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Morphotectonic Analysis of Pliocene–Quaternary Deformations in the Southeast of the Eastern Sayan

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Abstract—The paper is concerned with the kinematics of the major faults, their pattern, and the time of occurrence of compression and extension deformations in the southeast of the Eastern Sayan. The geometry of the mountain ranges and the kinematics of the major faults exhibit northeast-oriented compression responsible for the current processes of relief formation, which corresponds to the direction of the vector of deformations associated with the Indo–Asian collision. The results obtained thus far may be indicative of the remote influence of collision on the orogenic activity and transpressional deformations in the Eastern Sayan since the end of the Miocene. Morphotectonic analysis has shown that the areas of Quaternary extension-related deformations in the Eastern Sayan are not a response to active rifting in the Baikal Rift Zone. The position and geometry of the subsided blocks and magma ruptures point to the fact that they form locally as extension structural elements near the strike-slip faults. The strike-slip and thrust faults are widespread and play the leading role in the development of the southeastern part of the Eastern Sayan.

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INTRODUCTION

The classic concept of the relief formation in the Altay–Sayan region is based on extensive studies performed in the 1960s–1970s [5, 8, 13, and others]. The development of the ideas on the geodynamics of Central Asia [11, 47] opened a new period in geomorphic studies related to estimation of the role of the Indo–Asian collision in the formation of the mountain ranges in this region.

According to the results of recent thermochronological studies [36, 37, 42], the Altay–Sayan mountain region is considered to be the northernmost area of Central Asia where the formation of relief is associated with intracontinental compression induced by the Indo–Asian collision. Compressional and transpressional deformations are characteristic of most of the territories of Central Asia situated to the north of the collision front. Their occurrence is expressed in mountain building resulting in the formation of mountain systems from the Himalayas to the Altay [4, 10, 35, 39, 41, 42, 50]. The mountain massif of the Eastern Sayan extends along the southwestern boundary of the Siberian Platform as the northeastern termination of the Altay–Sayan mountain region (Fig. 1). In the south, this massif borders on the southwestern flank of the Baikal Rift Zone, which is transitional from the zone of active compression in North Mongolia to extension in the Baikal Rift. Several views on the formation of the Baikal Rift Zone exist. Some authors suggest that this process is related to local processes proceeding in the mantle [6, 52] (active rifting), whereas others see the cause in passive extension induced by within-plate deformations pertaining to the Indo–Asian collision [47, 49, 51]. The new fission-track dates of apatite published in [40] show that the Baikal Rift started to open in the Late Cretaceous–Early Paleogene and this process was probably related to the northward propagation of the system of Transbaikal basins. The abrupt increase in tectonic activity in the late Miocene–early Pliocene could have been induced by the Indo–Asian collision, which had reached the given region by that time.

In this paper, we make an attempt to determine in what tectonic regime the Eastern Sayan neighboring upon the Baikal Rift developed. The answer to this question could be helpful for understanding which agent was the dominant influence on relief formation, at least, beginning from the Pliocene, when rifting achieved its most active phase [15, 17, 44, 45]. If collision exerted a substantial effect on the opening of the Baikal Rift at that time, then transpressional deformation should dominate in the adjoining mountain massif. Thus, the southeastern part of the Eastern Sayan is a key region for providing insight into the character of deformation and its role in the formation of the main features of the present-day topography.

We present below the results of our study performed in the southeast of the Eastern Sayan on the basis of interpretation of aerial photographs and satellite images, analysis of topography, and field structural and geomorphic investigations of tectonic deformations.

HISTORY OF RELIEF DEVELOPMENT IN THE EASTERN SAYAN: AN OVERVIEW

The arching of the mountain massif of the Eastern Sayan was accompanied by rejuvenation of ancient deep faults, origination of intermontane basins, and basaltic eruptions [5, 13]. Two stages of Cenozoic mountain building are distinguished on the basis of the geochronolgy of volcanic and sedimentary rocks: (1) extensive uplift and erosion 22–15 Ma ago and (2) fast growth of separate mountain ranges beginning from 8.7 Ma ago [48]. Two main periods of Cenozoic mountain building are distinguished in [38]: ~20 and ~5 Ma ago. The second phase of active mountain building lasted from the entire Pliocene to the Quaternary and eventually led to the formation of the present-day topography with rearrangement of the drainage pattern, deformation of the planation surface, and volcanic eruptions. This epoch corresponds to the phase of sharp increase in tectonic activity within the Baikal Rift.

