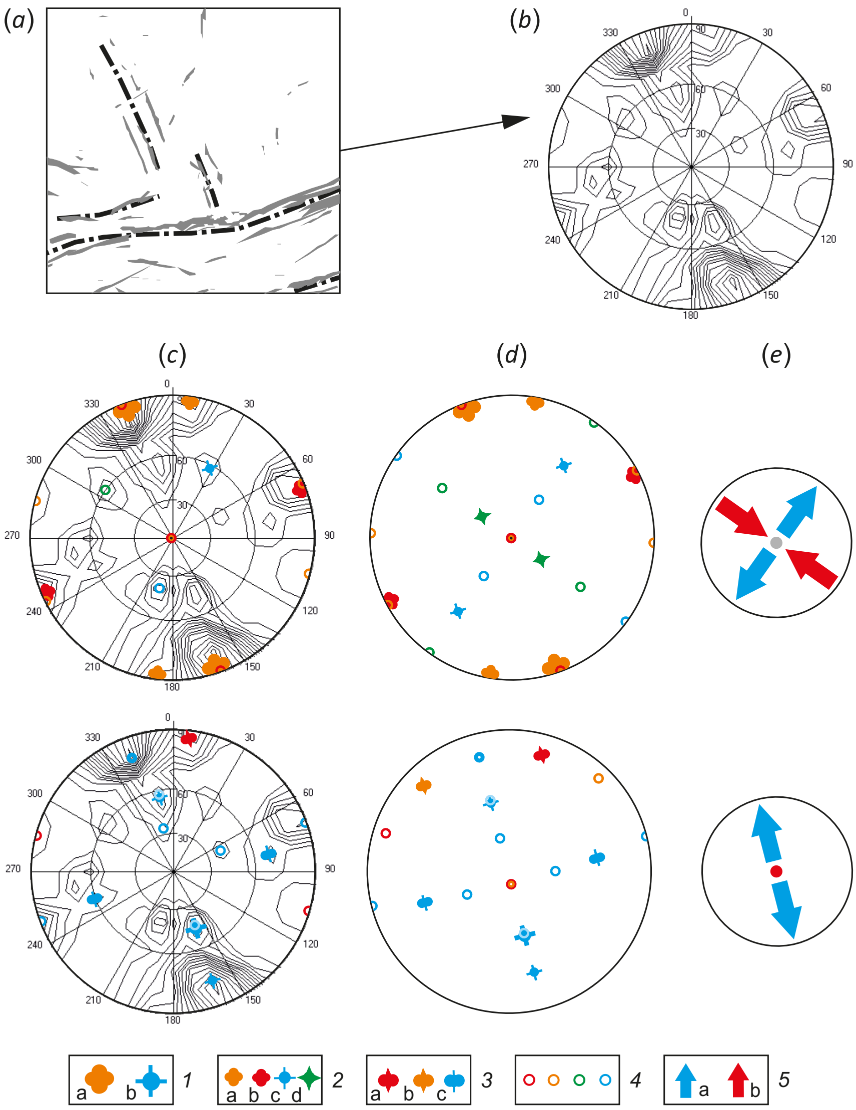

Fig. 4. An example of a paragenetic analysis of fractures extracted from a 3D seismic dataset within one cell.
(*a*) – position of fractures (gray color) and their concentration axes (black dash-dotted line) as seen from above. (*b*) – circular diagram of fractures (94 pcs.). (*c*) – result of comparing the diagram with the standard parageneses (*d*) in the form of two solutions: for the right-lateral strike-slip fault zone (top) and for the normal fault zone (bottom), and their corresponding strike-slip and extension stress tensors (*e*). *1* – poles of the planes of right-lateral strike-slip (a) and normal (b) 1st-order faults; *2* – poles of the planes of right-lateral strike-slip (a), left-lateral strike-slip (b), normal (c), and reverse (d) faults of the 2nd order; *3* – poles of reverse-strike-slip (a, b) and strike-slip normal faults (c) 2nd-order faults; *4* – poles of a secondary or additional system of small 3rd-order fractures; *5* – position of subhorizontal axes of principal normal extension (a) and compression (b) stresses.

but occur at different levels with varying degrees of manifestation which is indicative of specificities of the deformations of single complexes.

