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Neotectonic and Modern Stresses of South Sakhalin

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Abstract—Tectonophysical studies are conducted in South Sakhalin for identification of temporal–spatial changes in the geodynamic settings of the formation of the local structures. Analysis of the field data reveals 11 local stress state (LSS) in the large newest megastructures, which were formed on geological basement of different ages. The parameters of the tectonic stresses are significantly distinct in each LSS, especially the orientations (up to reindexation) of the compression and extension axes in different fault wings. Tectonic stresses of two ages and constant latitudinal and horizontal compression axis are reconstructed. The earlier cofold shear stress field with a horizontal and longitudinal extension axis is post-Miocene and the later stress field of the reversed fault with a vertical extension axis is orogenic. The LSSs reconstructed for the first time by the displacement vectors on slickensides, along with the data on the earthquake mechanisms, substantiate the reindexation of the horizontal extension axis with the vertical intermediate axis of major normal stresses at the postfold orogenic stage of evolution of the territory. These results are in agreement with previous data on the transformation of the dextral to reverse thrust displacements along the longitudinal fault systems. The young stress field is more confidently interpreted in the activation fault zones, which limit the orogenic blocks, whereas the traces of cofold deformations without younger orogenic stress fields better remain inside the blocks which are composed of older and strongly dislocated Mesozoic rocks.

Keywords: neotectonics, tectonic stresses, faults, slickenlines, stress axis, extension axis, Sakhalin Island

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INTRODUCTION

The region studied belongs to the Hokkaido–Sakhalin accretionary–collision area [29], which underwent intense Pliocene–Quaternary compression. The structure is continuing to be formed now along with the evolution of the structural elements of the bottom of the Sea of Japan and the Sea of Okhotsk, Kuril–Kamchatka, and Tohoku–Honshu island-arc systems [5]. The area studied spans the South Sakhalin territory up to 48° N (Fig. 1a).

The aim of our study is to characterize the neotectonic stress state of the region and to identify possible temporal changes in the geodynamic settings of the formation of the newest regional structures, as well as to verify the change in orientation of the tectonic stresses in the west and east of the region, which was probably caused by the influence of various tectonic plates.

The following tasks were solved to achieve the aim of the work:

1. Analysis of the published data on the regional geological structure with emphasis on neotectonic, fault tectonic, structural, and tectonophysical works.

2. Reconnaissance fieldworks to choose the objects of study and field mapping of indicators of tectonic stresses.

3. Interpretation of neotectonic stresses by the field data and modern stresses by the data on the mechanisms of the earthquake focuses.

4. Analysis of tectonophysical data and their comparison with the available published data.

The major field tectonophysical method of interpretation of the tectonic stresses in our work is based on the analysis of the slickenlines, which, in most cases, are the traces of recent displacements. Thus, special attention was paid to the regional neotectonics

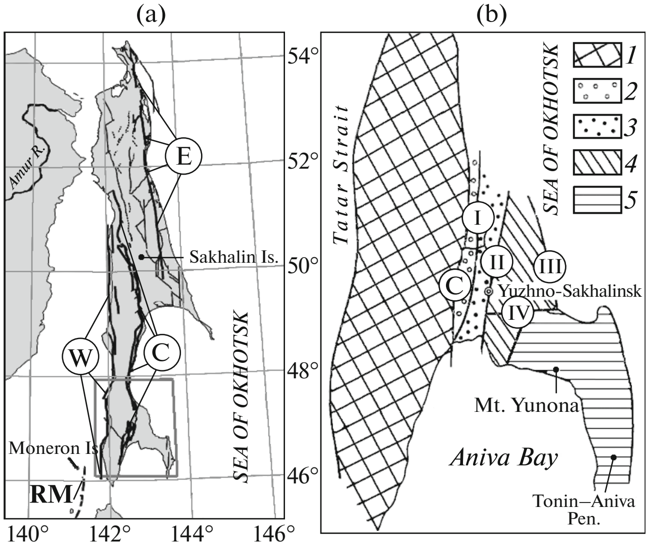

Fig. 1. Location of the studied region and systems of regional faults in Sakhalin (a) according to Rozhdestvenskii and Strel'tsov [22, 27] and scheme of tectonic zoning of modern orogenic structure of the southern part of the island (inside the frame (left map) according to Kuchai [14] and Zharov [9]). Tectonic zones: *1*, South Kamyshovaya; *2*, Teplovodskaya; *3*, Aniva; *4*, Susunai; *5*, Korsakov; fault systems: E, East Sakhalin; W, West Sakhalin; C, Central Sakhalin; RM, Rebun–Moneron; I, Klyuchevskaya; II, Susunai; III, Okhotsk; IV, Khomutovsk.

and the faults which are the most striking indicators of the tectonic stresses.

HISTORY OF STUDY OF REGIONAL NEOTECTONICS

The works of Kuchai [14] and Voeikova et al. [2], in our opinion, are the most modern studies of the regional neotectonics (stage of formation of the major features of the modern relief). These authors rest upon specific geological–geophysical methods of study of the relief and vast previous data on smoothing surfaces and age of the correlated newest sediments. According to Kuchai [14], "the proper orogenic processes, which result in the formation of the modern relief, started in the beginning of the Anthropogene, after termination of the Sakhalin fold phase." In their significant summary of the neotectonics and active faults of Sakhalin, Voeikova et al. [2] distinguished a neotectonic stage of the regional tectonic evolution, the beginning of which corresponds to the launch of accumulation of the Maruyama Formation in the second half of the Miocene [2]. The early ($N_1^2 - N_2^1$) and late ($N_2^1 - Q_1^4$) orogenic stages of evolution of the relief are distinguished in the newest stage, which is responsible for the evolution of the modern relief of the island. The approximate age of the beginning of the newest stage is 11 Ma [2]. The late orogenic stage is subdivided into two substages, which are distinct in the velocity of the processes: early ($N_2^1 - Q_1^1$) and late ($Q_1^2 - Q_2^4$). The early substage corresponds to the very intense regional Sakhalin Pliocene–Quaternary fold phase. The boundary of the subdivisions within the early substage of the postorogenic stage corresponds to the Pliocene–Eopleistocene boundary (1.8 Ma) [2, p. 33]. This boundary corresponds to the transformation of the dextral to reverse thrust displacements along the longitudinal fault systems [4, p. 40]. The following conclusions may be drawn from this brief review of the ages of the South Sakhalin Miocene–Quaternary tectonic events: before the Eopleistocene, it is reasonable to distinguish the Sakhalin fold phase (the final compression phase in the Pliocene–Pleistocene according to Grannik [6]), whereas, following Kuchai, the orogenic stage proper (the period of the formation of the modern relief) should be distinguished from the Eopleistocene (1.8 Ma).

