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Role of Shear along Horizontal Plane in the Formation of Helicoidal Structures

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Abstract—An unusual structural paragenesis, complicated by brachyanticlines, is revealed for the first time in the sedimentary cover of the West Siberian Plate by 3D seismic surveying. These are linear (in plan view) systems of en-echelon arranged low-amplitude normal faults related to wrench faults in the basement. On different sides off a wrench fault, the planes of normal faults dip in opposite directions, forming a helicoidal structure that resembles the blades of a propeller. In the section parallel to the wrench fault, the boundaries of the beds and normal fault planes dip in opposite directions as well. In the section across the strike of the normal faults converging toward the basement, the beds take the shape of an antiform with a crest sagged along the normal faults (flower structure). This structural assembly was formed as a result of interference of stress fields of horizontal shear in the vertical plane (induced by faulting in the basement) and in the horizontal plane (caused by gravity resistance of the cover). In this case, the displacements along the normal faults develop in both the vertical and, to a greater extent, horizontal directions, so that the faults in cover are actually characterized by normal–strike-slip kinematics. The regional N–S-trending compression of the West Siberian Plate is the main cause of shearing along the NW- and NE-trending faults in the basement, which make up a rhomb-shaped system in plan view. Petroliferous brachyanticlines, whose axes, notwithstanding tectonophysical laws, are oriented in the direction close to the maximum compression axis, are known in the large wrench fault zones of Western Siberia. Our experiments with equivalent materials showed that a local stress field arising at the ends of echeloned Riedel shears within a wrench fault zone may be a cause of the formation of such brachyanticlines. The progressive elongation of Riedel shears leads to the corresponding elongation of the brachyanticlines located between their ends. The performed study has shown that the known types of interference of elementary geodynamic settings such as horizontal shear along the vertical plane + horizontal compression (transpression) and horizontal shear along the vertical plane + horizontal extension (transtension) may be supplemented by combination of horizontal shears along the vertical and horizontal planes, resulting in tectonic lamination. By analogy, we propose to name this type of interference of elementary shear settings *translamination.* Petroliferous helicoidal structures arise in the given geodynamic setting of translamination.

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INTRODUCTION

The Epipaleozoic West Siberian Plate is a well-studied region with immense petroleum resources, which are recovered largely from the upper units of plate cover. Owing to extensive geophysical research, including 3D seismic survey, carried out in recent years, important, previously unknown data on the internal structure of the sedimentary cover have been obtained, and these data require adequate interpretation.

STATEMENT OF PROBLEM

In the last 20–30 years, structural paragenetic analysis, also called the concept of structural parageneses [2], has been widely used in tectonic and geodynamic research. The term *structural paragenesis* was introduced by Luk'yanov [9] in the 1960s and became firmly established in the textbook on structural geology published in 1986 [1]. Because of the controversial meaning of this term, we will stipulate here that in our understanding, it refers to "a set of structural forms created in a certain geodynamic setting" [6, p. 170].

Five elementary geodynamic settings (Fig. 1) are recognized [6]: (i) horizontal compression, (ii) horizontal extension, (iii) horizontal shear along the horizontal plane, (iv) horizontal shear along the vertical plane, and (v) vertical shear along the vertical plane.[1] In all these settings, the principal axes of normal stresses or the principal axes of tangential stresses are oriented orthogonally, i.e., in the horizontal or vertical directions.

Natural structural parageneses (assemblies) are not always formed in one elementary geodynamic setting, but are often combinations of multiple (typically two) settings, similarly to any vector in a plane, which can be

[1] In all settings listed above, the cases in point are shears parallel to a conditional orthogonally oriented plane in a volume (Fig. 1), rather than a shear in a specific fault plane.

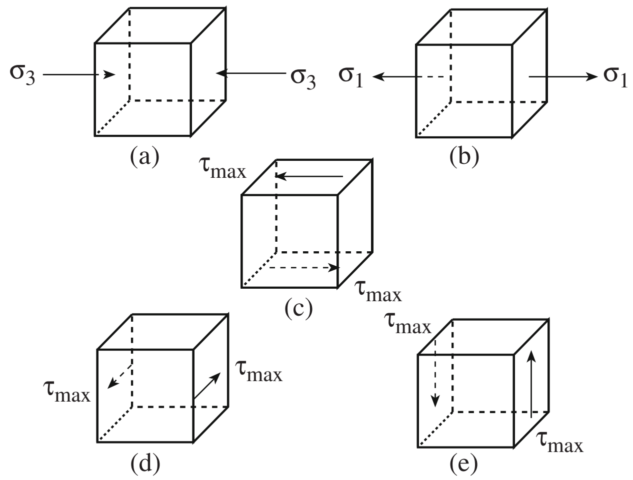

Fig. 1. Five elementary geodynamic settings: (a) horizontal compression, (b) horizontal extension, (c) horizontal shear along the horizontal plane, (d) horizontal shear along the vertical plane, and (e) vertical shear along the vertical plane.

presented as a combination of two vectors parallel to the coordination axes. The formation of verging folds serves as an example. In general, folding of a bedded sequence is a result of horizontal compression (one geodynamic setting), but its vergence is a consequence of contemporaneous horizontal shear along the horizontal plane (horizontal distortion is another setting).

The study of structural parageneses in shear zones indicates that many such zones are formed in combined elementary settings as well. These are the settings of transtension (combination of horizontal shear along the vertical plane with horizontal extension oriented normally to this plane) or transpression (combination of horizontal shear along the vertical plane with horizontal compression oriented normally to this plane).

Another possible combination of geodynamic settings is horizontal shear along the vertical plane occurring contemporaneously with horizontal shear along the horizontal plane. Does this setting take place under natural conditions? So far, this situation has not been considered, likely because structures formed in this way remained unknown.

Owing to the development of 3D seismic surveying, it has become feasible to describe tectonic structures in detail not only at the surface but also deep in the sedimentary cover. In this paper, we discuss the suggested mechanism applied to one of the well-studied districts in the north of Western Siberia.

FACTUAL DATA

New data on the local deep structure of sedimentary cover in the north of the West Siberian Plate (Fig. 2) within its petroleum fields have been obtained recently from interpretation of 3D seismic surveys [4]. The cover is composed of the Upper Jurassic–Oligocene sandshale sequence up to 4.5 km thick. Linear and en-echelon arranged normal faults are related, in our opinion, to wrench faults in the basement (Fig. 3). The NW- and NE-trending normal faults make up a rhomb-shaped system with acute angles of rhombs oriented in the N–S direction. The same strike is typical of the known faults in the basement of the West Siberian Plate [20].

The structural paragenesis of the Yetypur Swell is studied in most detail. The echeloned systems complicating this swell are shown in Fig. 4. On different sides off the axes of these systems, the planes of the normal faults dip in opposite directions, and their S-shaped ends are bent. Thus, the configuration of normal faults resembles a double-vane airscrew or propeller. In most cases, separate normal faults (echelons) do not make up a continuous fracture that crosses the axis of the echeloned system. The average angles between the strike of this axis and the strike of particular normal faults are about 30° in the lower part of the sedimentary cover and increase up to 50° in the upper part of the cover. In vertical section AB parallel to the echelon axis (Fig. 5), the dip angles of the normal faults are not steep (approximately 50°–60°); at the same time, the bed boundaries dip in opposite directions. On connecting the points of intersection of the coeval beds with the fault planes, a fold-and-fault level similar to the folding level can be constructed. In all sections parallel to the echelon axes, this level is nearly horizontal. The amplitude of the normal faults and the dip angles of the beds attain maximums in the middle part of the section and decrease both up- and downsection. In vertical section CD oriented across the strike of the normal faults (Fig. 6), these faults converge toward the basement, forming a flower structure, where the beds depict an antiform with the crest sagged along the normal faults, so that the fold-and-fault level remains nearly horizontal. All these structural features are schematically shown in Fig. 7.