4. STRESS STATE OF THE SEDIMENTARY COVER

4.1. The tectonophysical prerequisites for study

The tectonophysical methods of stress tensor reconstruction are divided into paragenetic (based on spatial relationships of faults) and kinematic (based on the orientation of fault and direction of sliding thereon) [Sim, 2013]. Oil and gas geology may involve both groups of methods but the first one is more in demand because determining the locations of small-amplitude fault planes is a less difficult task than determining the vectors of displacement along these planes. On the Kovykta area, there was used the author's version of paragenetic analysis of the faults [Seminsky, 2014, 2015], which is made on the types of parageneses taken as initial ones in the stress-state reconstruction. These are complete parageneses resulted from multi-phase faulting (see Fig. 2, a), during which, under the shear deformation, there occurs a regular change of the 2nd-order stress tensors.

Complete paragenesis of faults for the shear zone, consisting of the main fault (1st-order fault) and seven directions of the 2nd-order faults (*R*, *R'*, *n*, *n'*, *t*, *t'* and *T*-types), is shown in Fig. 2, b in the form of a circular diagrams of fault systems – patterns – by the example of the left-lateral strike-slip. Since the strike-slip, reverse and normal faults are mechanically similar to each other (as occurring in shearing), their standard patterns were obtained in an analogous way (Fig. 6 in [Seminsky, 2014]). The method consists in the comparison of standard reference patterns with the diagrams of natural fault networks, which, in case of a good agreement, allows obtaining a solution about the deformation of elementary volume (outcrop, rock block) in the fault zone with a certain kinematics and, respectively, about a stress-tensor type. The local solutions obtained are displayed on a schematic sheet (or in a 3D image) of the area of the object studied. Then, through the points with closely spaced one-type solutions, there have been drawn the borders of the zones whose substrate was deformed under the same conditions.

After that, for reconstructing the stress fields in which the studied crustal segment structure was formed, a ranking analysis is made on the identified fault zones [Seminsky, 2014]. The processing of local solutions allows conducting the reconstructions at the regional level first and then at a lower level. As a result, there remain several solutions (3-4 in general) which cannot develop at a time due to their type difference, i.e., they correspond to different stages of faulting. At the end of the paragenetic analysis, the stress field schemes are drawn for each of the stages: the solutions which can act as the 2nd-order stress tensors in the corresponding 1st-order stress field are selected from a local set of solutions and displayed on a schematic sheet (or in a 3D image) of the area of the object studied.

The faulting structures that become a subject of paragenetic analysis are usually identified by different ways for single sedimentary layers which is illustrated below by the example of the Kovykta area.

4.2. The upper sedimentary section

The stress state in the near-surface sedimentary section was reconstructed based on the analysis of two datasets and described in [Seminsky et al., 2018]. This geological-structural information on faults and fractures documented in rarely found outcrops only supports the solutions obtained from the areal data. The basis of these data lies in the network of fault zones represented by relief lineament concentrations (see Fig. 1, b). As a result of the paragenetic analysis of this network, it has been stated that in the upper sedimentary cover there occur at least three tectogenetic stages: NW–SE compression, shear with meridional orientation of the compression axis and latitudinal strike of the extension axis, and NW–SE extension. According to the literature data [Zamaraev et al., 1976; Sankov et al., 1997, 2017; Delvaux et al., 1997; Mats et al., 2001; Sizykh, 2001], these are precisely the settings which caused the most intense crustal deformations of the adjacent Baikal mobile belt in the Paleozoic (compression) and in the Early and Late Cenozoic (shear and extension, respectively).

4.3. The lower sedimentary section

The paragenetic analysis of the deep parts of the platform cover can be based on the 3D electrical and seismic surveys. The former covers fragmentarily the Kovykta licensed area [Buddo et al, 2018]. As a result, the reconstructions conducted over the network of high electrical conductivity zones were used as an auxiliary tool and did not generally contradict with the solutions obtained from the faults which were identified using the attributes of the 3D seismic dataset for the area as a whole. The azimuth and the angle of dip of such faults provided all necessary and sufficient information for using the author's version of paragenetic analysis which allowed reconstructing stress tensors almost everywhere.

Thus, on the Kovykta area, the stress state was determined for local volumes (cells) whose dimension was 5×5 km with a depth equal to a thickness of the sedimentary complex to which an elementary cell belonged: upper salt-bearing, lower salt-bearing or subsalt (618 cells in total) (see Fig. 3). An example of the stress tensor reconstruction for one of the elementary volumes is provided in Fig. 4. At first a circular diagram (Fig. 4, b) was drawn from dip and strike of faults falling within the cell (Fig. 4, a). Then the diagram was compared with standard patterns (Fig. 4, c, d). The standard pattern, most suitable in terms of a set of coinciding fault systems, determined the solution: the stress state which gave rise to their formation, and the structural elements and the morphogenetic type of the 1st-order fault zone. For each cell there were usually reconstructed several solution versions (2–6) which testifies to heterochronous stress states occurring in the process of tectonic development of the crustal segment studied. Two of them – shear and extension fields – are shown in the diagram presented in Fig. 4, e.

