Chapter

Neotectonics and Stressed State Patterns of the Sakhalin Island

Leonid Bogomolov, Lidia Sim and Pavel Kamenev

Abstract

The study of neotectonics, neotectonic and modern stress of the Sakhalin has been performed by the set of methods. The scheme of modern geodynamics of the island has been constructed by the data of neotectonic activation of the faults. Three types of zones with dissimilar geodynamic conditions have been distinguished: transtension, transpression, and strike-slip (simple shift). The results of Sakhalin modern stress reconstruction based on focal mechanisms of earthquakes allowed to characterize the distribution of the stress state parameters over the island surface: the Lode-Nadai factor and the direction of axes of deviatoric compression and tension. The changes in characteristics of modern tectonic stress field have been noticed at the boundaries of regions with different regimes of modern faulting. Specific orientations of compression axes of the neotectonic stress field are proper for North Sakhalin. Therein, the directions of compression axes become northeast in contrast to the predominant sublatitude orientation on the island as a whole. The obtained data on neotectonics and inherited modern stress field are applicable to the problems of engineering geological support of oil and gas projects' realization in the Sakhalin (new wells construction, control of the pipelines stability, accompanying urban planning, etc.).

Keywords: Amur and Okhotsk microplates, the Sakhalin, fault zone, neotectonic and modern stress, slickensides, focal mechanisms of earthquakes, geodynamic regime, transpression, strike-slip

1. Introduction

Sakhalin Island belongs to the tectonically active region of Northeast Asia. Within its boundaries, the border between the largest tectonic plates of the Earth—the Eurasian Plate, North American and Pacific ones—passes through the island territory. A wide boundary zone represented by a set of independently moving microplates expands along the convergent boundaries of these plates.

The border between the Amur and Okhotsk (Okhotsk Sea) Plates, the largest microplates, is often associated with the Central Sakhalin Fault of meridional strike. Inside the Sakhalin, the interplate border is drawn along the Western Sakhalin Fault in the south, and as the arc line, partially coinciding with the Eastern Sakhalin Fault (**Figure 1**) [1, 2], in the Central and Northern Sakhalin. Alternatively, this border goes along the Central Sakhalin Fault (Tym-Poronai Fault in the Northern Sakhalin) [3].

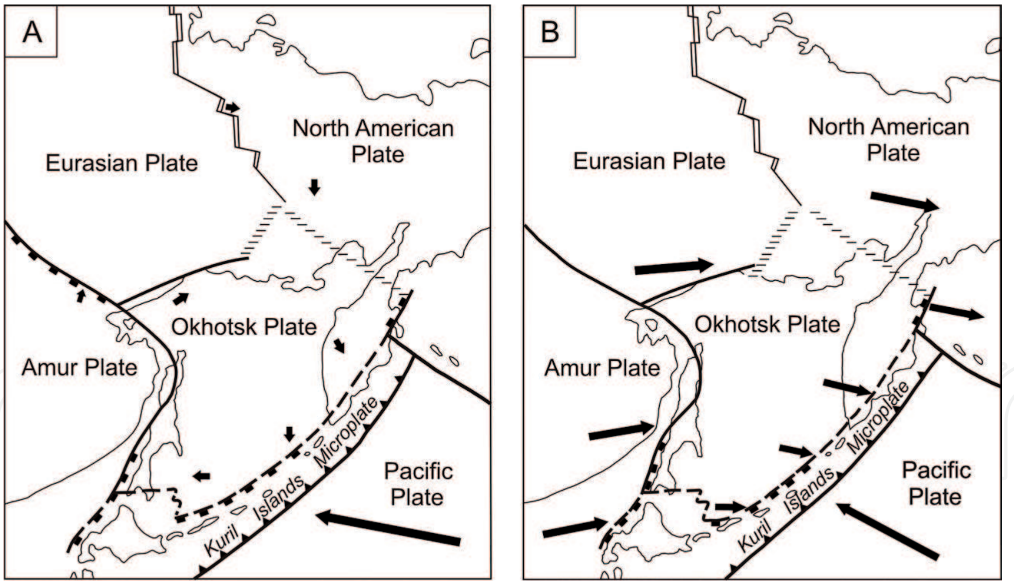

Figure 1.
Kinematics of the modern plate movements in the Okhotsk Sea region. (A) Relative to Eurasian Plate (not moving); (B) relative to Kuril Islands microplate. The arrows show the directions and values.

According to the paper [4], the interplate border is drawn along both the Western Sakhalin Fault and the Central Sakhalin Fault. The analysis of neotectonic stress to the West and East of the Central Sakhalin Fault allowed us to obtain new information about location of the border aforementioned [5–7].

In addition to our previous publications [5, 7], this chapter presents the results of extended tectonophysical studies based on a set of methods [6, 8–10], and the field measurements of 2019–2020 campaigns are involved. The paper presents the manifold manifestations of the geodynamic and seismic processes in the crust between the Amur and Okhotsk microplates, lying within the convergence zones of the Pacific, Eurasian, and North American tectonic plates.

The research aim is to study the recent tectonics, to reconstruct neotectonic stress by a set of methods, and to review the published seismological and geophysical data to approve or disprove the interplate border location. This involves the demonstration of effective but underused structural and tectonophysical methods to study the tectonics of some regions and to develop a model of the stressed state of Sakhalin Island. The above methods are able to give the characteristics of the post-Miocene stress field, but we will show (taking into account the seismological and GPS motion data) that the modern stress field in the Sakhalin crust is inherited mostly from the post-Miocene model. The modern stress nonuniformity as well as the climate change is proved to control both engineering geological processes and geotechnical conditions on the territory under consideration.

2. Structural-geomorphological method and the results

To reach the stated goal, the authors have compiled a structural-geomorphological (SG) map (neotectonics scheme) of Sakhalin Island using the method developed [11, 12], as well as a set of tectonophysical and structural methods, to study the modern stress state and kinematic types of individual faults. Thus, the patterns of neotectonic stress in the Northern and Central Sakhalin have been reconstructed by the structural-geomorphological (SG) method of shear stress reconstruction [13, 14]. The stress reconstruction has been performed also in the Southern Sakhalin by the following methods: the method of analysis of conjugate pairs of shear joints [8], the method of kinematic analysis of fracture structures [9], and the method of belts in the study of fracturing associated with discontinuous displacements [10].

Restored orientations of the axes of local stress states (LSSs) allow to build the unified single regional field of the Southern Sakhalin using the method [15]. The structural-geomorphological map of the Sakhalin is constructed on the grounds of the topography analysis using a topographic Sakhalin map of 1:500,000 scale. The longitudinal zonation of the newest structures is clearly shown on the map; the western and eastern zones of the latest uplifts are separated by the extended Central Sakhalin Depression. The Central Sakhalin Fault appears in the newest structure and serves as a border between the large Western ridge zone and the Central Sakhalin Depression. The zones of longitudinal strike are divided with the faults of various directions into a series of block-block uplifts, which differ in height. Some structures coincide with those that are marked in the work [16]. **Figure 2A** shows a selection of the newest structures.

The tectonic stress fields of Northern and Central Sakhalin have been reconstructed using medium-scale topographical maps and satellite images by the structural and geomorphological methods. This method envisages a special interpretation of megafractures—the small rectilinear relief elements, for which high density is an indicator of the lineament fault. The results of analysis of data on the orientations of subsidiary cracks in the shear zones have been summarized in [8] on the base of field simulation and shear zones mapping. If the mutual relative orientations of megafractures (two systems of joints and the ruptures, oriented along the bisector between them) correspond with the orientation of the subsidiary cracks in the shear zone (at this, they have a certain orientation to the fault plane), then the fault nature of a lineament is proved. Further, the orientations of compression and extension axes in the horizontal plane, the shift sign (right-left), and geodynamic conditions of the fault formation (transtension or transpression) are determined. The lower age limit of the fault activity is determined by the age of young Pliocene-Quaternary deposits, which are developed nearly throughout the study area and broken up with the megafractures and the latest faults. Neotectonic shear stress determinations by the faults, marked on the structural-geomorphological map, lend support to the validity of disjunction based on the terrane analysis. Different heights in the opposite walls of the fault allow to estimate the vertical movement component of displacement.