TYPICAL STRUCTURAL PARAGENESES IN SHEAR ZONES

A shear zone is commonly defined as a linear zone with predominance of horizontal shear along the vertical plane; i.e., only one of the three elementary shear settings mentioned above is recognized. The structures arising in the cover above a fault in the basement, whose walls are displaced along the strike, are the most frequent objects of description and modeling. Such structures are termed Riedel shear zones [22, 25, 28]. In terms of stress state, this is a heterogeneous simple shear [16].

The structural forms characteristic of such shear zones are shown in Fig. 8. Riedel shears—synthetic R-shears and antithetic R'-shears—and tension cracks are the main structural elements [18]. Other fractures (P and L), which appear at the late stage of development of shear zones [3], are omitted in the figure. Experimental data [3, 11, 19, 22, 28 amongst many oth-

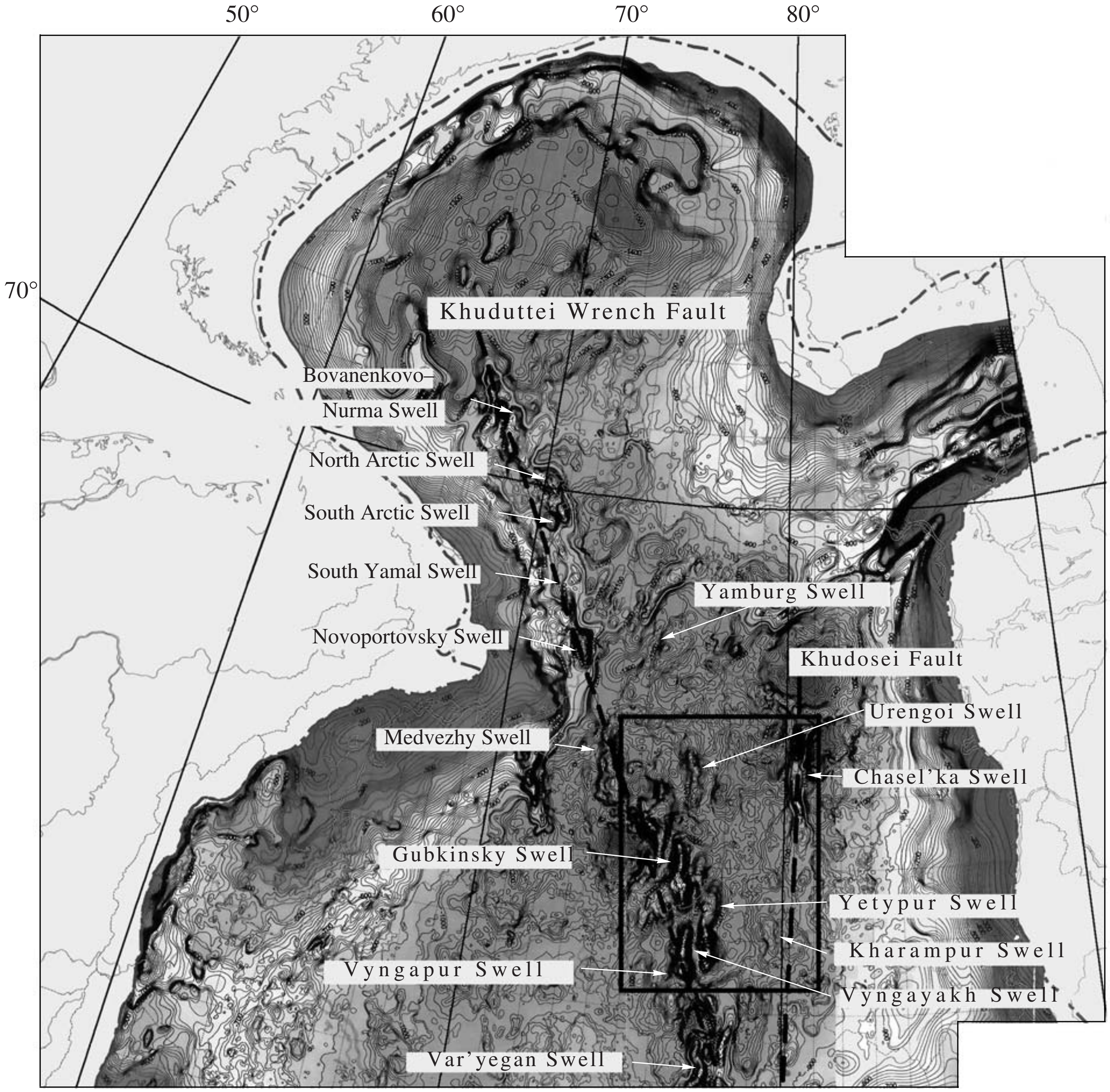

Fig. 2. Structural map of the West Siberian Geosyneclise at the roof of the Albian–Cenomanian sequence, after [13, 4]. The rectangle is the area with structures of horizontal shear proved by 3D seismic surveying (see Fig. 3). The heavy dashed lines are inferred linear sutures related to regional wrench faults in the basement (Khuduttei and Khudosei faults) in fragments or offsets of the Koltogor–Urengoi Rift reactivated at the neotectonic stage. The large swells and local uplifts are en-echelon arranged relative to the regional wrench faults in the basement.

ers] indicate that R' shears are most often formed simultaneously with R shears, but rapidly cease their propagation because of orientation at an almost right angle to the direction of shearing and antithetic character of displacement. Tension cracks develop only in brittle medium, for example, in clay samples moistened with water [19]. Thus, R shears commonly dominate at the early stage of evolution of shear zones. As follows from the results of analogue modeling using equivalent materials, beginning from the early experiments carried out by H. Cloos and W. Riedel in the 1930s and continuing up to recent experimental studies [3, 15, 18, 19, 22, 25, 26, 28, etc.], including those conducted by the authors of this paper at the Belousov Laboratory of Tectonophysics and Geotectonics of Moscow State University, R shears are formed at an acute angle to the direction of general displacement (15°, on average) and develop in the same direction as shear in the basement (Fig. 8, Fig. 10, lower part). Straight, near vertical, and, more frequently, bent S-shaped R shears were formed in the above-mentioned models. In the bent shears, their surfaces are vertical only in the central parts,