In total, on the Kovykta licensed area there was conducted a reconstruction of 1278 local solutions which were then ranked in accordance with the paragenetic analysis technique [Seminsky, 2014, 2015]. As a result, for the sedimentary cover as a whole there were reconstructed four regional dynamic settings: I – NW–SE compression, II – sublatitudinal compression, III – shear with a submeridional orientation of the compression axis and a sublatitudinal orientation of the extension axis, IV – NW–SE extension. For these settings, at the final stage, there were created the maps of distribution of local stress tensors (2nd-order fields), separately for each of the three sedimentary complexes studied (Fig. 5). To do this, from the total set of local solutions there were selected the solutions corresponding in type, i.e. those which were active in the regional stress field considered. They were plotted in the colors on the maps of corresponding layers – upper salt-bearing, lower salt-bearing and subsalt complexes. For a two- or three-dimensional "base", use can be made of the network of faults identified from a 3D seismic dataset (Fig. 5: a complete set of settings) or a zone-block structure represented by the fault zone axes (see Fig. 3: subsalt complex, NW–SE extension setting).

4.4. Concluding points

A new modification of the paragenetic analysis based on the current understanding of structural elements of the fault zones allowed determining the 1st-order stress tensors corresponding to the main stages of the formation of zone-block structure of the sedimentary cover of the Kovykta GCF. These are the fields of compression (Fig. 5, a), shear (Fig. 5, b) and extension (Fig. 5, d) which were reconstructed both for the upper and lower sedimentary strata. These fields correspond in type to the main stages of tectogenesis which is active in the axial part of the platform-adjacent Baikal mobile belt and, therefore, can be assigned to the Paleozoic, Early Cenozoic and Late Cenozoic, respectively. The origin of the fourth regional field reconstructed – that of the latitudinal compression field (Fig. 5, c) – is considerably due to the gravity factor because the corresponding solutions are widely common in the salt-bearing complex. The deformations occur at the last segment of the geological record, since in the layer considered, as seen in maps of Fig. 5, c, d, this field "drives out" the current extension field. Its manifestation areas are arch-shaped, with the eastern area having a corresponding reflection in the fault structure of the Bolsheirinsky berm (zone 2 in Fig. 3 and Fig. 5, c). In conjunction with a local topographic uplift in the eastern Kovykta area, this fact is indicative of the plastic rock flow moving westward therefrom due to the displacements along the thrusts and shear layers.

The maps of distribution of the current stress fields (Fig. 5, c, d) are of practical importance for solving problems related to productive-deposit prospecting in the Kovykta