BRIEF DESCRIPTION OF THE REGIONAL TECTONICS

Three large late orogenic megastructures are distinguished in South Sakhalin: the South Kamyshovyi megauplift, the Aniva–Susunai megadepression, and the Susunai–Tonin megauplift. The Poyaskovaya transverse saddle is the boundary between South and Central Sakhalin [2]. In the tectonic zoning of the modern orogenic structure, Kuchai names these megastructures as tectonic zones and identifies the Aniva–Susunai megadepression on the Teplovodskaya and Aniva zones and the Susunai–Tonin megauplift on the Susunai and Korsakov zones (Fig. 1b). The latter zones seem reasonable because they are composed of sediments of terranes of different ages distinguished by Zharov [9]. In spite of the somewhat inconsistent character of the boundary between the newest and older structures, the Susunai zone corresponds to the same named metamorphic Cretaceous–Early Eocene subduction terrane, whereas the Korsakov zone corresponds to the Early Eocene Ozerskii subduction terrane (settlement of Ozerskoe). Previously, Rozhdestvenskii distinguished these zones as a single unspecified metamorphic complex [22], whereas Khain ascribed them to the Central megazone of the Sakhalin–Hokkaido fold–nappe system with a complex nappe–thrust structure and western vergency [29].

These structures are bounded by the largest longitudinal fault zones. The westernmost West Sakhalin zone is characterized by reverse kinematics with a flattened fault plane at depth [27]. The mechanisms of the earthquake focuses which are considered to be related to this fault indicate reverse displacements. The Central Sakhalin fault zone (Tym–Poronai after [22, 30]) is a boundary between the South Kamyshovaya and Teplovodskaya zones; it has a complex structure, includes several faults, and is variously expressed on tectonic schemes of different authors. In kinematics, some faults are reverse faults and thrusts depending on the dip angle of the fault planes to the west [1, 2, 6, 9–11]. The Teplovodskaya structure is separated from the Aniva negative structure by the Klyuchevskii fault; these two structures are combined to the Aniva–Susunai megadepression [2].

The Central Sakhalin fault zone is composed of the fault of the same name and the Pereval'nyi fault, whereas the Klyuchevskaya zone includes the Uspenskii and Aprelovskii faults. In later works, all these fault structures are combined to the Central Sakhalin fault zone [10, 15], with the dextral component of the displacements strikingly expressed in the modern relief along with the reverse constituent [11]. In the Sakhalin fold phase, Rozhdestvenskii distinguished longitudinal dextral shears [21, 22]. The Susunai fault zone separates the Aniva structure from the Susunai and Korsakov zones, which are divided by the latitudinal Khomutovskii fault. Inside the Susunai–Tonin megauplift, Zharov distinguished the Merei suture sinistral shear zone (Fig. 2, after [4]), which "is marked in relief by the linear ridges caused by tectonic contacts of volcano–siliceous and terrigenous rocks" [9, p. 21–22].

The ideas on the orientation of the Sakhalin tectonic stresses are reflected in [4, 22]. As was noted above, according to Rozhdestvenskii, dextral displacements along the longitudinal faults over the entire Sakhalin occurred in the Paleocene–Miocene and from the Late Miocene to the present the structures have formed under latitudinal compression common to South Sakhalin as a whole [22, p. 94], which led to the renewal of longitudinal faults and change in their kinematic type to the reverse type. The opinion on the dominant E–NE compression (60°–90°) from the Pleistocene to the present is supported by Golozubov et al. [4], who conducted special structural studies in South and Central Sakhalin. The major elements of the geological structure of South Sakhalin are shown in Fig. 2 (after [4]).

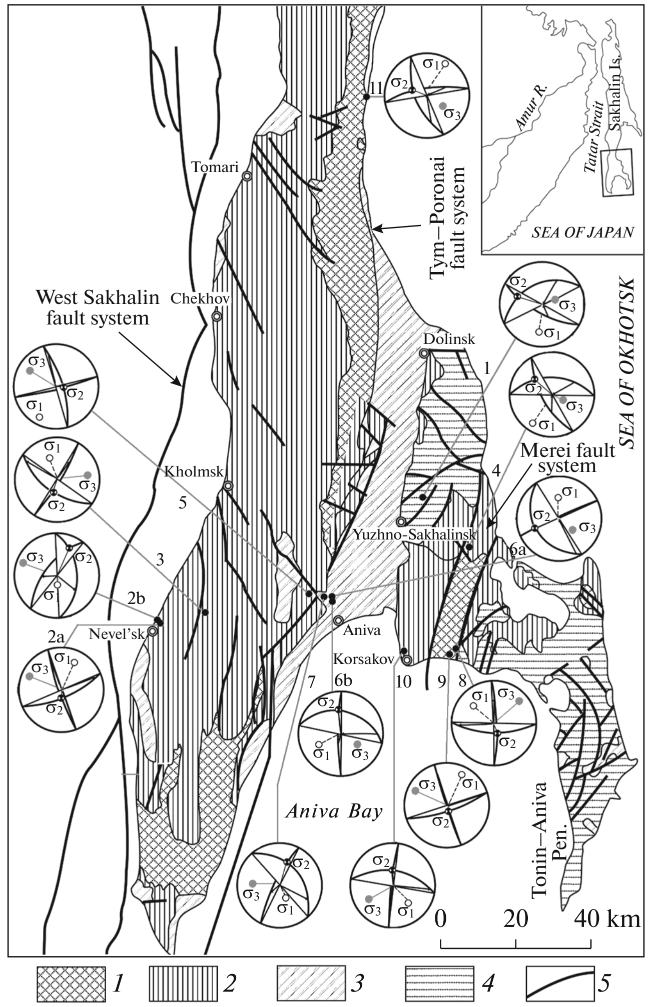

Fig. 2. Scheme of geological structure (simplified after Golozubov et al. [4]) and direction of axes of local tectonic stresses of South Sakhalin. (*1–4*) Complexes of rocks of various ages: *1*, Albian and Upper Cretaceous terrigenous, partly, tuffaceous–terrigenous; *2*, Paleocene–Miocene terrigenous, rarely, volcanic; *3*, Miocene–Quaternary terrigenous; *4*, Cretaceous and Paleocene–Eocene accretionary complexes of the Susunai and Tonin–Aniva terranes; *5*, faults. Stereograms show the axes of the major normal (σ_1, minimal; σ_2, intermediate; σ_3, maximal) stresses and the action planes of the maximum tangential stresses with displacement vectors of the absent wing (Wulff net, upper semisphere). Volumes 1–11, where the directions of the local stresses were determined, are described in the Table and numeration corresponds to the first column.