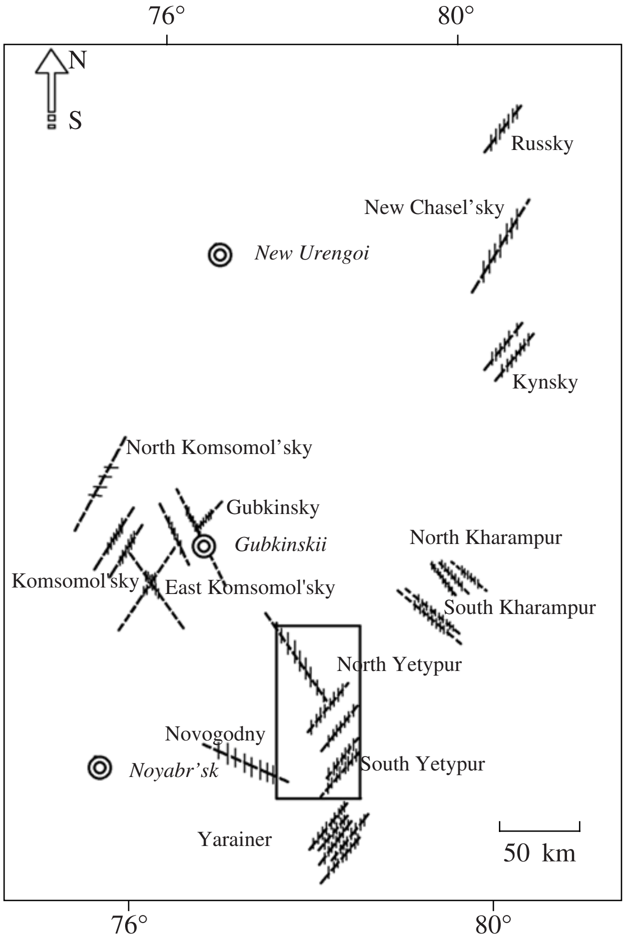

Fig. 3. Axes of shear deformations in the sedimentary cover at the petroleum fields in the central part of the northern West Siberian Plate from the data of 3D seismic surveying, after [4]. The axes of shear deformation (en-echelon arranged normal faults) make up NW- and NE-trending diagonal systems and mark wrench faults in the basement. These systems are oriented relative to each other at an acute angle, the near-meridional bisector of which corresponds to the maximum compression axis controlling shear deformation. The rectangle is the area of the Yetypur Swell covered by 3D seismic surveying (see Fig. 4).

whereas at the flanks, on different sides of the wrench fault, they dip in opposite directions. For the first time, the bent surfaces of R shears were described by Parfenov and Zhukovsky [14] from the results of their experiments. These authors compared such surfaces to a double-vane screw. Afterward, a similar shape was repeatedly described by experimenters [3, 11, 25] and called helicoidal, screwlike, sigmoid, or propeller-shaped. An example of the helicoidal configuration of Riedel shears is presented in Fig. 9. The results of mathematical simulation of horizontal shear zones have also shown that the shear fractures must have a complex screwlike morphology [16].

The structural parageneses arising owing to the combination of two geodynamic settings (shear + com-

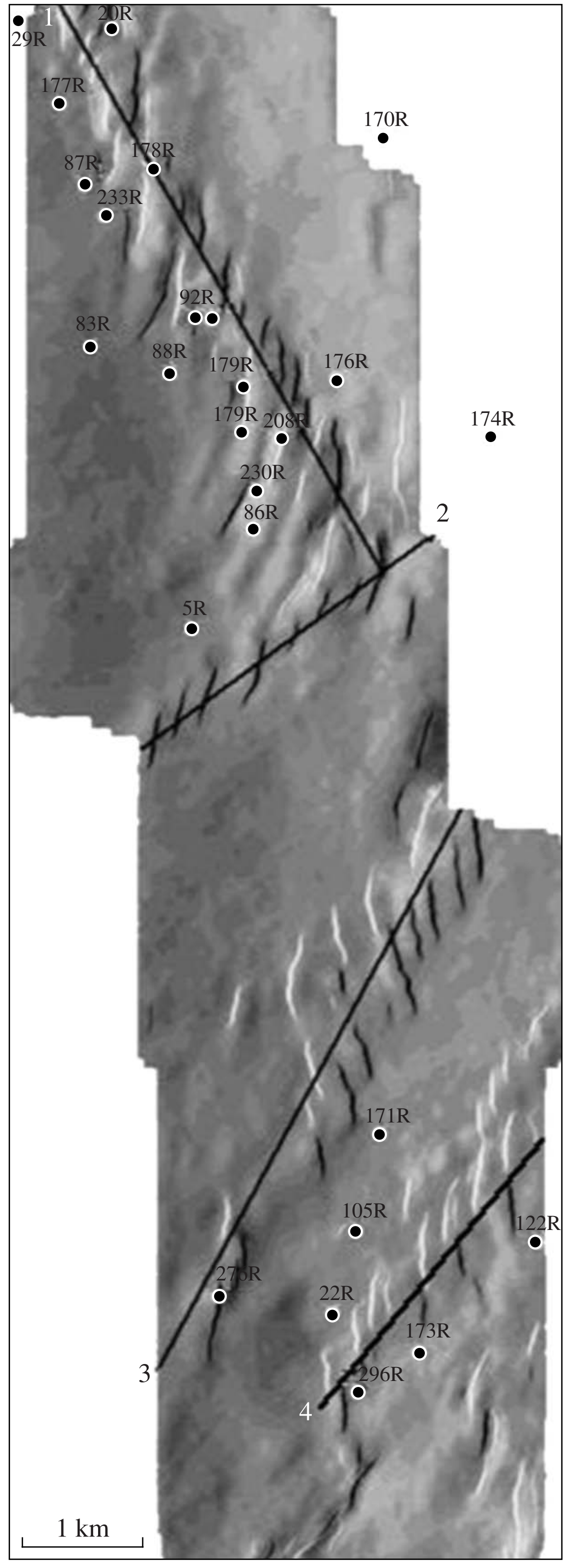

Fig. 4. Map of slope of the roof of Jurassic rocks (Horizon B) at the Yetypur Swell, after [4]. Variations in color correspond to the variations in slope. The solid straight lines are axes of the main en-echelon arranged systems of normal faults in the sedimentary cover above the wrench faults in the basement. The average angles between the axes and particular normal faults are 40°–50°. The numerals are well numbers.

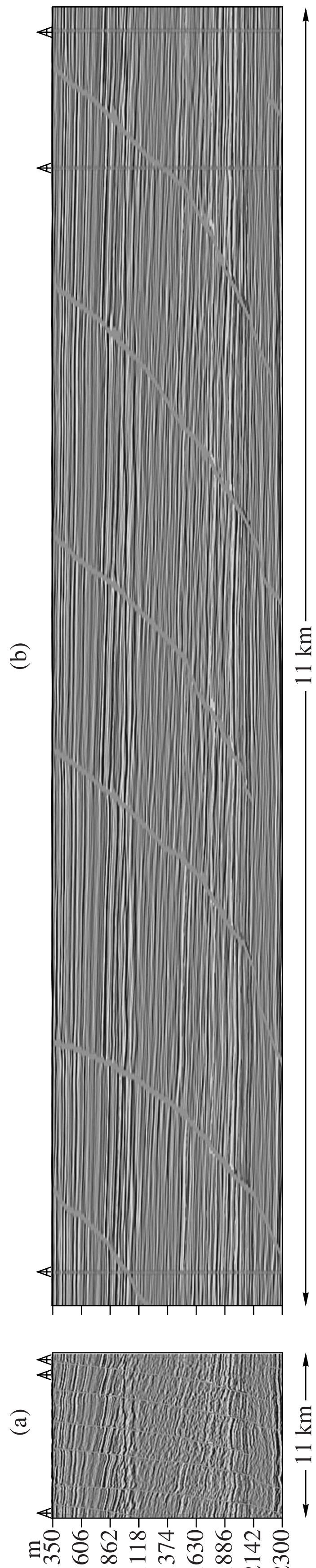

Fig. 5. Characteristic structure of horizontal shear—combination of beds dipping in one direction and normal faults dipping in opposite directions—in the vertical section parallel to the axis of the echeloned system of normal faults in one of its walls. The stratigraphic interval from the Lower Cretaceous to the Paleocene is shown, after [4]. (a) Vertical section with the same vertical and horizontal scales displays minor amplitude of folds and displacements. (b) Vertical section with exaggerated vertical scale clearly demonstrates near-horizontal fold-and-fault level. The rise of beds to the left is compensated by their downward displacement along the system of normal faults. The vertical lines are wells.

pression, or transpression and shear + extension, or transtension) were reproduced in the models as well [12, 23–25, 27, 29]. In the setting of transpression, uplifts accompanied by reverse and thrust faults appeared above the faults in the basement, whereas basins in association with normal faults were formed in the case of transtension.