It should be noted that one of the horizontal axes can be an intermediate axis of the principal normal stresses.

The shear kinematic types of the faults correlate with the definitions of the kinematics of discontinuous faults mapped on the Northern Sakhalin [17, 18] as well as with seismic dislocations formed during the Neftegorsk earthquake (EQ) of 1995, Mw = 7.0 [19]. The reconstructed patterns of tectonic stress point to mainly submeridional extension and sublatitudinal compression over the considerable part of the island; but the compression axis orientation changes to northeast when the study zone moves northward (**Figure 2B** and **C**). The compression axes that turn to the northeast on the Northern Sakhalin is consistent with the scheme of the ellipsoid of the pre-late Miocene deformations of the entire Sakhalin presented in the work [18]. According to this work, the ellipsoid of deformations had turned around during the Pliocene-Quaternary time, the C axis or the shortening axis became latitudinal, which brought to a change in the kinematic type of shifts along the longitudinal meridional faults of the Sakhalin to the overthrust reverse fault type. Since the detailed research of the folded and discontinuous structures of different age performed by Rozhdestvenskii and Rozhdestvensky [17, 18] relate mainly to the Northern and Central Sakhalin, one can assume the change of stress state type cannot be applied to the Southern Sakhalin. The more so, the author notes

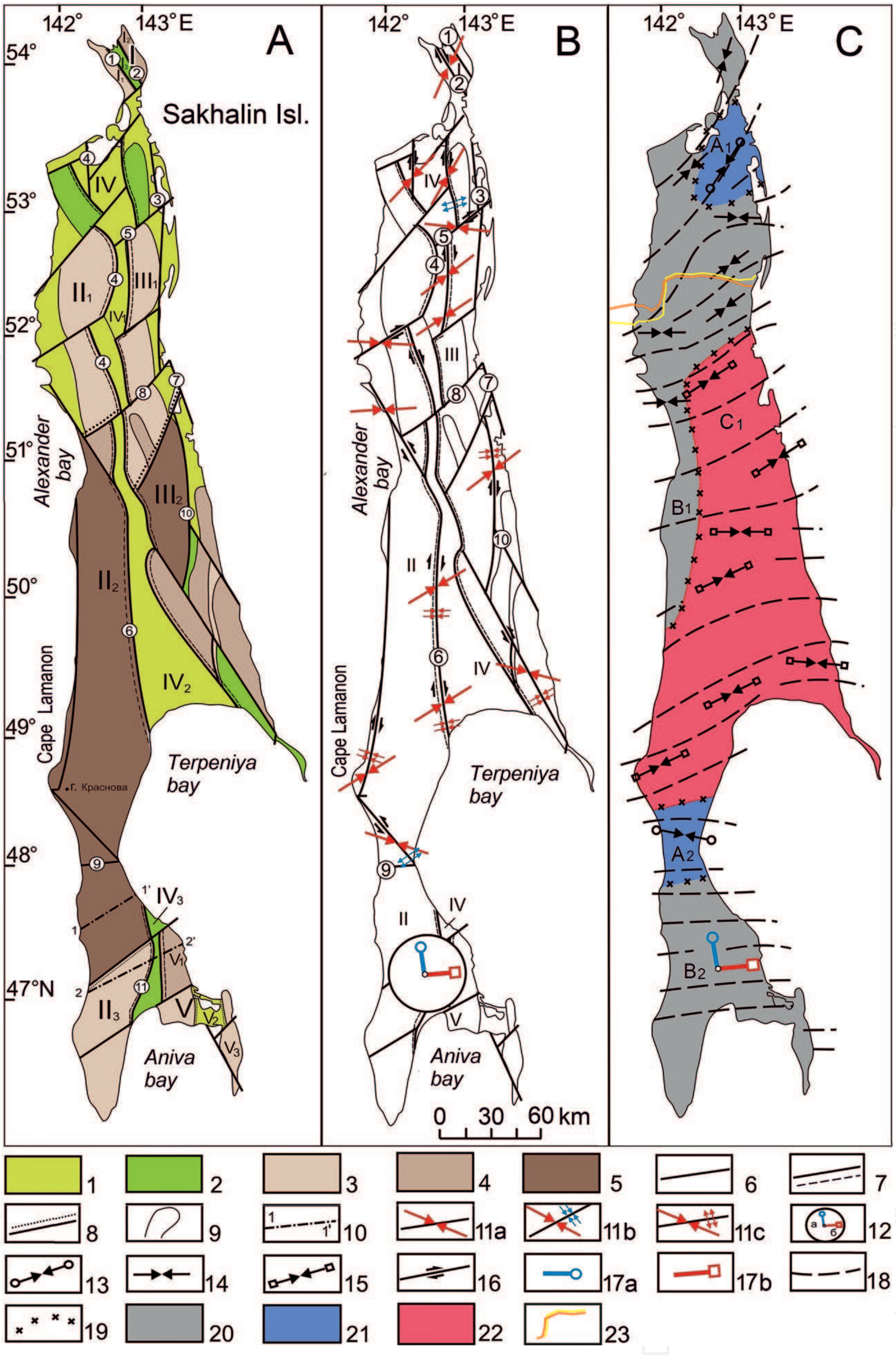

Figure 2.

Neotectonics and neotectonic stress of Sakhalin Island. (A) The map of Sakhalin Island, showing the structural and geomorphological features. 1–5: total syn-erosional uplifts; 1: less than 100 m, 2: 100–200 m, 3: 200–500 m, 4: 500–1000 m, 5: more than 1000 m, 6: the faults identified from the geomorphological data, 7: boundaries of the first-order structures, 8: boundaries of the second-order structures, and 9: the boundaries of uplifts and depressions. The digitals designate the uplifts on the map: I: Shmidt, II: West Sakhalin, III: East Sakhalin, V: Susunai, and IV: Central Sakhalin depression. Fault numbers are given in circles: 1: Central Sakhalin, 2: Hokkaido-Sakhalin, 3: Upper Piltun, 4: Nabilsky, 5: East Sakhalin, and 10: the geomorphological section line. (B) The scheme of neotectonic stress of Sakhalin Island. 11: Compression axes orientations in the horizontal plane and geodynamic conditions of their formation (reconstructed by the structural-geomorphological method); 11a: strike-slip, 11b: transtension, 11c: transpression, and 12: orientations of the subhorizontal extension (a) and compression (b) axes of the general stress field of the South Sakhalin. (C) The scheme of the latest geodynamics of Sakhalin Island. 13–15: Compression axes and geodynamic conditions; 13: transtension; 14: strike-slip; 15: transpression; 16: shift direction; 17: extension (a) and compression (b) axes reconstructed by the complex of field methods on the southern Sakhalin; 18: compression axes projections to a horizontal plane; 19: the boundaries of zones with different geodynamic regimes; 20–22: geodynamic regimes of 20: strike-slip, 21: horizontal extension (transtension), and 22: horizontal compression (transpression); and 23: oil and gas pipelines routes. The map of Bryantseva [5].

"appropriateness of the stress ellipsoid has been repeatedly questioned…," but its use has applied meaning, "although the anomalous structures, which are difficult to explain from this theory point of view, are observed" [18].

The zonation of the areas with different geodynamic conditions of faults generation within the latest stage has been conducted on the grounds of neotectonic stress, reconstructed for the Northern and Central Sakhalin (**Figure 2C**). General stress field of the Southern Sakhalin is shown below. Since the structural-geomorphological method is based on the patterns of mutual orientation of the subsidiary faults in the shear zone (by the data of simulation), the conditions of additional extension or compression, obtained in each certain case, need special additional studies to explain the cause of its occurrence. When shifts are simulating, the subsidiary fractures' different orientation to the actual direction of the shift has been obtained when additional compression or extension acted normally to the shear plane. Conducted zonation does not allow to separate the Western Amur and Eastern Okhotsk microplates (**Figure 2B**), as the compression axes' orientations on the Southern Sakhalin and south part of the Northern Sakhalin are uniform.