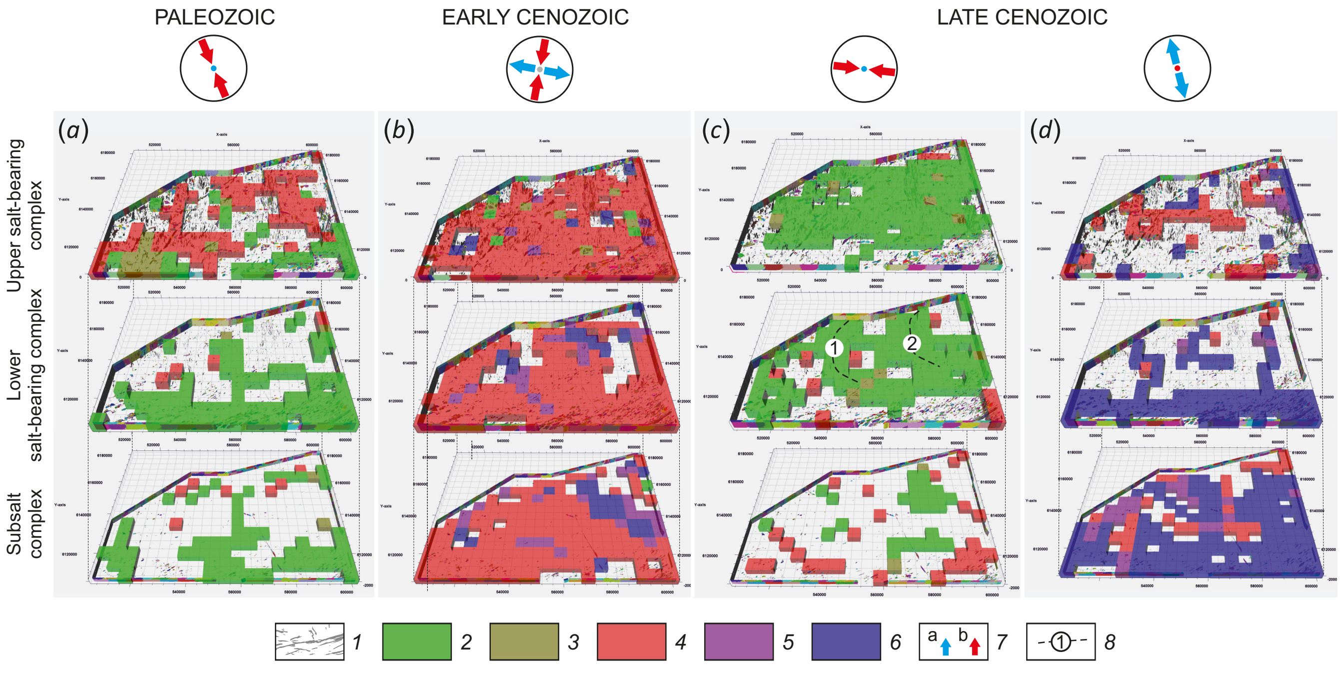

Fig. 5. A three-dimensional image of the stress-strain state of the upper salt, lower salt and subsalt complexes of the sedimentary cover in the Kovykta area.
(*a*–*d*) – regional stress fields of different ages reconstructed based on the results of paragenetic analysis of fracture networks extracted from a 3D seismic dataset: (*a*) – NW–SE compression field; (*b*) – shear field with a submeridional orientation of the compression axis and a sublatitudinal orientation of the extension axis; (*c*) – sublatitudinal compression field; (*d*) – NW–SE extension field. *1* – Ant-tracking faults for the corresponding sedimentary complex; *2*–*6* – types of local stress fields of the 1st and 2nd orders, reconstructed in the calculation cells: *2* – compression, *3* – compression with shear (transpression), *4* – shear, *5* – tension with shear (transtension), *6* – extension; *7* – position of subhorizontal axes of principal normal extension (a) and compression (b) stresses; *8* – axes of the sublatitudinal compression areas.

GCF and forecasting the abnormal events at well drilling. Since all the materials on the stress state and fault network are generated in the form of machine-readable three-dimensional datasets, the stress-strain map can be obtained quickly for any part of the sedimentary cover. For example, a map of the productive subsalt complex (see Fig. 3) provides an additional criterion for the selection of production well drilling locations on extension segments because that is where are 78 % of already drilled wells with a daily flow rate of more than 100 thousand cubic meters. There is also a possibility of showing the foreseeable issues of drilling a well at its intersections with the faults which are active in the stress fields considered.

Emphasis should be placed on the purely general nature of the above-presented approach to identification of problematic section intervals with a level of detail of 5×5 km in plan for the Kovykta area. But this is not enough to solve the problems of selecting the sites to drill wells. However, the technique developed allows constructing 3D models of the stress-strain state for single parts with a level of detail provided by key geophysical materials, primarily by the seismic survey data. Therefore, a large-scale research practice will provide further justification for failure-free drilling site selection with the prospect of discovery of natural gas accumulations.

5. MECHANISMS OF FAULTING IN SEDIMENTARY COVER

5.1. The tectonophysical prerequisites for study

Tectonophysics has a large set of methods of tectonic modeling which can be divided into two large groups: digital and analogue. In the first group, the model and its loading conditions are assigned by a system of equations, and in the second group a sample of an equivalent material (gelatin, clay pastes, plasticine, wax, rock etc.) experiences an impact force corresponding to a natural dynamic setting. In accordance with the Kovykta GCF data obtained, experiments were conducted using analogous elastic (jellies) and elastoplastic (brown clay pastes, plasticine etc.) models at the "Polariscope-polarimeter" and "Razlom" facilities with no regard to gravitational force and on a centrifuge which allows the estimation of role of the gravity factor in the structure formation. The experiment-conducting technique is described in special publications [Osokina, Tsvetkova, 1979; Sherman et al., 1983, 1991, 1992, 1994].

The modeling results presented below can be used for solving the key problems of the Kovykta GCF structure formation: real character of the structure formation mechanisms at the last tectonic stage, specificity of the Cenozoic stress state, and influence of rheological layering of the sedimentary cover on the character of faulting.