The facts mentioned in the introduction to this paper and the available neotectonic data allow us to state that the structural paragenesis of the Yetypur Swell in the sedimentary cover was formed at the neotectonic stage as a result of strike-slip displacements in the basement caused by regional N–S compression [4]. This paragenesis differs, however, from the assemblies obtained in experiments. The occurrence of only one system of en-echelon arranged shears in the cover most likely shows that these are R shears that are nearly vertical in their central parts; they arose at a low amplitude of displacement along the wrench fault in the basement at a small angle to the direction of displacement. In the Yetypur Swell, one system of echeloned fractures develops above each fault in the basement, and the angle between the strike of these fractures and the direction of strike-slip faulting reaches 50°. Another difference from the experimental data consists in the moderate dip angles of the fracture surfaces developed in the cover. Finally, one atypical phenomenon is the combination of anticlinal uplifts with normal faults. Thus, the structural paragenesis of the Yetypur Swell is actually unusual and cannot be explained either by heterogeneous simple shear or by a combination of such shear with compression (transpression) or extension (transtension). How could this paragenesis have been formed? To answer this question is the aim of our study.

A MECHANISM OF THE FORMATION OF HELICOIDAL STRUCTURES WITH MODERATE DIP ANGLES OF FRACTURE SURFACES

Experiments reproducing heterogeneous simple shear, when model material (cover) is deformed under the effect of horizontal displacement of underlying rigid plates, do not take gravity into account. In these experiments, the cover, resisting the horizontal displacement of the basement blocks, undergoes only a horizontal shear stress along the vertical plane. At the

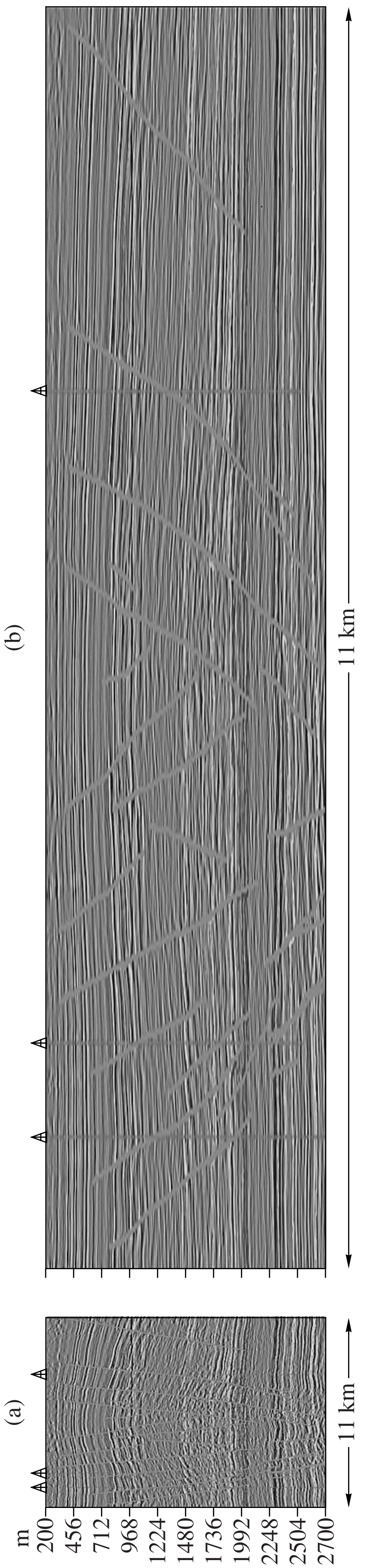

Fig. 6. The flower structure characteristic of horizontal shear in the vertical section across the strike of normal faults converging toward the basement (see Fig. 4). The stratigraphic interval from the Lower Cretaceous to the Eocene is shown, after [4]. (a) Vertical section with the same vertical and horizontal scales displays minor amplitude of folds and displacements. (b) In the vertical section with exaggerated vertical scale, near-horizontal fold-and-fault level is discernible. The upwarping of the antiform is compensated by the collapse of its crest along the normal faults. The folds are waning down- and upsection with upward widening of the zone of dynamic effect of shears in the flower structure. The vertical lines are wells.

same time, the load of sedimentary cover in the nature may be substantial. In the vicinity of the Yetypur Swell, the thickness of the cover locally reaches 4.5 km [21]. In addition, this cover does not terminate at the end of the fault in the basement, as in experiments. In other words, if the faults always have a finite length, then the cover is infinite. Thus, the natural sedimentary cover, whose bottom experiences a significant lithostatic load, also resists the striving of the roof of the moving basement to displace it by friction force in the horizontal direction. Therefore, the cover is affected by stress of lateral shear along the horizontal plane (setting of horizontal distortion responsible, for example, for vergence of folding). Such an elementary geodynamic setting is a homogeneous simple shear with vertical orientation of the plane, where the axes of maximum extension and compression are localized. In this setting, R shears are formed as gently dipping normal faults with dip angles of the fracture planes at approximately 15° (Fig. 10, the southern part). Such structures have actually been obtained in experiments (Fig. 11).

The interference of stresses in both of the aforementioned mutually perpendicular planes creates a stress field transitional between these two extreme cases. As a first approximation, it may be assumed that the dip azimuths and angles of Riedel shears formed in this field are also transitional. The interferential fractures with mean attitudes are shown in the center of Fig. 10. It can be seen that the fracture surfaces form a much greater angle with the fault in the basement than between the Riedel shear zones and, conversely, form a much smaller dip angle than in these zones. In addition, in the case of combined shear settings, Riedel shears must have a normal component. Since the walls of the wrench fault in the basement move in opposite directions, the dip of the normal faults on different sides of this fault will be different as well. This relationship determines the helicoidal shape of Riedel shears. In this case, the surfaces of these shears are nowhere vertical and they do not continuously pass from one fault wall to the other.

Thus, a combination of horizontal shears along the vertical and horizontal planes explains the structural attributes of the shear zones in the Yerypur Swell described above (Figs. 4–7): (i) atypical orientation of