Fifty-six local stress states (LSSs) have been determined with the set of field methods on the Southern Sakhalin. These LSSs indicate the significant variance of the axes of principal normal stresses of local level (**Figures 3** and **4**), demonstrating the results of tectonophysical and structural methods' application. The method of jointing belt distribution [10] is shown in **Figure 3A** and **B**. The outcrop is located in the footwall of the Central Sakhalin Fault, whose strike is taken from the structural-geomorphological map (**Figure 2A**).

If the fault strike is known, but there are no data for its plane orientation in the space, then the method allows to determine this plane. To do this, the P1-P2 jointing belt with the pole at the P point is identified in the stereogram of fracture density, which is measured near the fault. The plane of the R1PR2 fault with the R pole is reconstructed by the connection of the fault strike points on the external circle of the R1R2 stereogram with the point of the P fracture belt pole. The S1 point (an intersection of the fault plane with the P1P2 belt) is a point of the displacement line outcrop across the fault plane on the upper hemisphere. We get the required displacement line across the fault by its connection with the stereogram center. Here, this line clearly tells about the strike-slip with some component of the thrust constituent. Since the fault is a dextral reverse one with a strike-slip component [18, 20], as well as by the relief pronounce, where the western wall is hanging, the displacement line has a sign of the dextral strike-slip fault with a reverse component. The strike-slip component dominance is obvious. The compression (σ_3^{gen}) and extension (σ_1^{gen}) axes are charted on the stereogram of the general stress field of the Southern Sakhalin (see below). According to the kinematic method [9], we can obtain the whole interval of possible displacements over the fault in this general field: from the S1 point by uniaxial extension to the S2 point by uniaxial compression, connecting the pole of the R fault to the σ_3^{gen} and σ_1^{gen} with the arcs of large circles. Thus, the displacement line, reconstructed by the analysis of the jointing distribution belt method, coincides with the direction of the strike-slip fault with a reverse component (actually the dextral strike-slip), if the stress field has been characterized by the compression condition. Two conclusions follow from above: (1) most of the fractures formed by belt distribution are meant to be tensile cracks that occur under extension conditions and (2) dextral strike-slip displacement has occurred along the fault at this stage. Two maxima of fractures density, outlined with the 8% isoline—I and II, are highlighted on the fractures belt (**Figure 3B**). The belt axis matches the intermediate axis σ_2; the direction of the compression axis, σ, and extension one, σ_1, are defined from the bisectors of the angles between I-I and II-II fractures according to the method of Gzovsky [8]. The directions of intermediate axis, σ_2,

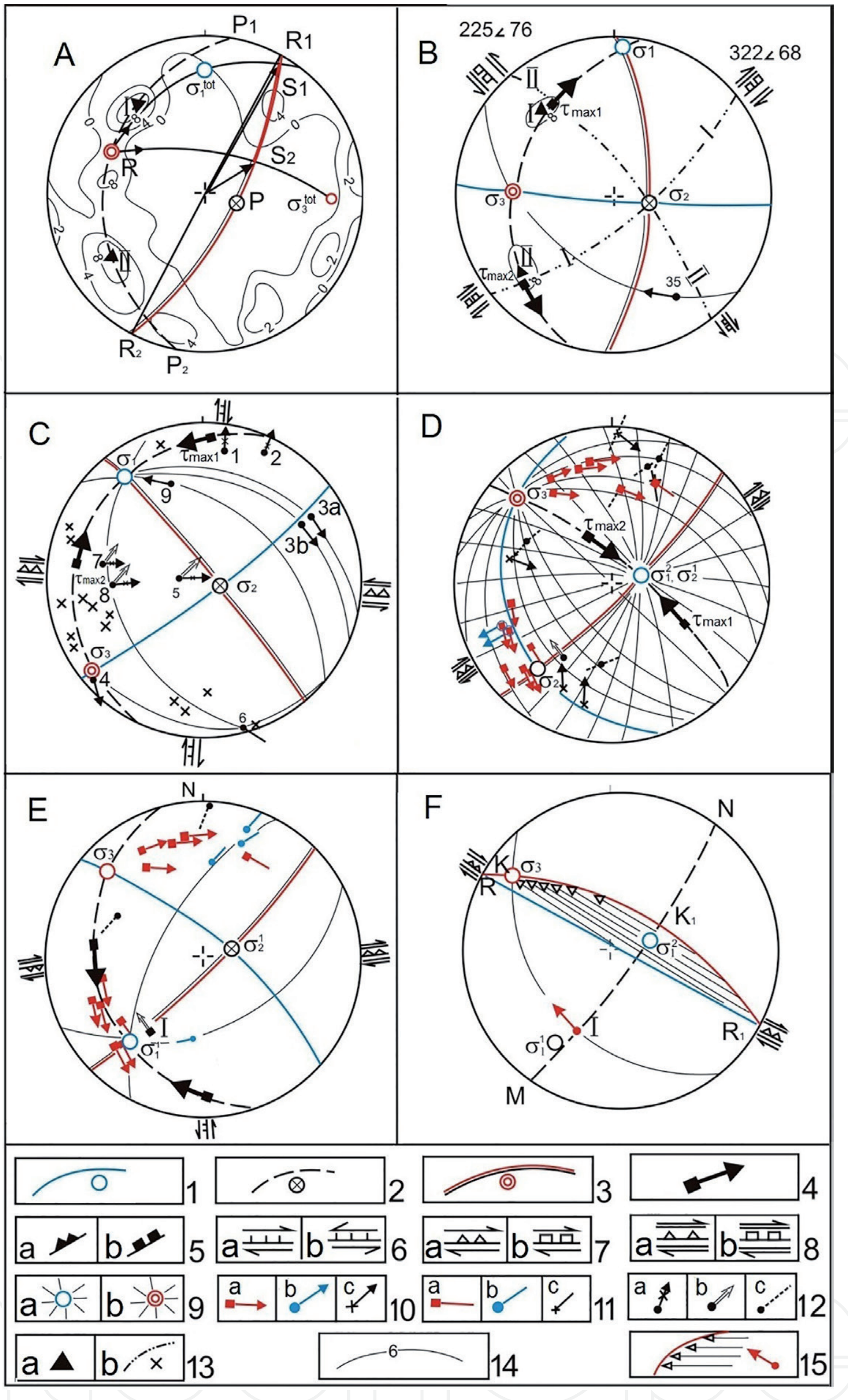

Figure 3.

Stereograms of the local stress state in the South Sakhalin. 1–3: Local stress state (LSS) axes and their action planes: minimal (σ_1); 2: intermediate (σ_2), maximum (σ_3) compression axes of the principal normal stresses; 4: poles of the planes of the maximum tangential stresses (τ_{max}) and displacement vectors; 5–8: strikes of the τ_{max} planes and fault kinematic types—5a: reverse faults, 5b: normal faults, 6a: dextral strike-slip faults, 6b: sinistral strike-slip faults, 7a: reverse faults with strike-slip component, 7b: normal faults with the reverse component, and 8: strike-slip faults with the reverse component; 9: strike-slip faults with the normal component; 9: arcs of the large circles divergent from—a: the extension axis and b: the compression axis; 10–13: displacement lines and vectors on the slickensides, which occurred due to—10a: uniaxial compression, 10b: uniaxial extension, and 10c: triaxial stress state; 11: the same, but with undefined displacement sign; 12: displacement lines—a: detected partial (vertical or horizontal) component of displacement, b: predicted, and c: contradict to the reconstructed LSS; 13: fractures—a: pole of the maximums of shear fractures and b: pole and plane of separate conjugated shear fractures or systems; 14: fractures density isolines; 15: pole and plane of the fault and displacement lines of the hanging wall. (A) and (B) Volume 16, the left bank of the Lyutoga river—(A) density and fracturing belt; (B) axes of the principal normal stresses; (C) volume 27, the right bank of the Vesely stream; (D–F)—South Sokolovskii quarry—(D) recent field, (E) ancient field of LSS in the hanging wall of the fault, and (F) the fault plane and displacement vector. Wulff-Gushenko modified grid, upper hemisphere.