METHODS OF STUDY OF PALEOTECTONIC STRESSES

Paleotectonic stresses were studied using the kinematic method [7, 8]. The major geological indicator includes vectors of tectonic displacements, which are registered on the planes of any genesis as slickenlines. The latter are mostly observed on the planes of both tectonic and lithogenetic fractures. In the kinematic method, it is accepted that the directions of displacements along the slip planes coincide with the direction of activity of the tangential stress on this plane under specific external tectonic stresses, which are oriented relative to some rock massif. The orientation of the displacement vector allows solution of the reverse task of reconstruction of the orientations of the parameters of the tectonic stresses which caused these displacements. In the kinematic method, the minimum amount of strias (displacement vectors along variously oriented planes) should be no less than five and the possibility of localization of the axes of major normal stresses depends on the dispersion of the orientations of the implemented planes. For example, ten measurements of the displacement vectors on the planes of one of two systems of shear fractures (at dispersion of

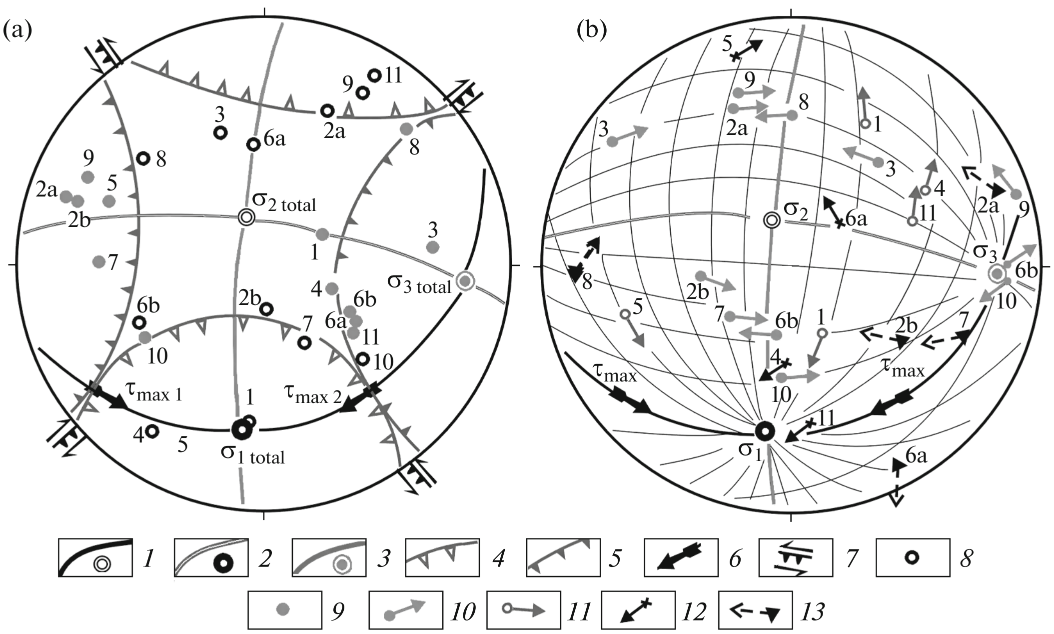

Fig. 3. Stereograms of neotectonic stresses of South Sakhalin. (*1–3*) Axes of major normal stresses of the common field and planes of their action: *1*, intermediate; *2*, minimal; and *3*, maximal compressed stresses; (*4*, *5*) cones: of minimal (extension) (*4*) and maximal (compression) (*5*) stresses; (*6*, *7*) action planes of maximum tangential stresses: *6*, pole and vector of displacement; *7*, strike and kinematic type of displacement; (*8*, *9*) axes of minimal (extension) (*8*) and maximal (compression) (*9*) major normal stresses of the local level; (*10–13*) poles of action planes of maximum tangential stresses of the local level and type of stress tensor: *10*, compression; *11*, extension; *12*, intermediate ($\sigma_1 \geq \sigma_2 \geq \sigma_3$); *13*, which contradict the common field (Wulff net, upper semisphere).

orientation of fracture planes of ±20° and displacement vectors on them of ±5°) localize the compression and extension axes with an accuracy of no more than 50°–60°. At the same time, with only two measurements of each system of shear fractures (four measurements in total), it is possible to determine the necessary axes with an accuracy of up to 5°–10°. Such a conclusion follows from the analysis of the distribution of orientation of the displacement vectors on the entire assemblage of variously oriented implemented planes calculated by Gushchenko [8]. In addition to the kinematic method, we define the shear joint fractures after Gzovskii [3].

The common stress field was determined according to the method of Sim [23, 24], which is substantiated by mathematical modeling of the stress fields near the fault under displacement along it [16]. According to modeling, the local tectonic stresses, which are changed due to displacement along the fault, follow certain rules: all axes σ_1 or σ_3 of the single-rank local stresses which are caused by displacement along the fault of the higher (greater) rank are described by compression and extension cones on the common stereogram with a top angle of 90° (Fig. 3a). No extension and compression axes should be present in the compression and extension cones, respectively. The cone axes are perpendicular to each other and are the compression and extension axes of the common stress field (of the given external field (in modeling) which caused the displacement along the fault), whereas the points of their contacts are the poles of the action areas of the maximum tangential stresses. The mutually perpendicular local compression and extension axes in the different fault wings at their ends fall into the area between the compression and extension cones. According to [23, 24], the precision of determination of the stress axes at a given number of measurements (informative slickenlines) is almost the same as in the kinematic method [8].

Depending on the scope of the studies, the common stress field which is reconstructed by this method may be interpreted as regional if the local stress states (LSS) are reconstructed in different regional structures (in fold wings, hinge, opposite fault wings, etc.) or as external relative to the structure studied (e.g., ore deposit). Additional analysis is needed when the distribution of the orientation of the axes of the local tectonic stresses do not meet the above-listed conditions. These could be local tectonic stresses of different rank (e.g., some determinations characterize the stress field disturbed, which is caused by displacement along a small fault in the volume with one LSS rather than in the unknown common stress field, or local tectonic stresses of different age are reconstructed, etc).