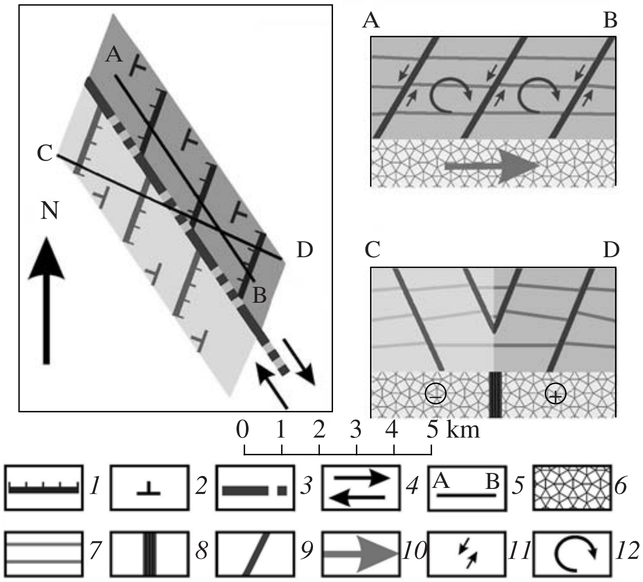

Fig. 7. Schematic morphology and kinematics of horizontal shear. The left panel is the integral structural scheme at the roof of a particular stratigraphic unit of sedimentary cover: (*1*) normal fault; (*2*) strike and dip symbol; (*3*) boundary between zones with opposite dip directions of normal faults located above the wrench fault in the basement; (*4*) direction of slip; (*5*) section line. The right panels are vertical sections: (*6*) basement; (*7*) sedimentary cover; (8) wrench fault in basement; (*9*) normal faults in cover; (*10*) direction of displacement in basement relative to cover; (*11*) direction of displacement along normal faults; (*12*) direction of rotation within brittle–ductile cells. The cover in the northeastern wall of the right-lateral wrench fault in the basement is shown in darker color. This wall moves to the southeast in plan view and toward the observer in section A–B (symbol + in circle as in electric battery). The cover in the southwestern wall of the right-lateral wrench fault in the basement is shown in lighter color. This wall moves to the northwest in plan view and away from the observer in section A–B (symbol – in circle).

Riedel shears, (ii) their normal-fault kinematics in absence of transtension, and (iii) special helicoidal morphology.

Occasionally occurring en-echelon arranged systems of normal faults with unidirectional dip of the fault planes (see Fig. 4, southeastern site) indicate that only one wall of the wrench fault in the basement has moved, whereas the other wall remains immobile. The occurrence of such a system testifies to the activity of only one wall of the underlying wrench fault in the basement and the passive behavior of the other wall. The recognition of attributes of absolute rather than relative offset of different fault walls is, in our opinion, a rather topical issue [8].

BRITTLE–DUCTILE CELLS

The next question concerns the existence of antiforms complicated by normal faults, which are not

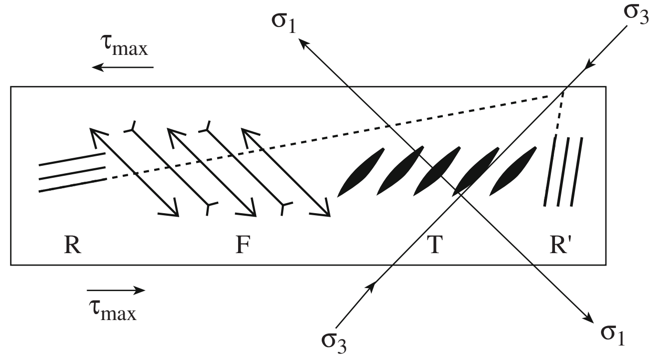

Fig. 8. Typical set of structural elements formed in the setting of horizontal shear along the vertical plane (plan view from above), modified after [6]. The shear zone is oriented parallel to the maximum tangential axis (τ_{max}). The maximum extension and maximum compression axes (σ_1 and σ_3), respectively) lie in the horizontal plane and are oriented at angles of 45° to the strike of the shear zone and at an angle of 90° to each other. The near-vertical tension cracks *T* are formed along the normal to axis (σ_1); near-vertical Riedel shears R and R' slightly deviate from axis τ_{max}, forming an acute angle with a bisector oriented along axis σ_3; upright folds *F* (anticlines and synclines) are oriented normal to axis σ_3.

characteristic of shear zones but nevertheless are documented in the Yetypur Swell (Fig. 5–7). As is seen in the section, the fold-and-fault level is nearly horizontal. Let us turn to schematic section AB that crosses one of the fault walls in the basement parallel to the surface of this fault (Fig. 7). Select a volume (cell) limited by ground and basement surfaces from above and below, respectively, and by the adjacent inclined normal faults on both lateral sides. All these boundaries remain immobile during deformation, and therefore, the selected volume resembles a convective cell with clockwise rotation of material in its center. In other words, the movement from above downward in the right part of the cell

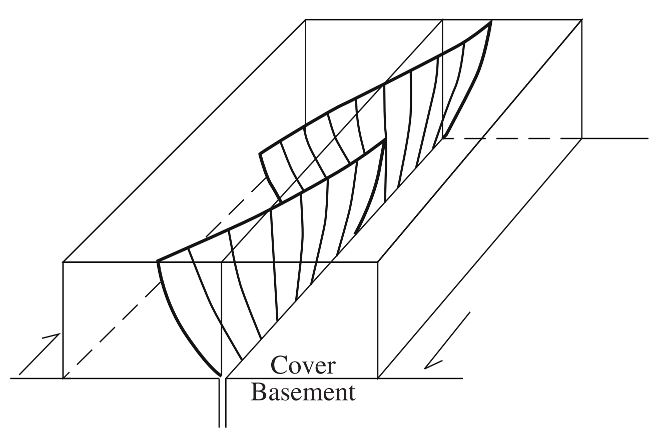

Fig. 9. Helicoidal Riedel shears in the right-lateral strike-slip fault zone from the results of analogue modeling using sand as an equivalent material, after [25].

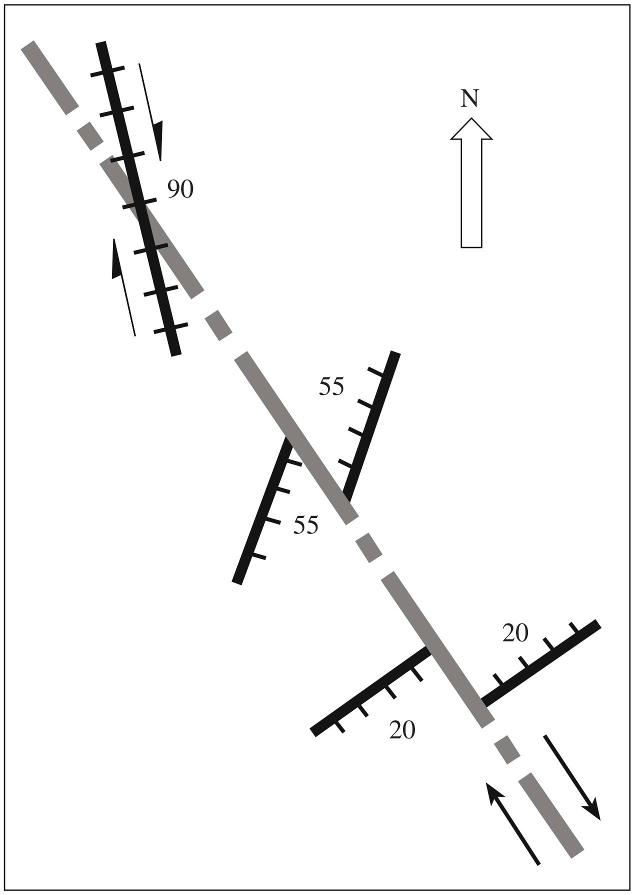

Fig. 10. Formation of helicoidal normal faults in the sedimentary cover. See text for explanation. Numerals are dip angles of faults.