5.2. Modeling of faulting mechanisms

Tectonic settings of faulting, identified for the Kovykta GCF area are the platform-reflection of the destruction processes which occurred with high intensity in the adjacent Baikal mobile belt at each tectogenetic stage. Faulting mechanisms are confirmed by experimental studies, the results of which can also be used for the description of the process covering the marginal platform area.

The Paleozoic compression as the most common process of interaction of large lithospheric blocks in the southern Siberian craton was many times obtained by analogue experiments [Davis et al., 1983; Peltzer et al., 1984; Mandl, 1988; McClay, 1991], including those conducted by the authors of this paper [Sherman et al., 1994; Seminsky, 2003]. Deformations under the action of lateral pressure propagate to the platform forming the fault-fold structure belt, with a gradual attenuation of the process expressed not only in deformation intensity but also in its changing nature: reverse faults–thrusts–horizontal shears. It is precisely the shear layers together with subvertical small-amplitude faults that represent the main paragenesis of fault zones hundreds of kilometers from the craton boundary. The application of the experimental data to the Kovykta area allows attributing the sedimentary cover division into the structural and compositional complexes described above – subsalt, lower salt-bearing, upper salt-bearing and post-salt – to large shears.

The Cenozoic shear and extension settings changing in time over the Kovykta area can be attributed to the dynamics of development of a single mechanism of the lithosphere deformations that works in the formation of the Baikal rift as a giant pull-apart structure [Seminsky, 2009]. In the experiments carried out, the one-layer elastoplastic clay-paste model was superimposed on two stamps. One stamp underwent a simple shear in the horizontal direction and, on the contact with another, made a bend similar in shape to the Pribaikalian segment of the marginal suture of the Siberian platform (yellow dashed line in Fig. 6, b). In modeling, a high degree of similarity was found for the first time between morphology and mutual location of basins of the Baikal rift zone (Fig. 6), and there was also conducted a reconstruction of the main regularities of its temporal development involving preparatory-shear to actual-rifting stages and, in the final formation of the structure, "slow" to "fast" rifting stages [Mats et al., 2001; Logatchev, 2003; Petit, Deverchere, 2006]. As applied to the Kovykta licensed area, the experimental results show that it must belong to the destruction zone periphery (Fig. 6). Therefore, the model-based structure formation mechanism is a real cause of a widespread occurrence of shear (see Fig. 5, b) and extension (see Fig. 5, d) settings in the platform cover.

The remaining regional setting – sublatitudinal compression – is related to the gravitational influence and, therefore, should be interpreted by using the "Centrifige"-based modeling data. A classical description of such experiments can be found in [Ramberg, 1970; Guterman, 1987], which partly deal with the study of deformations in the cross-sections of the plastic rock layers. It was shown that a few-degrees bed deviation from the horizontal is enough for the initiation of both upper-layer movement along the salt-bearing layer and the salt-bearing layer movement along the basement rocks. Therefore, the present-day local uplift near the eastern boundary of the Kovykta area may be a cause of gravity flow of the salt-bearing layers towards the west.

The action of body forces is one of the factors which complicate the tectonic structure of the platform strata and set a specific character to the dislocation of some sedimentary complexes. Another neotectonic factor is a different competence of sedimentary rocks to deformation which greatly hampers tracing disjunctives on seismic sections. Tectonophysical modeling is an effective method, the results of which clearly demonstrate morphological variability of the fault zone in the adjacent layers characterized by a different degree of plasticity. Fig. 7 illustrates the deformation response of more (wet clay) or less (wet sand) plastic cover at a vertical block movement along the basement fault. The fractures in elastoplastic material (Fig. 7, a, c) start propagating from basement to surface of the model within a wide zone, with the major suture formation requiring large-amplitude vertical displacements. In a more brittle material (Fig. 7, b, d), by contrast, the model is quickly destroyed by a single small-amplitude fracture. This is the cause of segmental manifestation of a single fault zone (Fig. 7, e) which has defined large fractures in competent layers and highly fractured sectors in clay varieties, unidentifiable by seismic attributes and much less by displacements of seismic sections. In this case, externally rootless structure in fact is not because of the lack of sensitivity of modern techniques in fault identification.