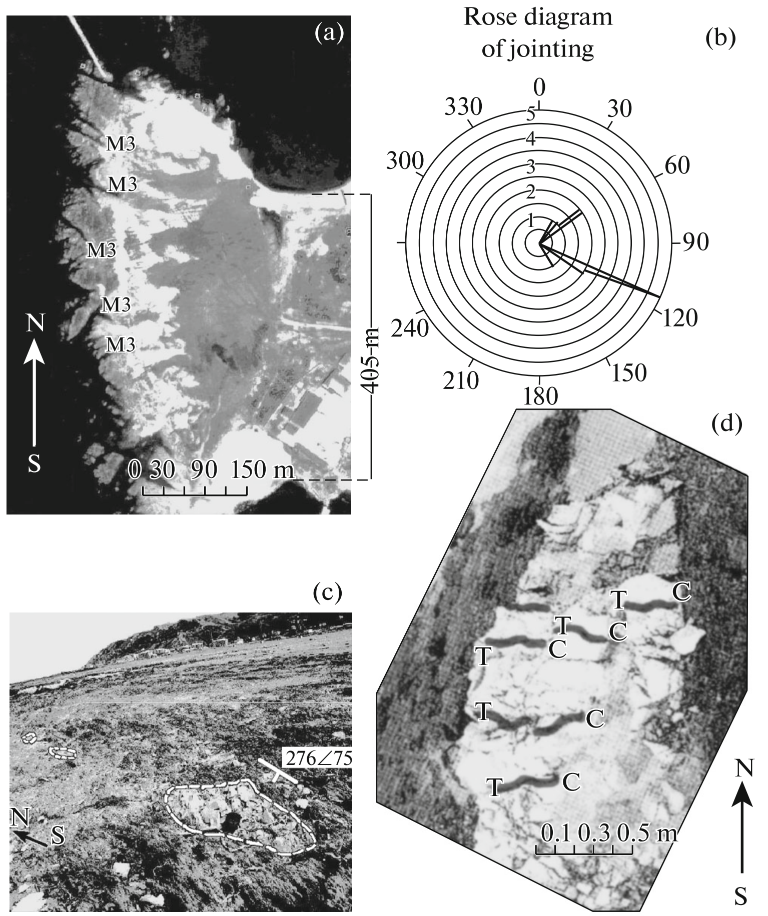

Fig. 4. Indicators of post-Early Miocene stresses on the newly formed marine terrace (dried bench in the southern part of the town of Nevel'sk). (a) Image of the terrace with a scale after www.yandex.ru/maps (2014) (dark is sea surface with visible minigulfs, mg); (b), rose diagram of jointing on its surface (compression axis by bisector of acute angle after Gzovskii [3] is oriented along azimuth of 92.5°); (c) location of three boudines on the newly formed marine terrace (the size of the photo camera is 25 cm); (d) tension cracks (indicated by T–C bands) in the boudine (the extension axis is oriented along the azimuth of 182.5°).

RESULTS OF STUDY

Tectonophysical studies were conducted in 15 observation points of South Sakhalin. To distinguish the homogeneously uniaxially loaded volumes of rocks, we combine the observation points with constant slickenlines located in a common structural position. If two or more observation points are situated, for example, in the same fold wing and the measurements of the displacement vectors agree with the determination of the common stress condition, these points were combined to the common volume with the LSS. For example, we combined points 3 and 4, which were documented in the monoclinal rocks at the northern edge of the town of Nevelsk (point 4) and the newly formed marine terrace (dried bench, point 3) in the southern part of the town. Figure 4 shows the general view of this terrace, the western coast of which is cut by an evident system of shear joint fractures flooded by elongated minigulfs (mg). The same shear system is measured in the foliated clayey shales of the Miocene Upper Dui Formation [4, p. 28] with a boudinated interlayer of silicified marl (Fig. 4c). At the variable dip azimuth of foliation from 250° to 280° and the dip angle of 70°–75°, the generalized compression normal to foliation is oriented horizontally and latitudinally, whereas extension is horizontal and longitudinal along the pulled apart marl boudines. By shear joint fractures (Fig. 4b), according to the method of Gzovskii [3], the compression and extension axes are oriented along the bisector of acute and obtuse angles between the joint fracture systems by azimuths of 92.5° and 182.5°, respectively; the extension axis is similarly oriented along the boudines. The measurements of the displacement vectors are combined in points 1 and 2 of the Bureya quarry and points 9 and 10 of the Petropavlovskii quarry. Other volumes with common stress condition include outcrops which are not disturbed by the faults. Special attention was paid to the presence of faults of various scales, which is related to multiple changes in the LSS parameters of various fault wings [24, 25]. Eleven homogeneously loaded volumes with LSS are distinguished (Table, Fig. 2). Below, the ref-

Orientation of tectonic stresses of the South Sakhalin

Volume number	Observation point Region or positioning	σ_1, azimuth and dip angle	σ_2, azimuth and dip angle	σ_3, azimuth and dip angle	τ_{max}, azimuth and dip angle	τ_{max}, azimuth, dip angle, type
1	1, 2—Bureya quarry, headwater of the Bureya River	6 ∠ 2	106 ∠ 25	243 ∠ 56	27 ∠ 68 NS	148 ∠ 35 ND
2a	3, 4—town of Nevel'sk, northern suburb and marine terrace in the southern part of the town, ancient field	202 ∠ 20	356 ∠ 67	110 ∠ 9	68 ∠ 82 RS	335 ∠ 69 RD
2b	3, 4—town of Nevel'sk, northern suburb and marine terrace in the southern part of the town, young field	356 ∠ 67	202 ∠ 20	108 ∠ 10	126 ∠ 57 DR	266 ∠ 38 SR
3	5—500 m east of Nevel'sk pass	162 ∠ 30	21 ∠ 55	264 ∠ 18	302 ∠ 80 RD	38 ∠ 56 RS
4	7—Listvennichnyi quarry	34 ∠ 10	130 ∠ 32	288 ∠ 54	60 ∠ 63 NS	180 ∠ 44 ND
5	8—Lyutoga River, near the bridge up of the village of Ogon'ki	18 ∠ 10	271 ∠ 68	112 ∠ 20	345 ∠ 83 ND	252 ∠ 70 S
6a	9, 10—Center of the quarry near the settlement of Petropavlovskoe, young field	176 ∠ 36	65 ∠ 28	306 ∠ 43	92 ∠ 82 DN	492 ∠ 34 NS
6b	9, 10—Quarry near the settlement of Petropavlovskoe, ancient field	65 ∠ 30	176 ∠ 32	302 ∠ 43	92 ∠ 82 NS	192 ∠ 34 ND
7	11—500 m from the barrier at the entrance to the Petropavlovskii quarry	330 ∠ 50	196 ∠ 30	90 ∠ 20	118 ∠ 74 DR	229 ∠ 35 RS
8	12—Mt. Yunona, upper bench of the quarry, SE wall	132 ∠ 23	343 ∠ 65	227 ∠ 10	268 ∠ 80 RD	2 ∠ 66 S
9	13—Mt. Yunona, lower bench of the quarry, SW wall	208 ∠ 10	345 ∠ 75	118 ∠ 10	76 ∠ 89 RS	344 ∠ 76 D
10	14—town of Korsakov, rocky wall, 150 m from ul. Vokzal'naya	314 ∠ 30	176 ∠ 52	58 ∠ 30	94 ∠ 84 RD	188 ∠ 54 RS
11	15—Tikhaya Bay, to the right of the Tikhaya River mouth	210 ∠ 5	116 ∠ 50	304 ∠ 40	172 ∠ 65 ND	70 ∠ 60 NS