The topography of the Eastern Sayan is stepwise (Fig. 2). While some blocks are uplifted to the height of 3000 m and higher, others are slightly dissected plateaus with remnants of the ancient planation surface at a height of 2200–2500 m. The southeastern part of the Eastern Sayan is characterized by the greatest height. Individual mountain ranges (Tunka, Kitoi, Kropotkin, and Munku-Sardyk ranges) tower up to 3491 m. Like the Greater Sayan Range, these ranges are deeply dissected by erosion and are plowed by glaciers. They are characterized by Alpine-type high-mountain topography. Only the Munku-Sardyk Range and the southern part of the Greater Sayan are affected by present-day glaciation.

Domains with older denudation topography almost unaltered by subsequent processes occur in various parts of the Eastern Sayan, primarily in the Oka Plateau about 400 km^2 in area, where the planation surface is a plain with rolling topography slightly dissected by river valleys.

The boundaries of the Oka Plateau with framing mountain ridges follow deep faults that control the formation of the main topographic features in the southeast of the Eastern Sayan. The Main Sayan Fault extends along the boundary with the Siberian Platform and controls the rise of the Eastern Sayan as a whole. The fault system determining the configuration of mountain massifs in the south of the studied territory includes the Tunka, Baikal–Mondy (western segment), and the Ikh-Khoro-Gol–Mondy faults; the Yamaata Fault separating the Oka Plateau from the Munku-Sardyk Range in the north and the Greater Sayan Range in the southwest; and the system of the

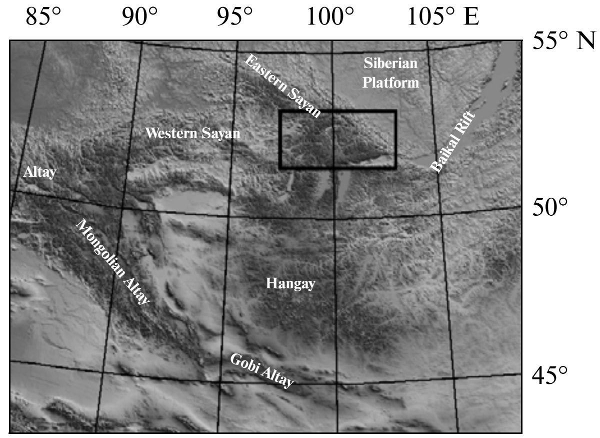


Fig. 1. Index map of the Altay–Sayan mountain region and the adjacent territories. The rectangle is the studied territory.

Azas–Sentsa and Oka–Zhombolok faults (the latter is the northern boundary of the Oka Plateau and controls the Kropotkin Range).

KINEMATICS OF THE MAJOR RELIEF-CONTROLLING FAULTS IN THE SOUTHEAST OF THE EASTERN SAYAN

The Main Sayan Fault is one of the major tectonic lines in the Altay–Sayan mountain region. Having originated in the Precambrian, this fault actively controlled the tectonic setting of the boundary zone between the Siberian Platform and the mobile belt, developing during various stages as a strike-slip, thrust, and normal fault. In the epoch of Cenozoic reactivation, the Main Sayan Fault operated as a left-lateral normal–strike-slip fault. The horizontal slip along this fault is clearly expressed in the topography. Left-lateral bends of the Greater Belaya and Lesser Belaya, Onot, Urik, Yerma, and other rivers that cross the fault are confined to the mylonite zone. The offset of such bends varies from 3 to 6 km. The largest in size is a zigzag curvature of the Irkut River valley more than 11 km in extent, which is controlled by the southeastern segment of the Main Sayan Fault. It is suggested that the Zyrkuzun Loop reflects the total offset along the fault zone [14]. Nevertheless, there is only one valley with such a large visible offset. It cannot be ruled out that this offset reflects the tectonic slip only partly and that erosion made a certain contribution to the formation of the Zyrkuzun Loop. In the course of paleoseismological study [27, 28], a seismotectonic dislocation 45 km in extent (East Sayan paleoseismodislocation) was traced in the southeastern segment of the Main Sayan Fault. The internal structure of this dislocation shows that movements in the late Pleistocene and Holocene corresponded to the left-lateral normal–strike-slip faulting.