5.3. Stress state modeling

Experimental modeling of stress field is usually conducted on optically active material (gelatin) which allows

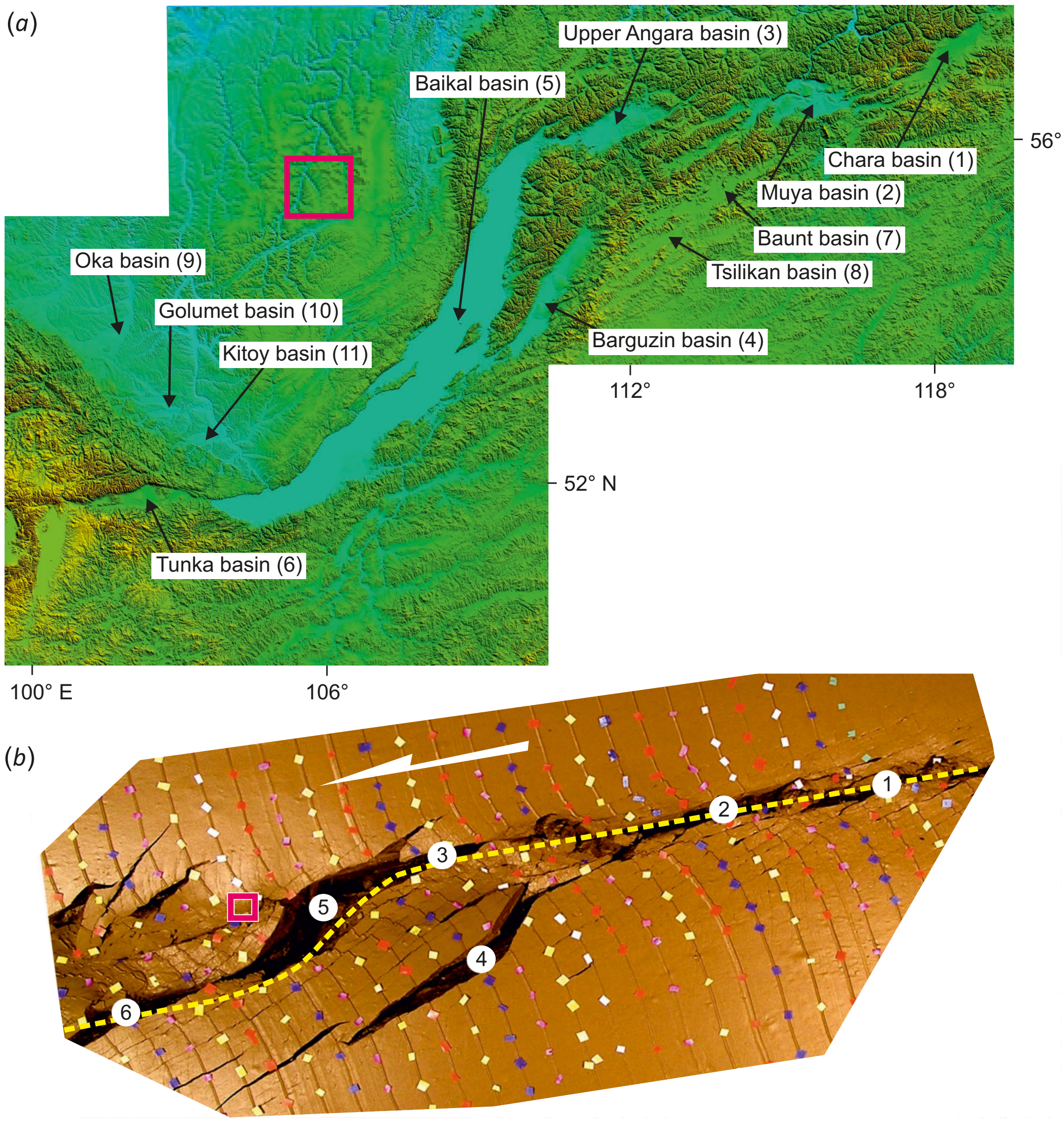

Fig. 6. Faults and depressions of the Baikal rift zone and the southern Siberian craton on a digital elevation model (*a*) in comparison with similar structures based on the elastoplastic model (*b*).
The yellow dotted line shows the approximate position of the edge of the movable stamp of the experimental device at the moment of taking a photograph, and the arrow shows the direction of its movement. Colored squares on the model surface mark the reference lines. The red rectangle is the Kovykta area.