Dip azimuth and angle of axes of major normal stresses: σ_1, extension axis; σ_2, intermediate axis; σ_3, compression axis; τ_{max}, dip azimuth and angle of action plane of maximum tangential stresses; kinematic type: R, reverse fault; N, normal fault; S, sinistral strike-slip fault; D, dextral strike-slip fault. Letters with dominant displacement types are underlined (PV, right strike-slip–reverse fault, reverse component is greater than strike-slip one). The action planes of the maximum tangential stresses, which contradict the common stress field (volumes 7, 8), are italicized. Common stress field: σ_1, 8 ∠ 20; σ_2, 159 ∠ 68; σ_3, 274 ∠ 9; τ_{max}, 233 ∠ 82, RS; τ_{max} 138 ∠ 70, RD.

erences to the position of all of the volumes with LSSs will be dropped because they are shown in Fig. 2 and the orientation of the LSS parameters is presented in the Table.

Five volumes with LSSs are distinguished in the South Kamyshovyi megauplift. Two of them are characterized by two LSSs: in the area of the town of Nevelsk (volumes 2a and 2b) and in the central part of the Petropavlovskii quarry of construction materials (volumes 6a and 6b). Determination of the temporal relationship of the two stress states took into account the rare planes with two traces of tectonic movements (one of which is younger because it cut the underlying traces of the earlier displacement) and expression of the slickenlines: the better expressed sliding traces with confident displacement sign were ascribed to young traces. In addition, the reversed mechanism of the Nevelsk earthquake of 2007 [12, 26], which was consistent with younger stress states, vertical extension (azimuth of axis plunge is 356 ∠ 67), and latitudinal compression axis, was considered on the newly formed terrace. The young stress condition is responsible, thus, for the modern stage. The lower age boundary of the older stress condition (post-Miocene) is determined by the age of the rocks, which are cropped out in the dried bench (on the basis of the age of the layers exposed in the bench). Volumes 6a and 6b in the western wing of the fault exposed in the Pet-

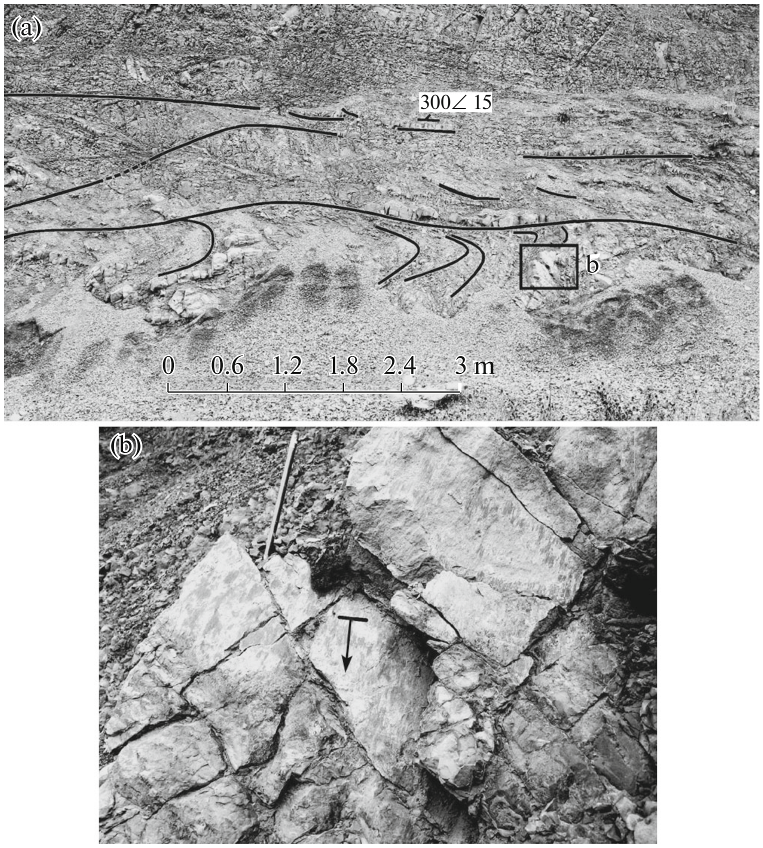

Fig. 5. General view of deformed rocks in the western wing of the fault exposed in the Petropavlosvskii quarry (a) and plane with slickenlines (b) (inset in Fig. 4a). Image (a) shows deformation of some horizons presumably caused by interlayer sliding at generalized dip of the layers along the azimuth of 300 ∠ 15. Image (b) exhibits the normal displacement along the slickenlines; the dip azimuth of the fracture plane is 170 ∠ 55; a pencil 20 cm long is oriented parallel to the displacement vector. It is evident that the slickenlines are not related to the deformation of the rocks registered in Fig. 5a.

ropavlovskii quarry include monoclinal small-rubble claystones, interlayers of gravelstones, and siltstones of the Neogene with dip azimuth of 300 ∠ 15–335 ∠ 10 (Fig. 5). On the cosmic image, the fault in this area is NNE-trending and WNW-dipping. In points 9 and 10 (volumes 6a and 6b, Petropavlovskii quarry), we distinguished two LSSs of different age due to two generations of slickenlines in observation point 10 on the planes of fractures 1 and 4 with dip azimuths of 220 ∠ 68 and 150 ∠ 68, respectively. No displacement signs were identified by older slickenlines, whereas, by the slickenlines of the second (younger) generation, which, on both planes, cut younger displacement vectors, we established displacements which contradict the common stress condition by orientation of the extension axis. The compression axis occurs in an acute angle, which is formed by joint fractures 1 and 4 and is in agreement with the position of the compression axis common for two generations of the slickenlines and two deformation stages. Other displacement vectors measured on other planes of this volume are consistent with a NW-dipping compression axis at an azimuth of 306–302 and angles of 40° and 43°; the difference in their orientation is within the measurement error of the displacement vectors; i.e., the compression axis can be considered constant at both deformation stages. Some displacement vectors agree with the extension axis which complies with the extension axis of the ancient stage, whereas other ones require its reindexation with an intermediate axis.