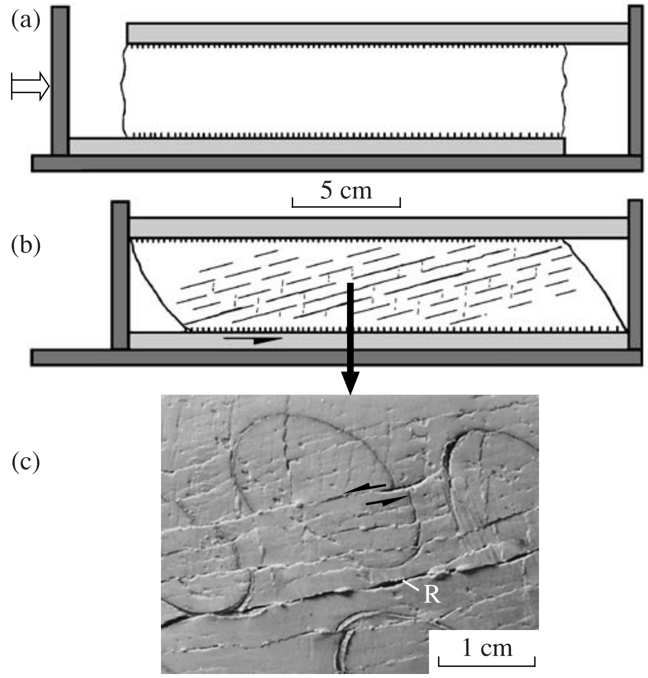

Fig. 11. Experiment reproducing deformation of horizontal distortion (homogeneous simple shear). A sample of wet clay was placed between two rigid plates. The lower plate (basement) is displaced in the horizontal direction; the upper plate is firmly fixed and puts up resistance to displacement: (a) sample before deformation; (b) shear for 1.4 cm; long and short dashes are R and R' shears; (c) a close-up of a lateral portion of the sample. Low-angle R-shears with normal-type displacements are clearly seen.

must be combined with movement from below upward in the left part of the cell with skewing of beds. The rotation is maximal in the center of the cell and decreases toward their horizontal boundaries, as is characteristic of convective cells [6]. As a result, a maximum displacement along normal faults and a maximum inclination of beds is reached in the middle part of the cover. In contrast to convective cells, where the adjacent cells have an opposite sense of rotation (as in linked gears), in our case, the adjacent cells have the same sense of rotation. When turning, the beds tend to stand perpendicular to the normal fault surfaces and therefore undergo some shortening, expressed in the formation of microthrusts (Fig. 12).

Now, let us turn to section CD, oriented across the strike of the normal faults (Fig. 6). The structure described above is reflected specularly relative to the symmetry plane that goes along the fault in the basement. This relationship makes clear the existence of antiform waning up- and downsection above the fault in the basement. Thus, a combination of the two aforementioned elementary settings allows us to explain the development of antiforms coupled with normal faults in the considered district and the near-horizontal orientation of the fold-and-fault level.

Maximal vertical shortening and compensating horizontal elongation took place in the cells located in the lower part of the descending flow of matter, i.e., in the lower part of the hanging walls of normal faults. At the same time, maximal vertical elongation and compensating horizontal shortening occurred in the lower part of the ascending flow of matter, i.e., in the lower part of the footwalls of normal faults, as is characteristic of convective cells as well [6]. This circumstance should be taken into account by estimation of the porosity and permeability of rocks affecting the petroleum resource potential and migration of oil and gas.

Only fracturing in the sedimentary cover above the wrench faults in basement is discussed above; in the general case, linear folds may be constituents of structural paragenesis as well (Fig. 8). It should, however, be noted that folds, as a rule, do not occur in association with tension cracks and Riedel shears. As can be seen from Fig. 8, the fold axes are perpendicular to the maximum compression axis σ_3. At the same time, in recent

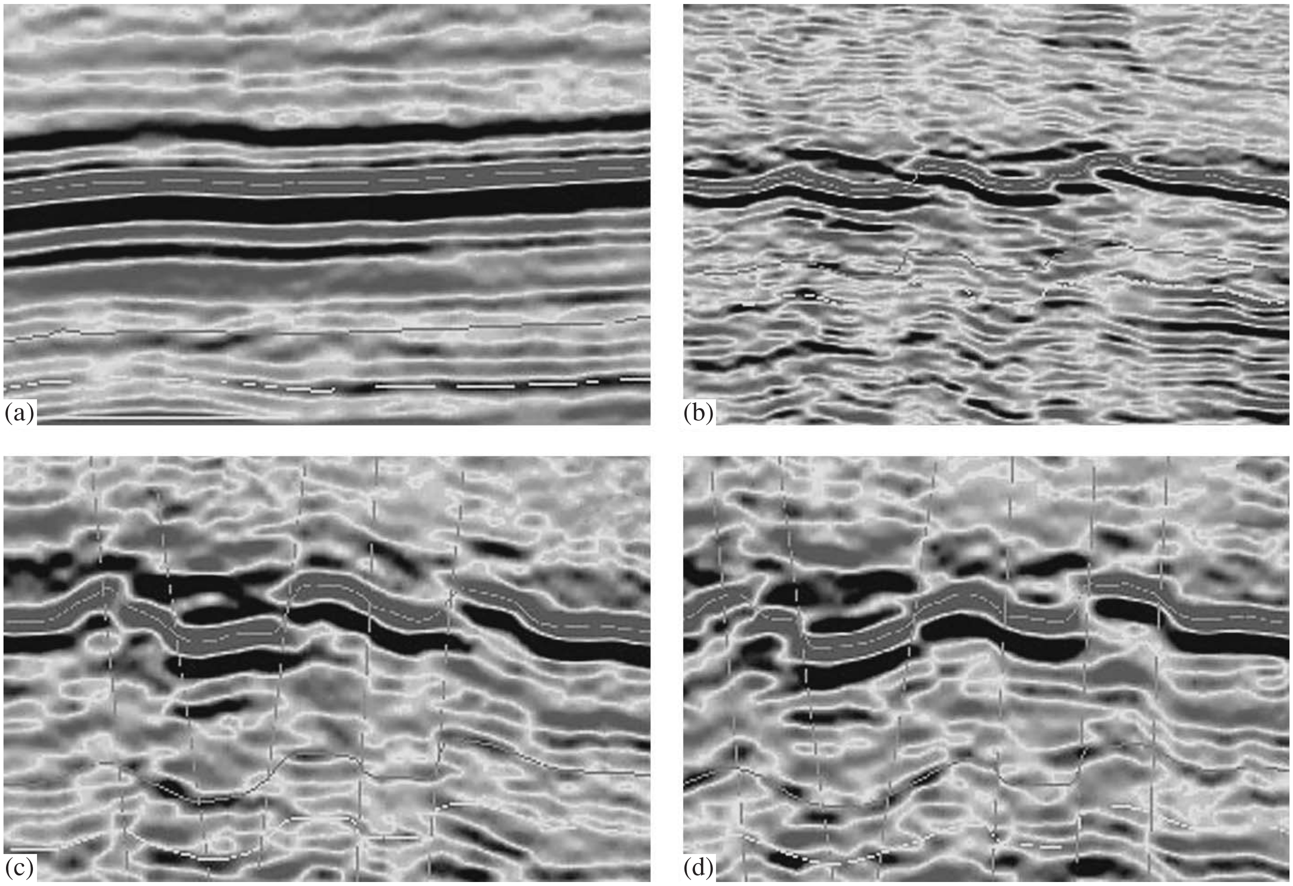

Fig. 12. Microthrusts and other structural elements formed in local setting of horizontal compression, after [4]. Examples of tectonic deformation of the sedimentary sequence in the zone of dynamic effect of horizontal shear of the basement at the level of the Bazhenovo Formation: (a) undeformed state, (b) disharmonic folding and foliation of rocks, (c) tiled onlap of broken fragments of the Bazhenovo Formation, (d) thrusting and boudinage in the Achimovo Formation and the Upper Jurassic.

shear zones of Western Siberia, petroliferous brachyanticlines are known, where fold axes are parallel to σ_3. The elucidation of the formation mechanism of such structural elements is one more objective of this study.