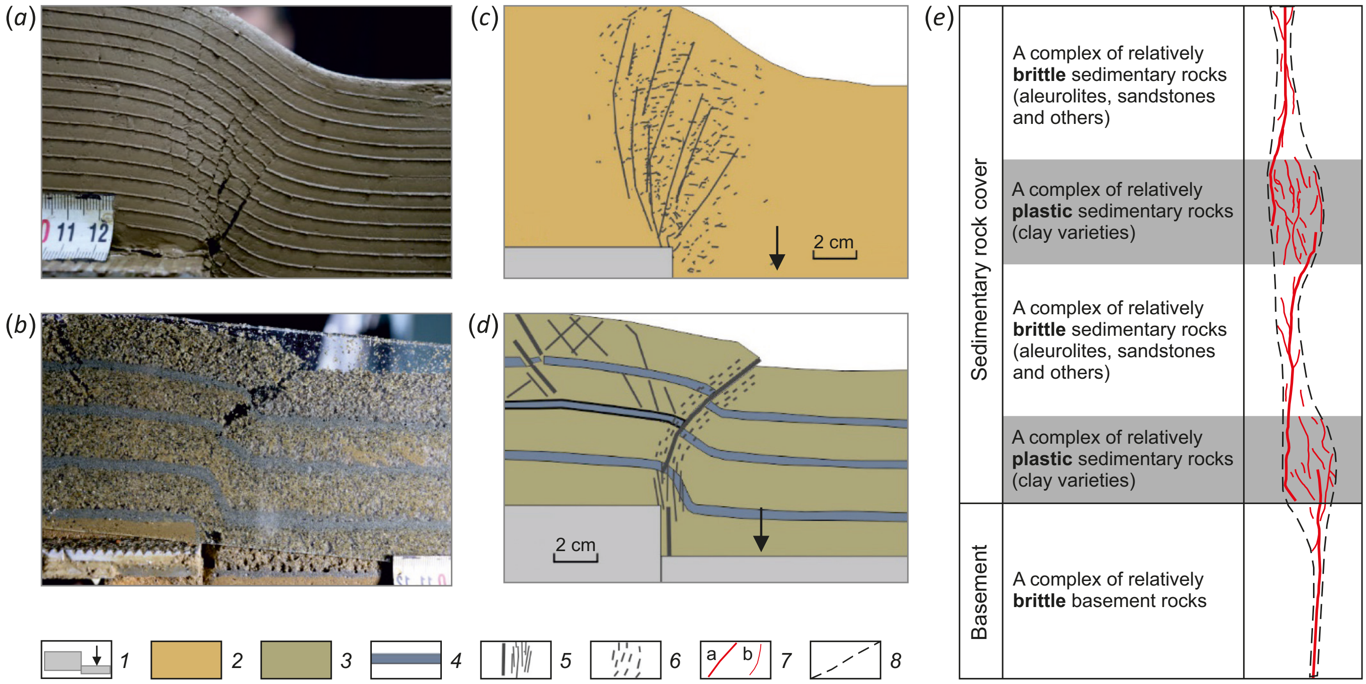

Fig. 7. The structure of the fault zone in different rheological environments.
(*a, b*) – fault zones formed over a certain time in active basement-fault cover in clay (*a*) and wet sand (*b*) models. (*c, d*) – fracture patterns in clay (*c*) and wet sand (*d*) models. (*e*) – principle scheme of the internal structure of a fault in a rheologically heterogeneous platform section. *1* – stamps of the experimental setup (an arrow shows the direction of movement of the active stamp); *2–3* – clay (*2*) and sand (*3*) models; *4* – markers; *5* – fractures; *6* – area of loosening of the model material, *7* – large (a) and small (b) fractures; *8* – boundaries of the fault zone.

determining the distribution of stress in the model loaded similarly to the natural analog. For the solution of problems in oil and gas geology there can be reconstruction of the stress state of folded structures [Zubkov, Bondarenko, 1999; Zubkov, 2019], though the method is most effective for the models of faults, generally assigned by simple fractures [Osokina, Tsvetkova, 1979]. The novelty of the experiments applied to the Kovykta licensed area [Seminsky et al., 2018] was the use of the process of healing the cross-sections by a lower-viscosity material which provides a possibility to study stress distribution in zone-block structures. The result of the experiment is color pictures obtained in the study of the loaded model in polarized light transmission.

As shown in [Seminsky et al., 2018], the materials for optical modeling confirm and refine the estimated natural degree of fault-zone activity at different tectogenetic stages and allow for dividing the fault zones into segments which is important for estimating the degrees of permeability. Moreover, they provide an opportunity to analyze the stress state of blocks which are characterized by irregular stress distribution. The comparison of the obtained pattern with productivity and abnormally high reservoir pressures in the Kovykta field wells shows that the first-approximation increased-rate ranges tend to lower concentrations of stresses and to the areas of extension, and the ranges of AHRP – abnormally high reservoir pressures – to high concentrations of stresses and to gradient areas. Therefore, the results of optical modeling can be used as an addition to the selection of suitable exploratory-well drilling sites.