Figure 4.
A slickenside on the outcrop of the Krasnoyarkovskaya suite K_2kr.

determined by two ways (both as the axis of the fractures belt and as the projection of the displacement line of two systems of the conjuncted shear fractures) coincide almost perfectly. This suggests the promising integration of different methods when studying the tectonic stress fields. According to the sum of displacements, the fault is a dextral reverse fault with a strike-slip component [20].

The unique point with the slickenlines in the Pleistocene alluvial-proluvial loams is located close to the Central Sakhalin Fault. Despite the small number of the slickensides, the local stress state (**Figure 3C**) of strike-slip faulting type with meridional extension and sublatitudinal compression axes has been reconstructed there. Measurement no. 1 and 2 are probably the traces of gravitational displacement along the slope.

Figure 3D and **E** show an example of the detection of two LSSs from the slickensides, measured in South Sokolovskii quarry, that has outcropped a melange of the West Susunai subterrane [21]. Most of the 37 displacement vectors have allowed to determine the LSS (**Figure 3D**), which is assumed to be more recent, as the most of slickenlines are the traces of latest displacements. The displacements vectors (slickenlines), which contradict this LSS, are marked with a special symbol, and their low integrity allows the LSS to be defined as more ancient.

The presence of clearly defined slickensides near the Central Sakhalin Fault points to high tectonic activity of the Southern Sakhalin (**Figure 4**). The outcrops of the Krasnoyarkovskaya suite K_2kr are presented with interbedding of tuffstones, sandstones, and tuff siltstones in the point of 47°01′51.00″ N and 142°30′00.40″ E coordinates. The slickensides originated with sinistral reverse fault with strike-slip component are shown in the right bottom part of **Figure 4**; the direction of motion of the lying wall of the fault is marked with an arrow.

Figure 5A and **B** show an example of detection of two LSSs of different ages as well as application of the method of fractures belt distribution by Danilovich to analyze the same planes with the slickensides.

Figure 6 presents the stereograms of the local stress state of the south part of the Central and South Sakhalin (56 determinations) charted on the scheme of the geological structure (according to Golozubov et al. [3], but simplified).

The unified regional stress field of this part of the island has been reconstructed previously from 56 determinations of the axes of the principal normal stresses in the South Sakhalin by the method justified in the works [14, 15]. The general field has the following angular characteristics: the extension axis ∠1–350∠10, the intermediate axis ∠2–112∠66, and the compression axis ∠3–260∠20. High-angle sinistral strike-slip faults with the dip azimuth of 32∠83 and dextral strike-slip faults with the dip azimuth of 125∠68 (**Figure 5E**) are the most frequent in this stress field.

A recent field studies has allowed to update the database on the local stress states both in the South Sakhalin and in the south part of the Central Sakhalin. All determinations are charted on **Figure 6**. The stereograms of different stressed state types

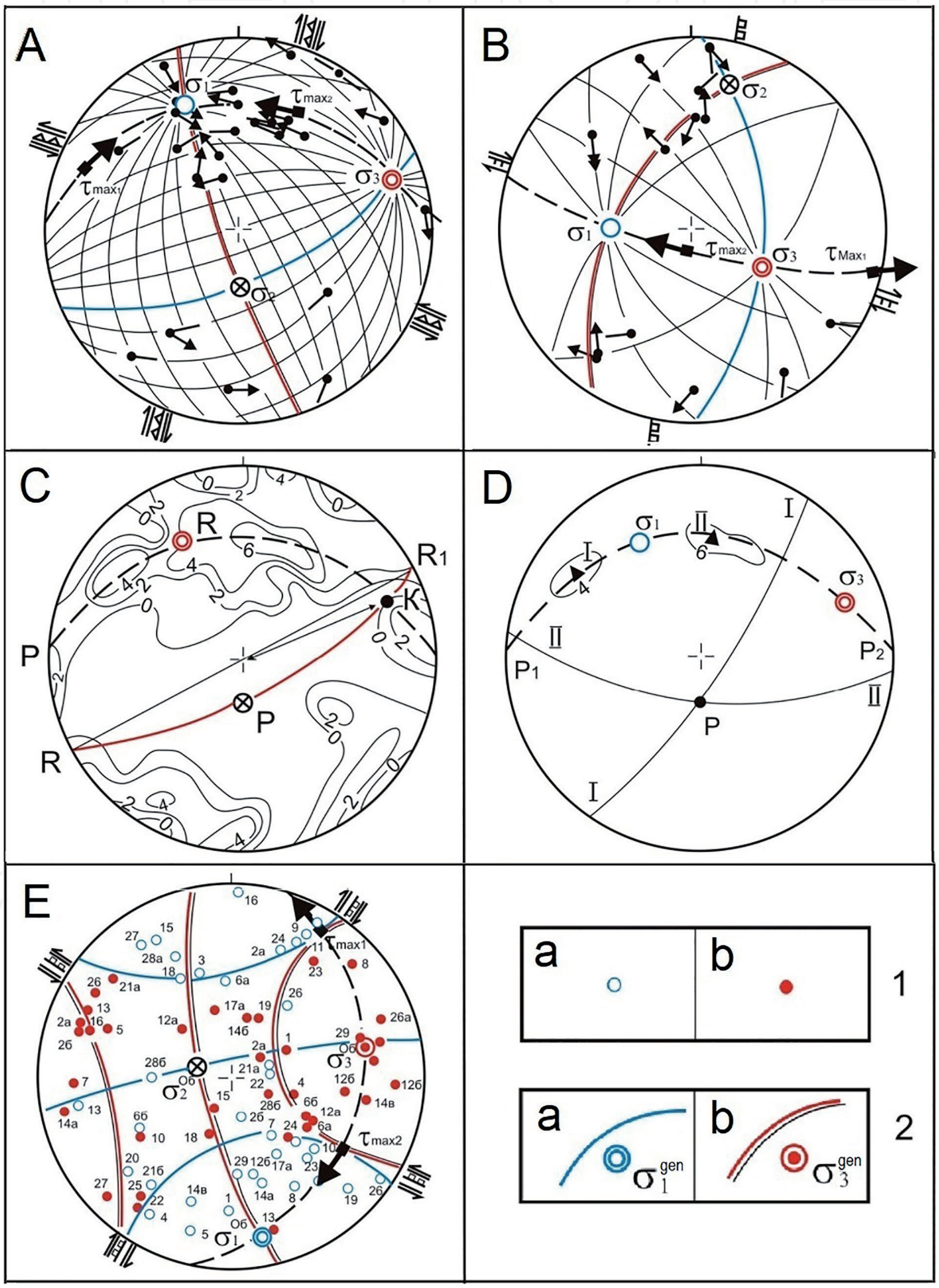

Figure 5.
*Stereograms of tectonic stress and general stress field in the South Sakhalin. The axes of principal normal stresses of the LSS are designated with the symbols inside the frame 1: a—extension and b—compression. Designations of the general stress field axes and their planes are showed inside the frame 2: a—extension and b—compression. See the other designations in **Figure 3**. (A)–(D) Limestone quarry and (E) the general stress field of the South Sakhalin.*