One LSS is reconstructed in a local longitudinal fault zone (dip azimuth of 85 ∠ 63) of Neogene sediments in the south wall of the road toward the town of Nevelsk at a 500-m passage to the east of the town (volume 3) and at the left bank of the Lyutoga River (volume 5) in the monoclinal Neogene siltstones and claystones with interlayer of conglomerates ~4 m thick (volume 5). On the stereogram of the common stress field (Fig. 3), flat latitudinal orientation of the compression axis in volumes 2a, 2b, 3, 5, and 7 are typical of the South Kamyshovyi megauplift. The steepest extension axes in this area are reconstructed in the structure analyzed: 50°–67° (volumes 2b, 7). The flat compression axes are also characteristic of weakly deformed monoclinal layers in the area of the village

Fig. 6. Fault zone in the Listvennichnyi quarry. Columnar structures of the Lower Cretaceous mafic volcanic rocks (upper left part of the image), some of which are deciphered (right upper part of the image), are seen in the hanging wing of the fault (dip azimuth of the plane is 140 ∠ 80, dextral normal–strike-slip fault, angle of inclination of slickenlines to the horizon is 16°).

of Ogon'ki (volume 5) and of the rocks near the Nevelsk pass (volume 3).

In spite of the small amount of homogeneously axial volumes, it can be suggested that, at the early orogenic stage, the structure underwent shear tectonic stresses at latitudinal flat compression, whereas at the late orogenic stage and constant orientation of the compression axis, the extension axis became vertical, which should lead to strongly dominant reverse component of the displacements, especially, along longitudinal faults. This suggestion is confirmed by the conclusions of Rozhdestvenskii [21], the data of Kuchai (who mapped the Aprelovskii thrust, along which Neogene sequences are thrust on Quaternary sediments [14]), and the conclusions of Golozubov et al. [4] on the flat compression axis in the west of South Sakhalin.

In the Lower Miocene foliated clayey shales with interlayers of silicified marls, two systems of shear joint fractures are well manifested in the western bank on the newly formed marine terrace in the southern part of the town of Nevelsk (the uplift which was formed during the Nevelsk earthquake on August 2, 2007) (Fig. 4a). The post-Miocene shear stress field with horizontal compression and extension axes is interpreted on the basis of the rose diagram of jointing (Fig. 4b) and the method of Gzovskii [3]. The boudines in the layer of silicified marls (Fig. 4c), as well as the tension cracks in the boudines (Fig. 4d), allow determination of the longitudinal and horizontal extension axis, which coincides with the extension axis reconstructed by shear fractures. Thus, the post-Miocene LSS with a latitudinal compression axis normal to the foliation surfaces and a longitudinal extension axis is reconstructed in volume 2a. In this volume, we also reconstructed the later stress field, where, under a constant compression axis, the intermediate axis replaced the extension axis (reindexation of axes) and the later stress field became reversed. This corresponds to the focus mechanisms of the Nevel'sk earthquake of August 2, 2007.

The Susunai–Tonin megauplift is characterized by five LSSs, including one LSS within the Cretaceous–Early Eocene Susunai metamorphic subduction terrane (Table, Fig. 2), one LSS of the Merei suture zone, and three volumes within the Early Eocene Ozerskii terrane (classification of the terranes is given after Zharov [9]). Shear–normal fault LSSs with flat extension and steep compression axes are reconstructed in the Bureya (Bureya River, volume 1) and Listvennichnyi (Listvennichnoe settlement, volume 4) quarries. The striking small structural forms (evident shear fractures, numerous quartz veins, small folds), which indicate numerous stages of the formation of the common structure exposed in the quarry, are features of the stress condition of Cretaceous gray shales with dip azimuth of foliation planes of 50–75 ∠ 40–55 in the Bureya quarry. For example, quartz veins fill both the shear fractures, which are transversely oriented to foliation, and the planes among the shale members, which are parallel to foliation. Locally, shear fractures cross the veins displacing them and the veins shift the shears along the foliation, indicating repeated extension conditions after metamorphism. Japanese and Sakhalin researchers have established three deformation stages in the Susunai terrane during subduction, its underthrusting at a depth of more than 6–10 km, and exposition on the surface [5, p. 61]. Nevertheless, the traces of the most recent displacements (slickenlines) along both the fractures and the foliation planes evidently register the steep WSW-trending compression axis at an azimuth of 243 ∠ 56 and flat longitudinal extension axis (volume no. 1).

The NE-trending fault with a dip azimuth of 140 ∠ 80 is exposed in the Listvennichnyi quarry. Altered mafic volcanic rocks with typical basaltic columnar structure (Fig. 6), which are faulted against terrigenous country rocks, are cropped out in the western wall of the quarry. Joint planes of igneous rocks with dip azimuth of 140°–180° and dominant dip angles of 50°–60° are streaked by thick slickenlines indicating right-lateral shear with an insignificant normal component. Two action planes of maximum tangential stresses are reconstructed in this volume, one of which (latitudinal, 180 ∠ 44, volume 4) is evidently distinguished on the LSS stereogram by the maximum planes with slickenslides.

The analysis of the factual data from the Listvennichnyi quarry shows that the strikingly expressed fault in the rocks of the quarry does not belong to the major faults of the NNE-trending Merei suture zone and the reconstructed stress condition in the hanging wall of the NE-trending fault can have a local character of the near-fault stress condition.

The three LCSs in the Early Eocene Ozerskii terrane are confined to the different benches of the Prigorodnyi quarry (settlement of Prigorodnoe, southern slope of Mt. Yunona) and to the northern edge of the town of Korsakov (volumes 12–14), which are combined by the shear stress condition with flat variously oriented compression and extension axes.