5.4. Concluding points

Modeling is an effective research technique that is used to study faulting mechanisms and stress state of rock massif of the hydrocarbon deposits similar to the Kovykta GCF. The models of lateral compression and shear with a consequent extension settings cover the area which is consistent with the nature of platform margins. Besides the mere fact of their existence, the experiments illustrate the dynamics of structure formation and specificity of stress field as a whole and their details in particular – a specific manifestation of fault zones in sediment layers of different competence. According to the experimental data, rheological layering is the cause of not only irregular disturbance of zone substrate but also of occurrence of true rootless structures. They form in the process of gravitational sliding of plastic salt-bearing rocks at their minimal deviation from horizontal bedding.

6. CONCLUSION

The use of modern methods and techniques of tectonophysical analysis of various types of geological-geophysical data allow establishing the main regularities of faulting structure and stress state of the platform cover of the Kovykta GCF. The materials from the publications cited herein show that such regularities can also be related to other hydrocarbon deposits characterized by a complex structure. This provides an opportunity of their generalization in the form of tectonophysical model of the sedimentary strata hosting hydrocarbon resources. The model contains characteristics of the structure of sedimentary cover with an emphasis on specificity of stress state and mechanisms of its formation under the action of forces of different origin.

The disjunctive structure of the platform cover is zone-block, i.e., represents the block hierarchy which is largely formed by the network of primarily subvertical and subhorizontal zones of concentration of relatively short faults. The network of the largest subvertical zones reflects the zone-block basement structure. Most of the basement faults are the main (1st-order) faults whereas in the cover these are wide zones whose inner structure is in its early stages, i.e. represented by the 2nd-order faults, a dense network of fractures, and folded forms. The same zone may consist of fragments with more or less mature internal structure in adjacent layers with different rheological properties. Subhorizontal shear-layer and thrust zones tending to the interlayers of plastic rocks (salts, clays) divide the platform cover into structural and compositional complexes whose structure may differ in the degree of disturbance, type of fault network, and stress state caused by forces of different origin and direction.

The state of zone-block structure and stress field of the sedimentary cover is determined by the combined effect of regional tectonic forces and gravity, the source of which can be related to both regional and local stresses. The tectonic effect on the cover occurs through the basement from the adjacent mobile belts, i.e., is due to the deformation history therein. Gravitational effects are most intense in plastic complexes and result from uplift-to-low slide of rocks with the rootless-structure formation.

In the tectonophysical model, a system of subvertical zones in combination with rheological layering determine the inhomogeneity of the cover in terms of stress state, degree of disturbance and, as a consequence, permeability for liquid and gaseous hydrocarbons. The development of complex-structure deposits should be based on fracturing or fracture porosity of the reservoir. In such conditions, the most permeable are extension areas of zone-block structures in rock massif, among which are extension quadrants at the junction of active fault zones and highly fractured secondary-fault subzone therein.

The descriptive part of tectonophysical model is accompanied by a series of three-dimensional representations of the structure and stress fields of the Kovykta deposit at different scale levels and separate tectogenetic stages shown in Fig. 1, 3 and 5. These materials can nowadays be obtained quickly from 3D relevant datasets within "Petrel", "Kingdom" and other software packages.

The paper as a whole presents the methodological approach which allows for generating 3D stress state of complex-structure parts of the sedimentary cover with a degree of detail provided by the key geophysical data and, above all, by seismic survey. In the applied aspect, this provides another justification (additional to those already available in industries) for the selection of sites for failure-free drilling of exploratory wells with the prospect of discovery of natural gas accumulations. Besides, the experience of application of this approach for different deposits will yield the original data for a new solution to hydrocarbon-migration and hydrocarbon-origin problems.

7. ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to D.P. Gladkochub, Corresponding Member of RAS, Director of the Institute of the Earth's Crust SB RAS, and to Yu.A. Agafonov, Candidate of Technical Sciences, General Director of "SIGMA-GEO" LLC for comprehensive support at all stages of the study, and to A.V. Cheremnykh, A.G. Vakhromeev, V.V. Ogibenin, V.A. Sankov, A.A. Bobrov, S.A. Sverkunov, N.V. Misyurkeeva, I.A. Shelokhov and A.V. Parfeevets for their help in collection and processing of the geological-geophysical dataset on the Kovykta GCF.

8. CONTRIBUTION OF THE AUTHORS

All authors made an equivalent contribution to this article, read and approved the final manuscript.

9. DISCLOSURE

The authors declare that they have no conflicts of interest relevant to this manuscript.

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