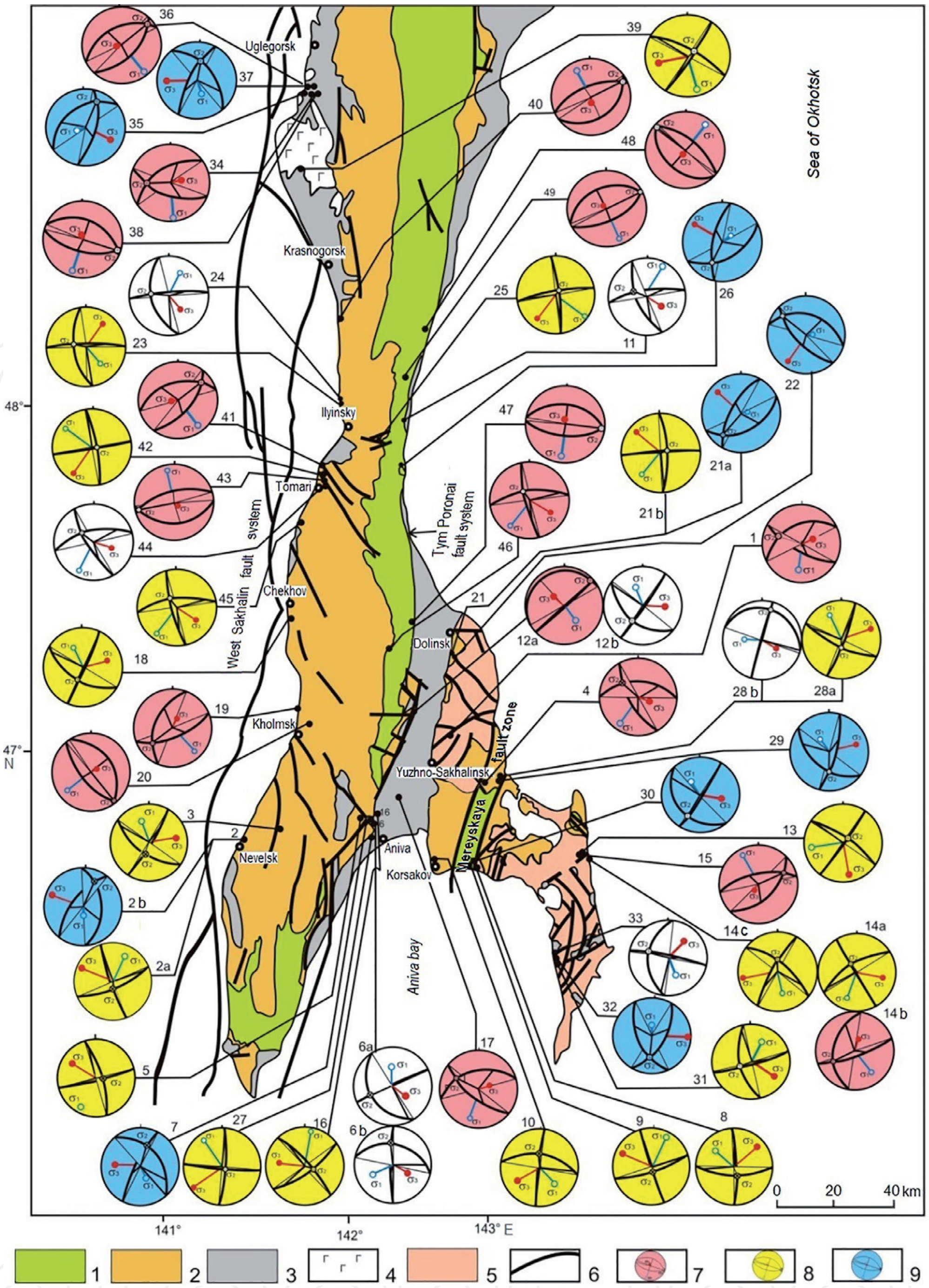

Figure 6.
The scheme of the geological structure (from [3], simplified) and local tectonic stress of the Southern Sakhalin (56 determinations), according to Sim et al. [5]. 1–5: heterochronous rock complexes; 1: Albian and upper cretaceous terrigenous, partly tuff-terrigenous, 2: Paleocene-Miocene terrigenous, volcanic are not general, 3: Miocene-quaternary terrigenous, 4: Pliocene basalts, and 5: Cretaceous and Paleocene-Eocene accretionary rock complexes of the Susunai and Tonino-Aniva terranes; 6: faults; 7-9: types of stereograms; 7: LSS of normal fault, possibly with strike-slip component, 8: LSS of reverse or oblique fault, 9: strike-slip fault LSS. The stereograms show the axes of principal normal (σ_1: minimum, σ_2: intermediate, and σ_3: maximum compressive) stress and the planes of maximum tangential stress with displacement vectors of the lacking wall (Wulff grid, upper hemisphere).

are highlighted with color. The stereograms of the LSSs of normal fault and normal fault with strike-slip component types are highlighted with reddish color and mean compression axis is to be oriented at an angle of 50–90° with the horizon; the LSSs of reverse fault and reverse fault with strike-slip component types are highlighted with blue color, and the extension axis is oriented at an angle of 50–90° with the horizon; the LSSs of strike-slip fault type, in which the compression and extension axes are oriented at an angle of 0–30°, are highlighted with yellow color; and the stereograms of the LSSs of unknown type, when all three axes are tilted 40–60°, are highlighted with white color. It is apparent that normal fault and normal fault with strike-slip component LSSs prevail over reverse fault with strike-slip component and reverse fault ones, which contradict the hypothesis of the post-fold change of the stressed state of strike-slip fault type to the reverse fault in the Sakhalin [7, 17].

Such hypothesis of work [7] was based on 15 LSS determinations only in the South Sakhalin. The later studies involving 56 points of LSS determinations as well as the analysis of seismicity (see below) have proved the prevailing strike-slip stress field both in fold and orogenic stages.

Explicit indicators of submeridional extension and sublatitudinal compression have been revealed on newly occurred marine terrace in the southern part of the town of Nevelsk. This terrace is a peculiar case of outcrops considered, because it resulted from the coseismic seabed uplift during Nevelsk earthquake (EQ) of August 2, 2007, M = 6.2 [22]. The vertical displacement of the earth surface reached 1.2 m near the coastline. The new marine terrace (actually the drained bench, **Figure 7A**) is located on the west wall of the West Sakhalin Fault, at 15–20 km distance from the Nevelsk EQ hypocenter. Two systems of cleft joints are well expressed in this bench in the Lower Miocene laminated shales with interlayers of silica marls. The post-Miocene field of strike-slip fault type, with horizontal extension and compression, has been reconstructed on the basis of the rose diagram of

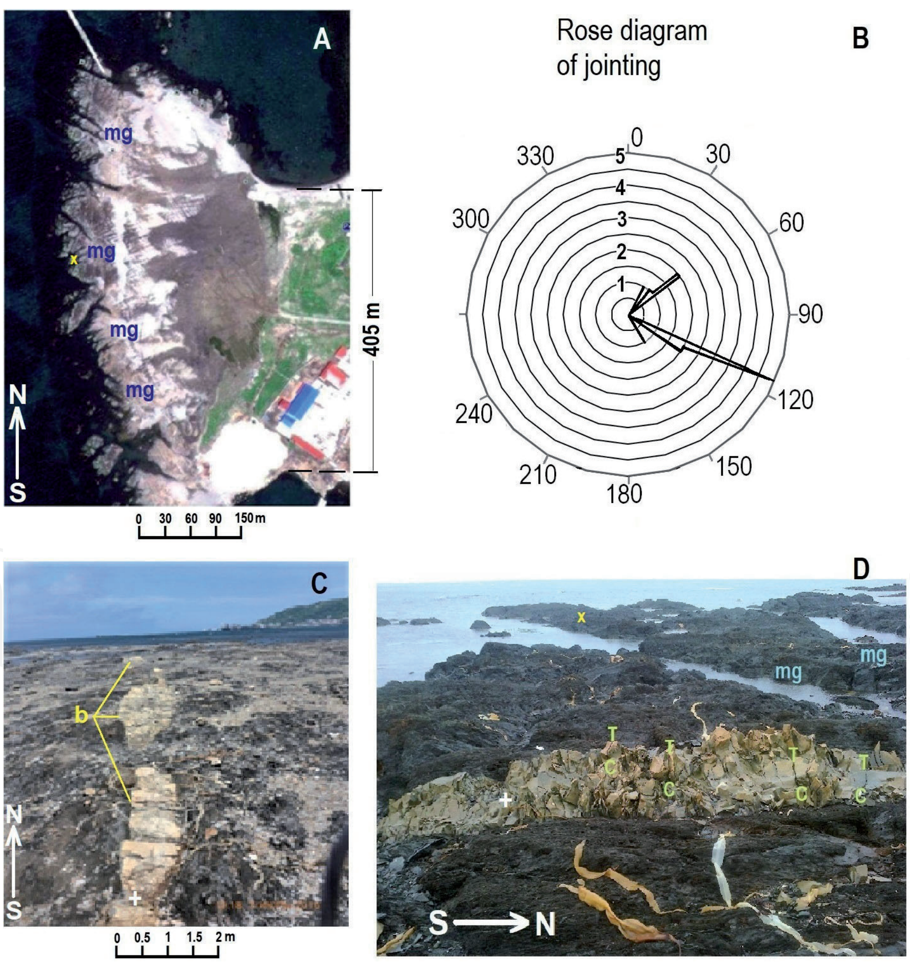

Figure 7.
Indicators of post-early Miocene stresses on the newly formed marine terrace (dried bench in the southern part of the town of Nevel'sk). (A) Image of the terrace with a scale after www.yandex.ru/maps (2014) (dark is sea surface with visible minigulfs, mg); (B) rose diagram of jointing on its surface (the compression axis by bisector of acute angle after Gzovsky [8] is oriented along azimuth of 92.5°, and the extension axis is oriented along the azimuth of 182.5°); (C) view of three boudins on the dried bench; and (D) relative position of a boudin and two minigulfs, mg, and tension cracks (indicated by T–C characters) in the boudin b4 specified in ***Table 1****. Yellow "x" symbol denotes a point of reference near coastline, white "+" is a point of reference inside b4 boudin.*