ORIENTATION OF RECENT PETROLIFEROUS BRACHYANTICLINES ALONG MAXIMUM COMPRESSION AXIS: TECTONOPHYSICAL INTERPRETATION

Reproduction of Riedel shears and uplifts in shear zones using equivalent materials. The deformation of sedimentary cover under the effect of near-vertical wrench faults in the basement was reproduced at the Belousov Laboratory of Tectonophysics and Tectonics of Moscow State University. The formation of brachyanticlines with unusual orientation of their axes was reproduced. The structural evolution of the cover consisting of sand and cup grease in the zone of dynamic effect of a wrench fault in the basement was driven by gradually increasing the amplitude of shear. In the experiments, this looked as follows.

First, echelons of small, near-vertical tension cracks arose; further, they were combined into near-vertical Riedel shears (Fig. 13c), supporting the previous suggestion about the origination of shear fractures [5]. Riedel shears were en-echelon arranged above the wrench fault in the basement at an angle of 10°–15° to the strike of this fault. The direction of shear in both the basement and cover was the same.

At the subsequent stages of shearing (Fig. 13d), the areas of the cover located between the ends of neighboring parallel echeloned Riedel shears underwent horizontal compression along the axis oriented close to the strike of the shears. As a result, domelike uplifts appeared with a tendency to stretching in the same direction with progressive elongation of shears and overlapping of their ends. Compression was caused by location of these inner areas of mutual overlapping in the frontal part of the walls of the adjacent shears moving to meet one another. This motion is labeled in Fig. 13d by minor arrows (symbol 3). At that time, the outer areas in the back portions of the opposite walls underwent extension and subsidence. As a result, the

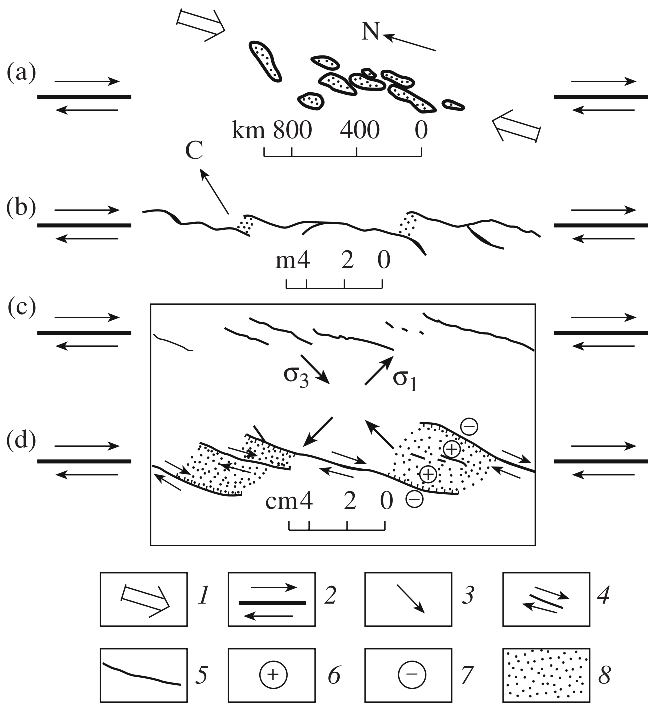

Fig. 13. Brachyanticlines in (a, b) and experimental (c, d) shear zones: (a) arrangement and orientation of recent petroliferous uplifts in the zone of dynamic effect of the regional right-lateral Khuduttei Wrench Fault in the West Siberian Plate (Fig. 2), significantly simplified; (b) uplifts that arose at ends of en-echelon arranged fractures in the zone of dynamic effect of right-lateral strike-slip fault reactivated during 2003 Altai earthquake [17, Fig. 6c]; (c) origination of vertical Riedel shears at initial stages of shear deformation in a model sample; (d) further structural evolution of the sample. (*1*) Direction of regional compression that determines offset along the Khuduttei Wrench Fault; (*2*) arrangement and orientation of wrench faults in basement, which induce folding and faulting in the sedimentary cover; (*3*) orientation of principal stress axes (σ_3, compression; σ_1, extension) in the cover, induced by strike-slip faulting in basement; (*4*) direction of relative displacement along Riedel shears with (*5*) reverse component at their ends; (*6*) sites of compression and uplift at frontal zone of moving walls of Riedel shears; (*7*) sites of extension and subsidence in back zones of moving walls of Riedel shears; (*8*) region of rising.

shear surfaces tilted with a reverse component antivergent with respect to the uplift axis. The shear planes on different sides of the wrench fault dip in opposite directions, forming a helicoidal structure.

Thus, in contrast to the folds in a classic set of structural elements in the shear zones shown in Fig. 8, the folds reproduced in our experiment occur not only in the evident structural paragenesis with faults, but are genetically related to the faults.

Strike of brachyanticlines. As is seen from Fig. 13d, the strike of gradually elongated domes transforming into brahyanticlines is close to the orientation of the maximum compression axis. At the same time, the antivergent configuration of the reverse–strike-slip faults (ends of Riedel shears) framing the uplifts gives the false impression of the formation of these uplifts in the usual way of horizontal compression oriented across the strike of their axes. In fact, no outer (in regard to the brachyanticlines) compression took place. Instead of this, initially near-vertical Riedel shears have been distorted at their ends. As was noted above, the brachyanticlines are not only oriented close to the compression axis, but also elongated in this direction in the process of their growth due to the progressive elongation of the generating Riedel shear that bounds them on both sides. The ends of these en-echelon arranged shears overlap each other further and further, like two trains moving to meet each other.

The petroliferous brachyanticlines of the West Siberian Plate, which arose recently in the zone of dynamic effect of the right-lateral Khuduttei Wrench Fault (Figs. 2, 13a), are examples of atypical folds with forbidden, in terms of tectonophysics, orientation. The Urengoi Uplift is widely known amongst them. Numerous data [4, 21] indicate that near-meridional compression dominated in this region over recent time. In particular, this setting caused the right-lateral offset along the Khuduttei Fault. The orientation of the brachyanticline axes is obviously inconsistent with the trend of regional compression.

The recently published data on the localization of uplifts between the endings of en-echelon arranged fractures in the zone of dynamic effect of the seismogenic right-lateral strike-slip fault reactivated during the 2003 Altai earthquake [17] are noteworthy (Fig. 13b).

It cannot be ruled out that some natural brachyanticlines, including petroliferous swells of the West Siberian Plate (Urengoi, etc.), were formed precisely in this way, that is, in shear setting under compression along their strike. It should be kept in mind, however, that hypothetical large near-vertical Riedel shears as splays of the Khuduttei Wrench Fault are not yet proven by seismic surveying.