Brecciated tuffaceous sandstones, silty sandstones, and siliceous horizons are intercalated in the Prigorodnyi quarry, at the southeastern slope of Mt. Yunona. The northern wall of the quarry (in the upper bench, point 12) exposes beige tuffaceous sandstones with subordinate siltsones, which are intensely altered in the NE-trending fault zone (dip azimuth 320–330 ∠ 75–80). The LSSs, the axes of major normal stresses of which almost replace each other, are reconstructed in the hanging wall of the fault of the upper bench and are well-exposed in the footwall of the lower bench. The flat compression axis in the hanging wall (volume no. 8) is SW–NE-trending and close to the extension axis in the footwall (volume no. 9), whereas the flat SE–NW-trending compression axis in the footwall is close to the extension axis in the hanging wall. Such reindexation of the axes of the major normal stresses is evidence of the activity of the fault [24, 25], which corresponds to redistribution of the local axes of major normal stresses in the vicinities of the faults caused by displacement along the fault according to modeling [16]. The LSS with orientation of major normal stresses for the flat (dip angle 30°) WSW-dipping siltstone layers (volume no. 10) is similar to that in the hanging wall of the fault in the Prigorodnyi quarry: flat NE- and NW-trending compression and extension axes, respectively.

A complex zone of the East Sakhalin longitudinal fault with several fault planes (dip azimuth of 80–90 ∠ 85 and 280 ∠ 75) and a transverse fault (160–170 ∠ 87) is identified in the Miocene boulders, conglobreccias, and conglomerates (dip azimuth of 200 ∠ 52) of Tikhaya Bay (the northernmost observation point). In the transverse fault zone, we measured 18 orientations of the displacement vectors as slickenlines, which are the basis for reconstruction of the normal fault–shear LCS with the NW-dipping compression axis (304 ∠ 40) and SW-dipping extension axis (210 ∠ 5) (volume no. 11). The numerous longitudinal quartz veins in the observation point are characterized by averaged orientation with dip azimuth of 80–90 ∠ 70–80, which are parallel to the seacoast. They are consistent with the downwarping of the Okhotsk plate and contradict the extension axis found by slickenlines indicative of a young stress field, which caused their formation.

The common shear stress field, which is reconstructed for the entire area (Fig. 2) on the basis of 13 determinations of the LSS axes in 11 homogeneously axial loaded volumes (in two of them, we identified two LSSs), is characterized by the following parameters: $\sigma_1 - 8 \angle 20$, $\sigma_2 - 159 \angle 68$, $\sigma_3 - 274 \angle 9$, τ_{max} 233 $\angle$ 82, left-lateral reverse strike-slip fault, τ_{max}138 $\angle$ 70, right-lateral reverse–strike-slip fault with dominant shear component of the displacements by both planes (Fig. 3a).

It should be noted that the local axes of the major normal stresses, which are reconstructed in the different wings of the fault in the Petropavlovskii quarry, indicate latitudinal compression. Only under such compression should the NW fault wing move to the NE and cause the local compression, which is parallel to the fault plane in the frontal part of the moving wing. In such a case, in the rear of the SE fault wing, the extension axis becomes parallel to the fault plane because of the movement of this wing to the SW. This supports the latitudinal and flat compression in the eastern part of the studied area.

Generally, in most volumes, the LSSs are interpreted by a small amount of planes with slickensides, which prevent the correct estimation of the stress condition tensor characterized by the Lode–Nadai coefficient μ_σ. Thus, we estimated this parameter for the entire region, plotting all action planes of maximum tangential stresses in all volumes (26 determinations), and interpreted the axes of the major normal stresses of the common stress field on the same stereogram (Fig. 3b). The arches of the large circles which pass through the compression and extension axes are graphically drawn for qualitative determination of the coefficient μ_σ. Following the kinematic method [8], the displacement vector on any plane should coincide with the arches of large circles which are split from axis σ_1 in the case of uniaxial extension ($\sigma_3 = \sigma_2 \neq \sigma_1$) or from axis σ_3 in the case of uniaxial compression ($\sigma_1 = \sigma_2 \neq \sigma_3$), or should occur in the range of an acute angle formed by the arches of large circles split from the axes σ_1 and σ_3 ($\sigma_1 \neq \sigma_2 \neq \sigma_3$). If the displacement vector fits the range of the obtuse angle between the different arches, such a displacement contradicts the found common field; i.e., no displacement by the plane with such an orientation can occur in this stress field. The analysis of the stereogram shows that 12 and 5 displacement vectors coincide with the arches of large circles which split from the compression and extension axis, respectively; four vectors occur in the range of the acute angle between these arches; and five more contradict the common stress field. Such statistics indicate that South Sakhalin was deformed under dominant compression conditions. Both action planes τ_{max} under compression are determined in volumes 5, 6b, 9, and 10, whereas both action planes τ_{max} under extension are typical only of the rocks of the Bureya quarry. Such a local condition of these metamorphic rocks is supported by numerous quartz veins of different age in the Bureya quarry.

Five action planes of maximum tangential stresses in the local volumes, which contradict the common shear stress field, are ideal, when the extension axis σ_1 in the modern stress field would reindex with the intermediate axis σ_2 and the common stress field would become reverse at constant orientation of the compression axis, as was registered in the Nevelsk dried bench. All 12 planes which coincided with planes which are split from axis σ_3 remain consistent with a new, young stress field, whereas the five planes that coincided with arches of large circles split from the extension axis contradicted the new reverse field. Thus, we reconstructed the early shear stress field with a horizontal and latitudinal compression axis and horizontal longitudinal extension axis and less confident reverse stress field with constant compression axis and vertical extension axis. The earlier stress field most likely belongs to the Sakhalin folding phase, while the late one, which is responsible for the modern stage as well, is orogenic.

MODERN STRESS STRAINED STATE OF THE SOUTH SAKHALIN

The distribution of the orientation of the modern regional seismotectonic deformations and stresses of the Earth's crust are studied using the parameters of the focus mechanisms of the crustal earthquakes that occurred in South Sakhalin. These data were taken from the collections "Earthquakes in USSR" and "Earthquakes of Eurasia" and the NEIC (National Earthquake Information Center) international catalogue from 1982 to 2007. The general amount of events used for the map of seismotectonic deformations and stresses was 40 with M = 4.3–6.3.

The orientations of the major deformation axes were determined by the method of Riznichenko and Kostrov on the basis of seismic data [13, 20]. This method involves finding of the average tensor of the focus mechanisms for a set of seismic events with hypocenters in the elementary volume, the area of which for the island territory was 0.25° × 0.25°. The increment of the tensors of seismotectonic deformations in each averaging cell was calculated on the basis of the mechanisms of the earthquake focuses, the results of which are given in [28]. According to the calculations for the western part of the southern end of the island, the area of the town of Nevel'sk and settlement of Gornozavodsk is characterized by steep dip angles of the major elongation axes with mosaic azimuthal direction of the deformation vectors. In the eastern part, the dip angle is flatter and has a southwestern direction. The major shortening axes are latitudinal almost everywhere with a dip angle of less than or close to 15°, which is in agreement with the results of geological studies [26] and recent synthesis [12].