# boudin	Length, m	Width, m	Distance to the next boudin, m	Extension, %	Remark
b1	3.8	0.55	3	69	First line, 30 m East from the water's edge
b2	4.8	0.95	4.6	80	
b3	1.4	0.65	8.3	405	
b4	10.3	1	13.2	117	
b5	2.8	1.05	8.2	213	
b6	4.3	1.25	29.2	526	
b7	7.1	1.3	41	488	
b8	5.1	0.95	23.5	388	
b9	4.1	0.5	2.16	47	
				259	Mean over first line
b10	2.16	0.65	2.2	78	Second line, 24 m to east of the first
b11	1.4	0.35	0.7	40	
b12	1.3	0.35	7.4	448	
				267	Mean over second line
b13	7.4	1.7	5.9	65	Third line, 23 m to east of the second
b14	Fragmented and partially under water				
b15	1.3	0.92	1.5	68	Fourth line,
b16	>1.6	Partially under water			26 m from the third
				217	Overall mean

Table 1.
The parameters of the boudins on the newly occurred marine terrace and the estimates of tensile strain.

jointing for these data (**Figure 7B**). The method of Gzovsky [8] has been used for this reconstruction.

The boudins in the layer of silica marls (**Figure 7C**) as well as the tension cracks in the boudins (**Figure 7D**) have confirmed surely that the extension axis is horizontal and its direction is close to the north-south one. We have measured the length and width of each boudin and the distance between neighboring ones in the direction of elongation to evaluate the maximal strain. The results are represented in **Table 1**. The level of tensile strain has been evaluated as the ratio of this distance to the half sum of their lengths. After averaging, we come to the estimate of post-Miocene extension of nearly 200%.

3. Discussion: correspondence with geophysical data

Generally, our obtained data on the absence of significant difference in stressed state in the West and East Sakhalin do not contradict the results of the global project "The World Stress Map" applied to the region of the North West Pacific, that is, the Sakhalin surroundings [23]. This project takes into account the data on Sakhalin earthquakes' focal mechanisms that are relevant to the pattern of the recent tectonic stress and strain. Although the statistics of such focal mechanisms was scanty in [23], the obtained map with the border between Amur and Okhotsk microplates

(**Figure 8**) is of special interest. One can see in **Figure 8** that this border is close to the location of the Central Sakhalin Fault (Tym-Poronai Fault) in the Central part of the island. Its location in the Northern Sakhalin corresponds well with that of Upper Piltun and Nabilsky Faults, see **Figure 2A**.

The southern part of the microplates boundary in **Figure 6** diverges with the West Sakhalin Fault. This aspect is not consistent with our approach, and we take into consideration additional regional data. The spatial distribution of the aftershocks of strong earthquakes, Gornozavodskoe EQ, 17.08.2006, M = 5.9, and Nevelsk EQ, M = 6.2, occurred nearly in the West Sakhalin Fault [22], which gave extra reason that this fault had labeled the debated boundary. It is more vital that the detailed analysis of the earthquake focal mechanisms, carried out in [23], has demonstrated rather a lateral zonation of the orientation of modern tectonic stress.

A convincing argument for the dominant regime of horizontal compression and strike-slip is the results [24] obtained from the data on the deep borehole drilling in the north and south of the Sakhalin. It has been shown in this work that the maximum sublatitudinal compression may exceed the vertical stress by 1.2–4 times (on average) both in the north and south of the Sakhalin. The caliper logging data have demonstrated the horizontal stress (sublatitudinal compression) to predominate over the vertical one. There are significant wellbore breakouts of the studied vertical holes in two antipodal angular sectors pointing the direction of the maximum stress-strain effect in a number of studied vertical boreholes in the Northern and Southern Sakhalin.

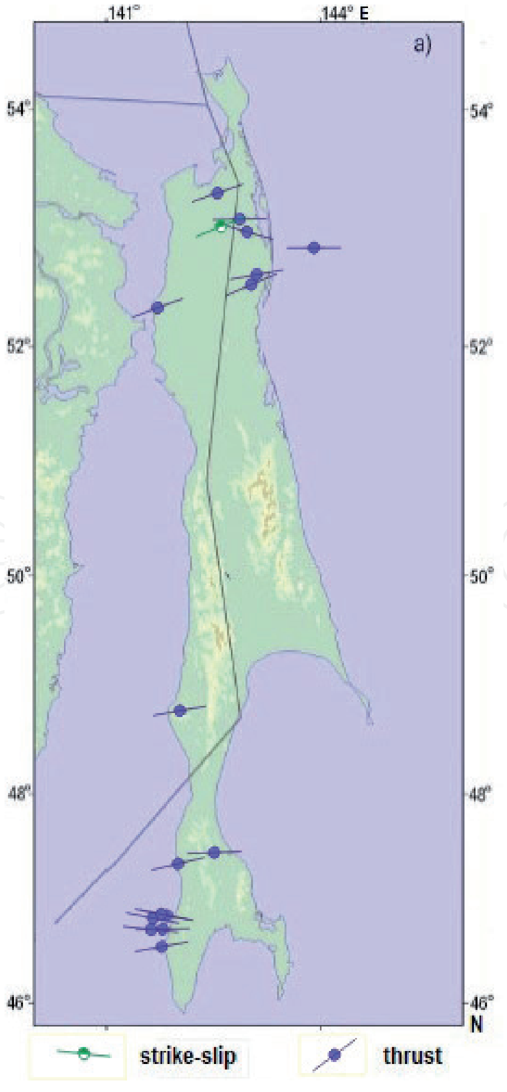

Figure 8.
The World Stress Map data regarding to the Sakhalin, according to Heidbach et al. [23].

Besides, the data treating of IFZ-19 profile of deep seismic sounding [15], which transected (crossed) South Sakhalin from the southwest to the northeast, gave tilted reflecting area M1 lying in 40–60 km depth and descending toward Okhotsk Sea. Meanwhile, there is no large fault in the Sakhalin Island, which could be associated with the border between the Amur and Okhotsk microplates. It is correspondent with the assumption from the work [20], that the Central Sakhalin Fault is an eastern branch of the Western Sakhalin Fault with the westward dip and lesser propagation depth, while the main Western Sakhalin Fault has the eastward dip. The simulations of interaction of tectonic plates surrounding the Sakhalin Island, which are based on GPS displacement surveys [25], have shown that one can draw the most likely border between the Amur and Okhotsk microplates along the Western and the Central Sakhalin Faults on the Southern Sakhalin territory, and along the Upper Piltun and Nabilsky Faults (**Figure 2A**) on the Northern Sakhalin. Seismological data, namely, the significant concentration of earthquakes hypocenters on the western coast of Sakhalin Island and in the Tatar Strait [25], can also testify that the border between the microplates passes along the Western Sakhalin Fault, while the Central Sakhalin Fault is its branch ending at the minor depth.

The analysis of tilt of the P and T axes by the catalog of focal mechanisms of the earthquakes occurred in 1962–2011, published in [26], has shown the obvious non-uniformity of orientations of these axes, see **Figure 9**. The maxima of the tilt angles of both P and T axes are 60–70°. This implies the reverse and normal faults. The strike-slips have a subordinate meaning. The graphs in **Figure 9** are bimodal, with two maxima of the P and T axes tilt distribution, and this prevents the assumption that the recent stress field is characterized as a reverse faulting type.