RELATIONSHIP BETWEEN THE ATTITUDE OF NORMAL FAULTS IN HELICOIDAL STRUCTURES AND SHEAR STRESSES

A question arises, why the structures of regional rank depicted in Figs. 10 and 13a and, as a first approximation, reproduced in experiments (Figs. 13c, 13d), are characterized by near-vertical Riedel shears oriented at a small angle to the inducing wrench fault in the basement, whereas the local structures (Figs. 3–7) are distinguished by a predominance of normal faults that form an angle of about 45° with the inducing wrench fault. The surfaces of normal faults have medium dip angles (Fig. 12, northern and central parts). In both cases, sedimentary cover of similar thickness of about of 4 km, exerting resistance to horizontal displacement of the basement blocks, creates a geody-

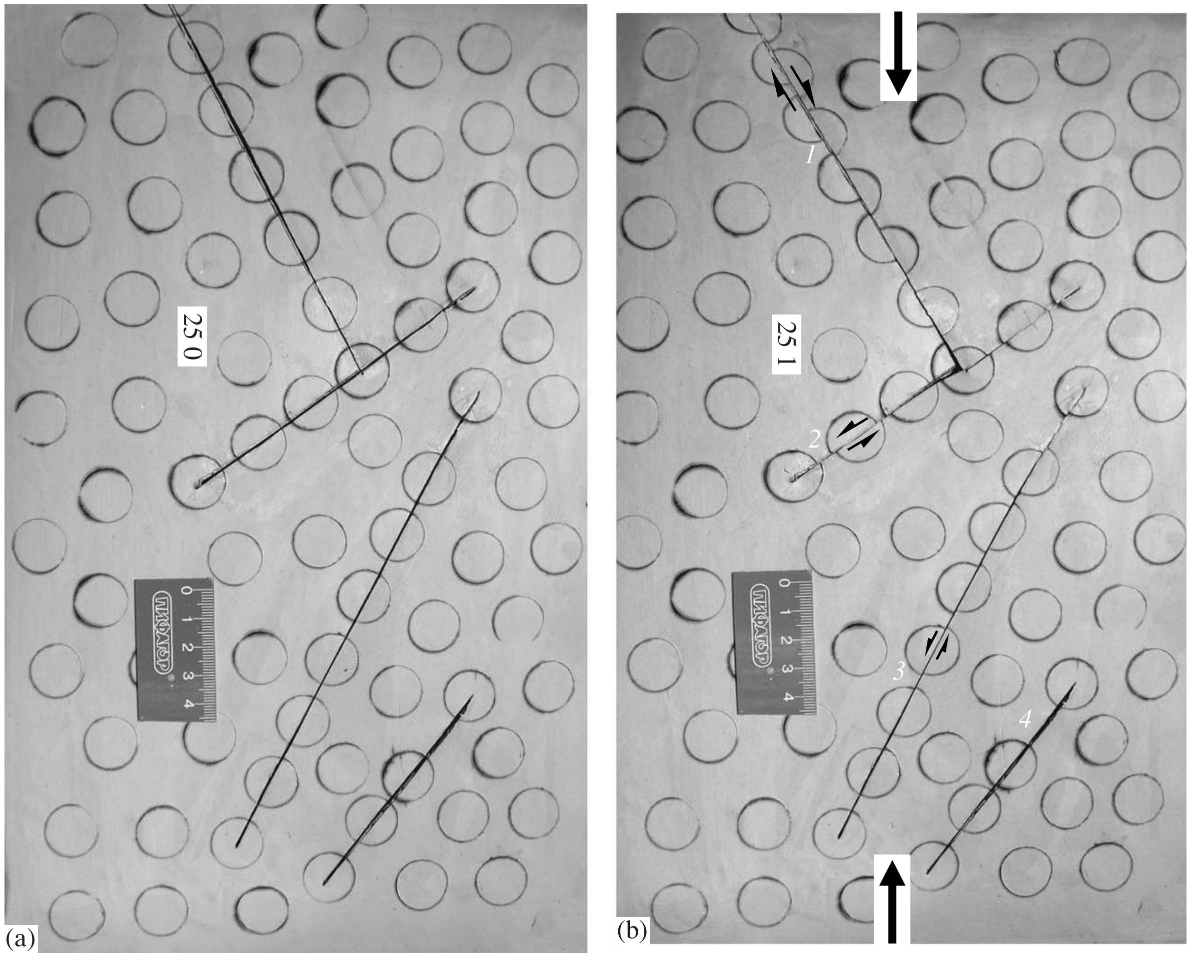

Fig. 14. Progressive development of deformation in experiment. A sample of very viscous clay simulates the basement. The slots made therein correspond to the faults in the Yetypur Swell (Fig. 4). The sample was affected by compression. (a) Sample before deformation, (b) shortening by 0.9 cm with shearing along all faults (arrows) except fault 4.

namic setting of shear along the horizontal plane. Why in the local structure does the strike and dip of the fractures deviate from the strike of the inducing master fault and from the near-vertical orientation, whereas in regional structures such a deviation is not observed?

The following interpretation of this phenomenon seems to be the most plausible. As was shown above, in both cases, a wrench fault in the basement induces horizontal shear along the vertical plane in the overlying sedimentary cover. The shear stress, however, differs in value in a regional wrench fault in the basement, for example, the Khuduttei Fault, which is responsible for the formation of an assembly of fault-line brachyanticlines, and in local shear fractures that complicate one such anticline, for example, the Yetypur Swell. If shear stress along the horizontal plane caused by resistance of the sedimentary cover is approximately equal in both cases, the regional shear stress along the vertical plane is much higher than the local shear stress.

A semiquamtitative term *relative intensity of stress field*, based on estimation of the intensity of fracturing, has been introduced recently [10]. It was shown that regional faults function in a more intense stress field than local faults.

Thus, the effects of vertical and horizontal shear stresses are not equal. In the case of regional faults, the contribution of horizontal shear stress is not great, whereas in local faults, this contribution is commensurable with the contribution of vertical shear stress.

According to this treatment, the normal faults of the echeloned systems above the wrench faults in the basement (Figs. 3–7) are actually R shears deviated from their traditionally accepted near-vertical attitude and orientation close to that of the master fault. These normal faults inevitably have a horizontal component of slip, which is not recorded by 3D seismic surveying but can be estimated in another way.

Statistical processing indicates that separations along faults of various ranks are directly correlated with their extents [10]. In our case, the extent of faults along the strike (Fig. 4) is much greater than the extent down or up the dip (Figs. 5–7). Thus, the horizontal component of slip along normal faults significantly exceeds the vertical component, and in fact, these faults are characterized by normal–strike-slip kinematics. A specific estimate of the horizontal component may be obtained from the vertical component recorded by 3D seismic surveying (Figs. 5, 6) using the statistical relationship between amplitude and length of faults given in [10].

The intensity of shear stress in the vertical plane depends on the orientation of the wrench fault in the basement. The systems of echelons 1 and 2 shown in Fig. 4 strike in different directions. The amplitudes of displacements along the corresponding wrench faults 1 and 2 in the basement are shown in Fig. 14 from experimental data. It is clearly seen than the amplitude of displacement along fault 1 is greater than along fault 2. This implies that the tangential stresses that brought about displacement along fault 1 exceeded those along fault 2. Therefore, the shear stresses in the vertical planes in the zone of dynamic effect of fault 1 were more intense than in the zones of dynamic effect of fault 2. Since the shear stress in the horizontal plane caused by resistance of sedimentary cover was approximately equal (see above), it may be stated that the angle between the strike of normal faults 1 and the fault in the basement should be smaller than the similar angle for echelon system 2. Indeed, in echelon system 1 this angle is 38–40°, whereas in system 2, its average value is 47°. This difference supports our interpretation.

The variations of the strike azimuths of the normal faults and dip angles require further examination.

CONCLUSIONS

The performed study showed that the known types of interference of elementary geodynamic settings—horizontal shear along the vertical plane + horizontal compression (transpression) and horizontal shear along the vertical plane + horizontal extension (transptension)—may be supplemented by a combination of horizontal shear along the vertical and horizontal planes giving rise to lamination. This combination takes into account gravity loading of the sedimentary cover.

By analogy, we propose to call this type of elementary shear geodynamic setting *translamination*. Petroliferous helicoidal structural elements are formed in precisely this tectonic setting.

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