The stress tensors were interpreted on the basis of cataclastic analysis (CA) elaborated by Rebetskii [17–

19]. This method is characterized by the formation of a sampling of earthquakes which occurred in homogeneously deformed volumes with further reconstruction of the relative or absolute values of the stress tensor components for these volumes. The first interpretation stage uses the same data on the parameters of the focal mechanisms as in the calculation method of seismotectonic deformations [13, 20, 31]. Because the application of CA is described in many publications (monograph [18], etc.), let us directly pass to the calculation results. The stress field interpreted by the parameters of the earthquake focuses is characterized by latitudinal and near-horizontal maximum deviator compression and near-vertical (angles with vertical of 80°) axes of maximum deviator extension with small dip angles to the southwest [28]. In recent works [12, 28], the analysis of the orientation of the axes of stresses and deformations on the basis of the mechanisms of the earthquake focuses confirmed that the Earth's crust of the southern part of Sakhalin Island undergoes latitudinal near-horizontal regional background compression and mostly near-vertical extension. In this stress field, the direction of the major shortening axes is relatively stable and elongation changes its direction from near-vertical in the western part to near-horizontal over the remainder of South Sakhalin.

DISCUSSION

As a result of tectonophysical studies, we made an attempt to answer the following questions for identification of the temporal change in the geodynamic settings of the formation of the structure of South Sakhalin: are the parameters of the tectonic stresses distinct by area depending on the previous evolution of the formation of the newest structures and the presence of faults and how do the geodynamic settings of the fold and orogenic evolution stages differ. Answering these questions requires substantiation of the different age of the interpreted tectonic stresses and their temporal succession.

On the basis of fieldworks, we distinguished 11 LSSs in the large newest structures, which were formed on the geological basement of different age. The stress parameters are significantly distinct in every LCS; however, no strong distinctions were found in the orientation of the compression axes of the South Kamyshovyi and Susunai–Tonin megauplifts. The common features are dominant longitudinal strikes of the extension and latitudinal compression axes; however, maximum deviations of the compression axes to the SE–NW direction (azimuth 302–306°) are reconstructed for the South Kamyshvyi megauplift in the Petropavlovskii quarry and in Tikhaya Bay, whereas the deviations of these axes to the SW–NE (azimuth 227°, 58°) are reconstructed in the Prigorodnyi quarry and in the rocks of the suburbs of the town of Korsakov. Steep dip angles of the compression axes, which lead to mixed normal fault–shear stress states, are also determined in both structures. For example, two LCSs reconstructed in the Petropavlovskii quarry are characterized by intermediate shear–normal fault stress states: all three axes of the major normal stresses are oriented at angles of 28°–43° to the horizon. The orientation of the compression axis is stable and the axis dips to the NW (azimuth of 302°–306° and angle of 43°–46°) and causes the shear component of the displacements by the action planes of the maximum tangential stresses. The intermediate axis σ_2 of the tectonic stresses of different stages of volume 6 in the Petropavlovskii quarry is reindexed with extension axis σ_1: in the older and younger LCS, the axis dips to the south and ENE at angles of 36° and 30°, respectively.

In the older rocks of the Susunai–Tonin newest structure, in the Bureya and Listvennichnyi quarries, we reconstructed the steepest dip angles of the compression axes: 56° and 54°, respectively. In the fault zones of different strike and in different fault wings, the orientations of the local compression and extension axes sharply change, as is especially manifested near the fault in the quarry of Mt. Yunona, where practical reindexation of compression and extension axes occurs.

The key issue of the problem of the age of the tectonic stresses is the data on the newly formed marine terrace in the southern part of the town of Nevel'sk, which allowed division of post-Miocene and modern LSSs. In this area, there was a clear change in the post-Miocene shear stress field to the modern reverse one without change in the orientation of the compression axis. The post-Miocene ancient stress field is interpreted by the shear fractures and orientation of minigulfs elongated along the jointing.

Stable temporal orientation of the compression axis is evident from the local compression axes of different age reconstructed in the Petropavlovskii quarry.

Determination of the common stress field by all reconstructed LSSs showed a rather confident shear stress field typical of the entire studied part of South Sakhalin. It is characterized by latitudinal compression and longitudinal extension without division of this common stress field on the western and eastern part of the island of different age and orientation. Special analysis of the action planes of the maximum tangential stresses of all reconstructed LSSs showed that most planes in this common shear stress field correspond to uniaxial compression. The occurrence of these planes in the Bureya quarry under extension indicates a cofolded stage of the reconstructed common shear stress field, which is consistent with previous data on the shears along the longitudinal regional faults. The calculated displacements on the action planes of maximum stresses in the LSS (five units), which contradict the common shear stress field, ideally correspond to the common reverse stress field, where the extension axis changed by the intermediate axis. The action planes along which the displacements in the LSS should occur under stably oriented uniaxial compression remain in agreement with the younger reverse stress condition, but, in the plane τ_{max} with displacement under uniaxial extension, contradict the young reverse common stress field suggested. Because there are five units of mutually excluding planes τ_{max} in both the common stress field of the shear (cofolded) and reverse (orogenic) stages, it may be suggested that the slickenlines and other parameters of the shear and reverse common stress field are almost identical to the preferable tectonic stress of the cofolded stage. It should be taken into account that two LSSs are reconstructed in the Cenozoic sediments of the South Kamyshovyi megauplift. This supports, first, that all of the above suggestions and statements on the different age of the tectonic stresses belong to post-Miocene age. Second, concerning the young orogenic stress field, it, along with the cofolded field, is more confidently reconstructed in the activation fault zones, which restrict the orogenic blocks. At the same time, traces of cofolded deformations can better remain inside the blocks without reflection of the younger orogenic stress fields.

CONCLUSIONS

Two common stress fields are distinguished in the post-Miocene stress fields of South Sakhalin independent of the influence of the western and eastern displacement zones of different plates of the studied area: the earlier cofolded common stress field is characterized by the shear type with horizontal compression axes of latitudinal strike and longitudinal extension. For the first time, the joint analysis of the displacement vectors on the action planes of the local stress states in combination with data on the earthquake mechanisms substantiates the reindixation of the horizontal extension axis with the vertical intermediate axis of major normal stress at the orogenic stage of evolution of the territory, which began 1.8 Ma ago. Although the results of the studies are based on a small amount of data, they are consistent with the data of Golozubov et al. [4] and Rozhdestvenskii [22] on transformation of the dextral to reverse thrust displacements along the longitudinal fault systems.

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