So, the actual results mentioned above contradict the conclusions about the border between the Amur and Okhotsk microplates passing along the Central Sakhalin Fault, which have been made on the grounds of the field two-dimensional tectonophysical studies using the ellipsoid of deformations. Those studies have demonstrated the different tectonic forces orientation in the Sakhalin, induced by differently directed movement of the tectonic plates, specified in [3]. On the Northern Sakhalin, the explicit maximum of earthquakes epicenters concentrates in the eastern part of Shmidt Peninsula and may correspond to the border between the microplates (**Figure 1**). Besides, the distribution graphs of the P and T axes tilt angles (**Figure 9**) also contradict the conclusion about the change in the regime of Sakhalin Island tectonic evolution within the folding stage (i.e., the regime of strike-slip type modified to the reverse faulting during the following orogenic stage).

The reconstruction of recent stress by the data of earthquakes focal mechanisms was carried out by Savvichev and published in the works [5, 6]. There are the orientations of maximum deviatoric extensions on the left, and compressions ones are on the right (**Figure 10**). Obviously, the western part of the island is more seismically active in comparison with the eastern one due to the border between the Amur and

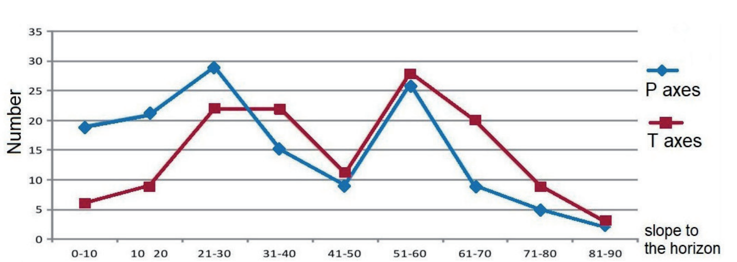

Figure 9.
The graphs of P and T axes tilt angles according to the earthquakes' focal mechanisms (1962–2011) by the catalog [26]. 135 determinations of the P and T axes in total, according to Konovalov et al. [26].

Okhotsk microplates, which passes along the Western Sakhalin Fault. Seismicity of the Northern and west of the Southern Sakhalin is considerably more active than in the central part of the island.

In this connection, the NE orientations of the subhorizontal axes of maximum deviatoric compression dominate in the north of the Northern Sakhalin, and they change the orientation to the ENE southward, up to 53°N. The first latitudinal band of nonstable orientation of the stress axes is distinguished directly southward of 53°N. The section with vertical orientation of the compression axis engages the attention in this band, indicating that the local geodynamic regime is a horizontal compression with latitudinal direction. The focal mechanism of destructive Neftegorsk earthquake in 1995 [19, 27] is able to confirm such regime. The second band of nonstable orientations of the stress axes is distinguished between 51° and 52°N in the northern part of the Central Sakhalin. The isolated group of the earthquake focal mechanisms with a subhorizontal latitudinal orientation of the maximum deviatoric compression and steeply descending south-eastward extension ones is distinguished in the western part of the Central Sakhalin between 49.5–50.0°N and 142.0–42.9°E. This approximates to the geodynamic regime of horizontal compression. The western part of the Southern Sakhalin is characterized with stable orientations of horizontal compression, which become less stable, changing the orientation to the WNW and ENE, as the Poyasok Isthmus is approached. In the same northern part of the Southern Sakhalin, the steep orientations of the maximum deviatoric extension in the west become unstable when approaching eastward, where the steep dip angles are noted in the central part and the slow ones to the SE in the eastern part. Variability of the orientations of recent deviatoric extensions and compressions is evidently associated with the boundaries of different geodynamic zones distinguished during neotectonic stress consideration.

Resuming, we note a reasonable correspondence of the presented results on orientation of the principal compression and extension axes with the results of studies of the earth surface strains in the vicinity of active faults of Sakhalin Island on the base of GPS/GLONASS surveys data [28]. In accordance with this work, the

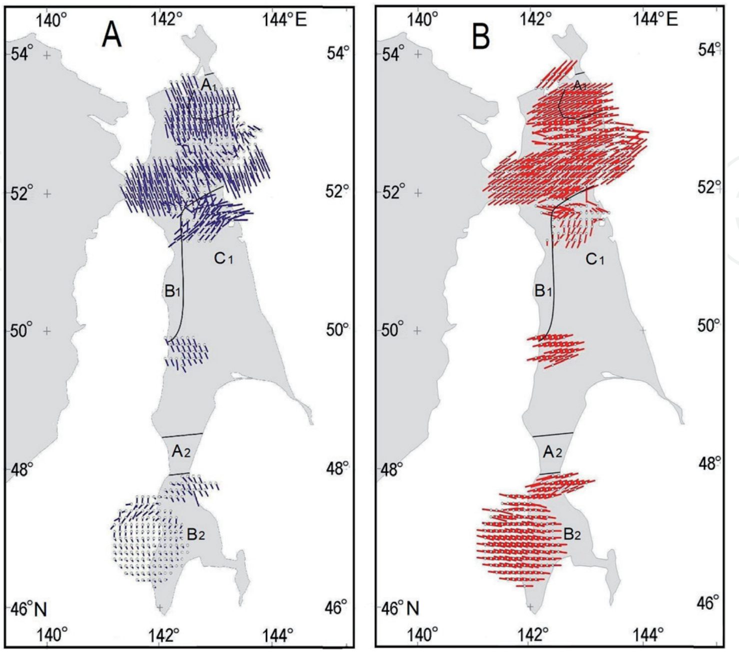

Figure 10.
*The projection of principal maximum deviatoric extensions (A) and compressions (B) to the horizontal plane. The point of dip vector origin is marked with a circle; when the dip angles are less than 15°, the circle locates in the middle of the dip vector. The areas of different geodynamic conditions are marked with black lines (see **Figure 2C**), according to Sim et al. [5].*

GPS/Glonass surveys for three cross sections (on the northern, central, and southern parts of Sakhalin Island) provided initial information on the horizontal velocities of the GPS displacements and the error of their determination, which allowed to estimate strain of the earth's surface of Sakhalin Island. The GRID_STRAIN software suite [29] has been used for computations. The GPS-observation points location, vectors of the average annual horizontal velocities, and the computed horizontal deformations of surface in the northern, central, and southern parts of Sakhalin Island are shown in **Figure 11**. As can be seen in **Figure 11B**, the shortening of the earth's crust of Sakhalin occurs mainly in the sublatitudinal direction, and it slightly varies from region to region. The heterogeneity of the surface deformation field is appeared in the distribution of the principal elongation and shortening axes over the Sakhalin area (the terms elongation and shortening are used to characterize the strain field and extension and compression for the stress field).

The territory of the northern part of the island (**Figure 11B**, upper frame) is subjected to compression in a southwestern direction. Maximum velocities of deformation up to 13 × 10^{-8} per year appear in its eastern part. Directions of the deformation velocities, in general, are consistent with the orientation of the compression and extension axes in the restored field of tectonic stress of the Northern Sakhalin

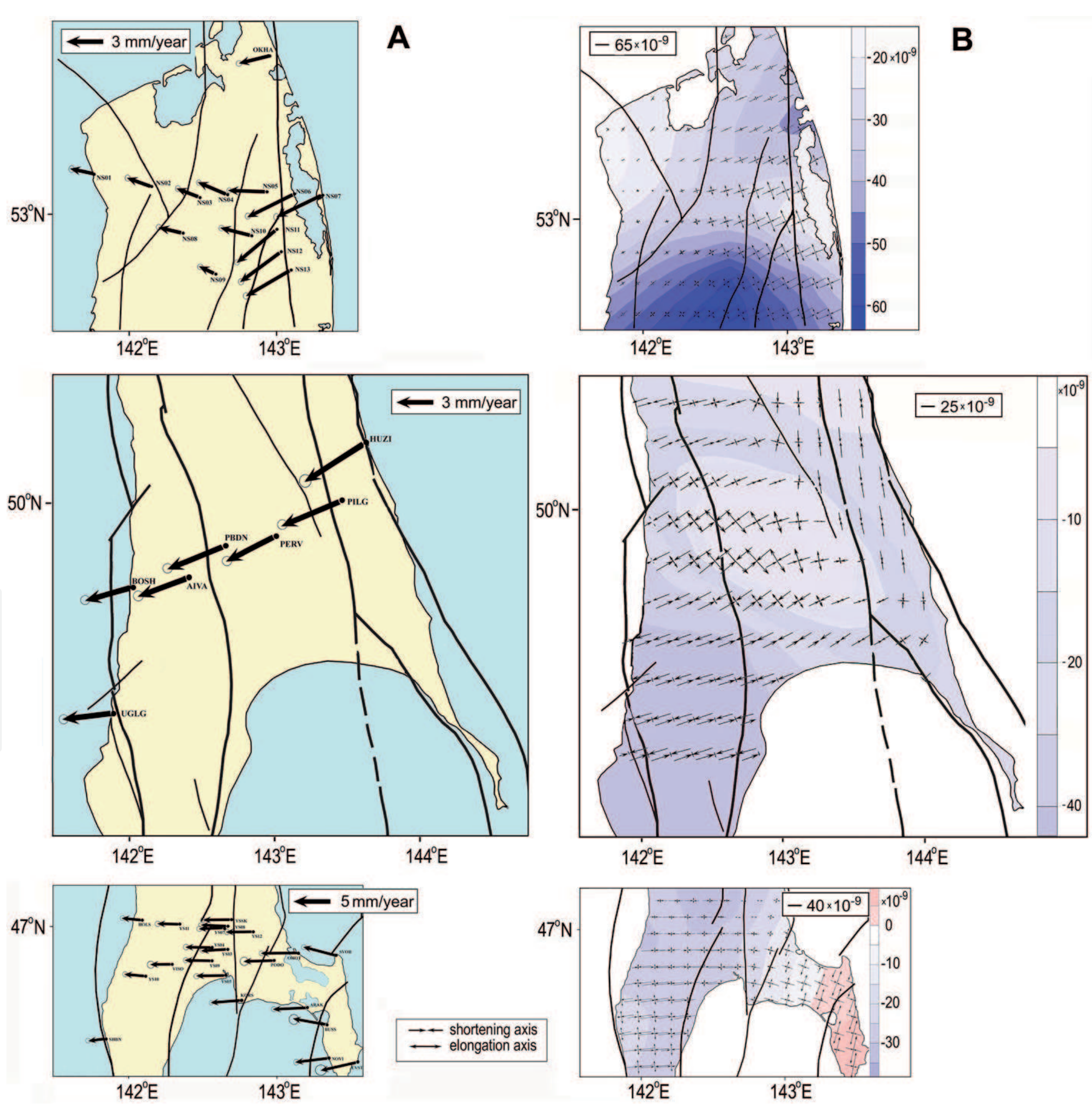

Figure 11.
Horizontal velocities at the GPS observation points of the Sakhalin Island in relation to the Eurasian tectonic plate (A), and velocities of dilatation and main axes of earth surface deformation (B). Upper frame: the measurements in the northern part of the Sakhalin during 2003–2013; midframe: the same in the central part in 2000–2011; and bottom frame: the same in the southern part in 1999–2009, according to Prytkov and Vasilenko [28].

(**Figure 2C**) [5, 6]. However, according to the GPS measurements, no extension area was found in this part of the island as opposed to **Figure 2C** with an extension zone to northward of 53°N. Low values of the velocities of deformation of the earth surface, not exceeding ~5×10^{-9} per year (**Figure 11B**, midframe), are typical for the central part of the island. Hokkaido-Sakhalin Fault delimitates the territory with different geodynamic conditions: the southwestern direction of the compression axes turns to the submeridional orientation at the fault's boundary. Alongside the dominant sublatitudinal shortening, prevailing over most of the Southern Sakhalin territory, the extension area is distinguished to eastward of 143°E (**Figure 11B**, the bottom frame). The maximum velocity of deformation of shortening is ~8×10^{-9} per year. In the vicinity of the Central Sakhalin Fault, the axes of shortening change their western direction to northwestern, and the compression of the northeastern direction becomes a prevailing regime of deformation. This zone has not been revealed when reconstructing of neotectonics stresses due to the insufficiency of initial data for the LSS determination.

Therefore, at the subregional scale (100 km and more), one can see the correspondence of the results obtained using three methods: structural-geomorphological, geophysical (seismological data), and GPS measurements. Discrepancies are observed for the zones of ~30 km length, they may be related to the complexity of fault structure on the Sakhalin, including multiple local breaks [16–18, 21], as well as to very short period of seismic and GPS monitoring. Partially motivated by this correspondence, we foresee the results represented in **Figure 2C, 6, 10** and **11** to be used for several regional issues of engineering geology works and developments. The information about the direction of maximal horizontal stress action is extremely important for new wells' construction in the oil and gas fields in the Northern Sakhalin (including the Sea of Okhotsk shelf). This action may cause wellbore breakouts followed by negative incidents: casing collapse or stuck pipe. The safe directions of near horizontal wells drilling are determined considering stress conditions. In the case of dangerous azimuth of the well, they (the operators) can compensate the horizontal stress bias by drilling mud treatment like the mud weight increase, the use of oil-based mud and inhibition additives. The data we obtained may be used for this technology in addition to the limited information of the WSM project data [23], and this will contribute to the technological safety of wells drilling and production.

Characteristics of the modern stress field controlling the earth surface deformations are significant also for the geological support of railway and main roads operation. These communications run in the vicinity of Central Sakhalin Fault. Moreover, the fault zone in the center of South Sakhalin is the most populated area in the island. The boundary between the microplates implies a zone of enhanced seismicity (see the paragraph after **Figure 8**), and seismic hazards for civil engineering. Therefore, the particular result that the segment of this boundary in the Southern Sakhalin does not follow the Central Sakhalin Fault is crucial for detailed seismic zoning and seismic microzoning before urban development. Finally, we remark that the pipelines from Sakhalin oil and gas terminals to the continent cross the active faults of submeridional strike. Our result about the location of microplates' boundary in the Northern Sakhalin speaks in favor of that the pipelines stability control to be focused on the section crossing eastward faults (Hokkaido-Sakhalin Fault, Upper Piltun one, etc.) rather than the West and Central Sakhalin Faults.

4. Conclusion

Zonation of the subregions of various geodynamic conditions of the latest faults formation has been originally carried out on the Sakhalin on the base of tectonophysical and structural-geomorphological (SG) methods. The boundaries of the mapped zones have evinced a variability of the modern stress field parameters. Reconstruction of the recent tectonic stresses of the Sakhalin has revealed a dominance of strike-slip type of stress state with subhorizontal compression and extension axes. The compression axis is sublatitudinally oriented, and the extension is submeridional. Sublatitudinal compression axes, reconstructed for the Central and Northern Sakhalin by the two-dimensional SG method, are turning to the northeast. The computed parameters of tectonic stresses as a whole are consistent with the results obtained from the earthquake focal mechanisms and GPS/GLONASS movements of earth's surface. The results of this work have demonstrated that the border between the Amur and Okhotsk microplates along the Central Sakhalin Fault on the Southern Sakhalin and change of strike-slip stress field during the folding stage to the reverse fault one to be inappropriate. The further research by SG and other tectonophysical methods of stress field reconstruction may result in the specified map of geodynamical regimes and geohazards in the Sakhalin. Such updated map will not be so complicated as structural geological one in **Figure 2A**. However, the visible indicators of local stress state are rare on the studied territory due to the forest cover. Therefore, the next research stage is expected to involve wider processing of satellite images to get raw data on faulting for the neotectonic and modern stress field reconstruction.

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Author details

Leonid Bogomolov[1]*, Lidia Sim[2] and Pavel Kamenev[1]

1 Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia

2 Schmidt Institute of Earth Physics, RAS, Moscow, Russia

*Address all correspondence to: bleom@mail.ru

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