A series of near-latitudinal faults (Tunka, Oka–Zhombolok, etc.) are attached to the Main Sayan

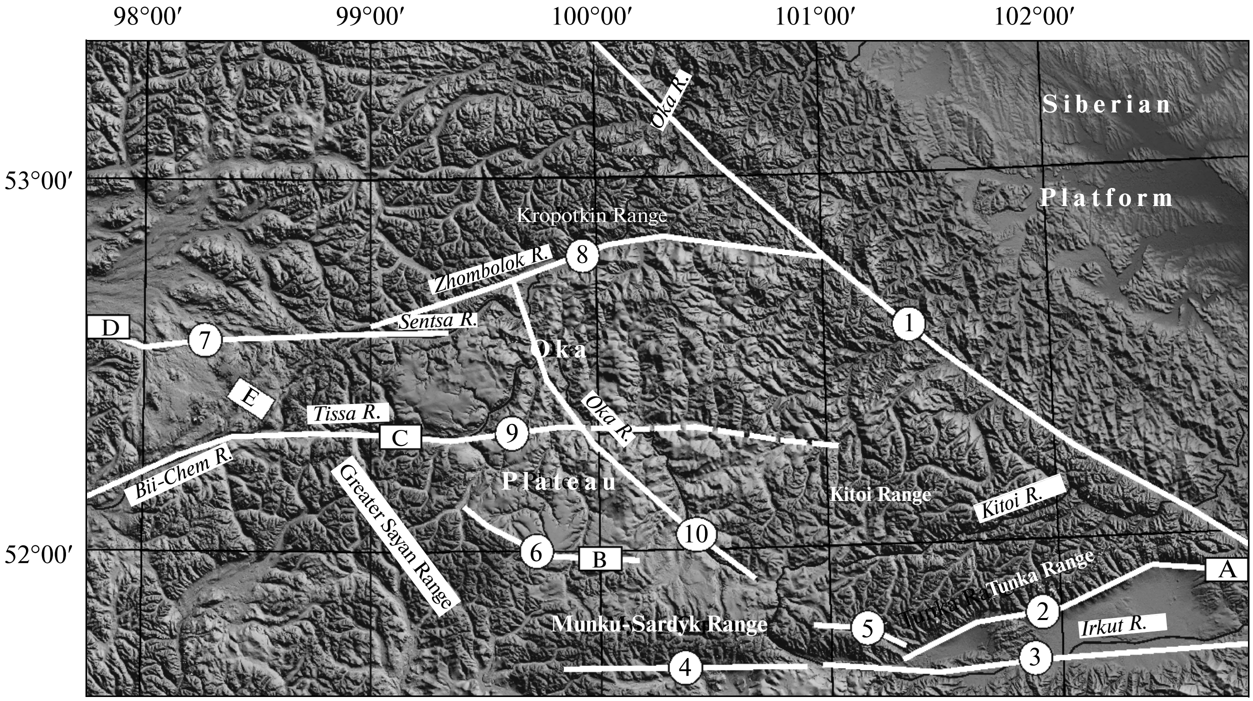


Fig. 2. Digital model of topography of the southeast of the Eastern Sayan. Major relief-controlling faults (numerals in circles): 1, Main Sayan; 2, Tunka; 3, Baikal–Mondy; 4, Ikh-Khoro-Gol–Mondy; 5, Ikhe-Ukhgun; 6, Yamaata; 7, Azas–Sentsa; 8, Oka–Zhombolok; 9, Bii-Khem–Tissa; 10, Oka. The white rectangles are the locations of Pliocene and post-Pliocene structural elements formed as a result of compression: A, basaltic flows deformed as a result of NE compression [23]; B, Late Pliocene basalts involved in thrusting [21]; C, D, deformed basaltic flows in the uplifted southern walls of the faults [8]; E, system of gentle folds in Pliocene sediments [7].

Fault in the west. The near-latitudinal Bii-Khem–Tissa Fault loses its master suture with approaching the Main Sayan Fault, whereas in the west the Bii-Khem–Tissa Fault is clearly expressed in the topography. These faults are the eastern segments of more extended regional tectonic lines striking in the W–E and ENE directions and revealing lateral and vertical displacements of tectonic blocks.

The Tunka Fault that separates the Tunka Range from the system of basins bearing the same name is a long-lived deep fault expressed as a left-lateral normal–strike-slip fault at the Cenozoic stage [29]. Normal separation along this fault is related to the opening of the Baikal Rift and subsidence of the Tunka system of basins in its southwestern wall, which began in the Oligocene and Miocene [15, 16]. The first stage of subsidence was insignificant and characterized by deposition of the fine-grained sediments of the Tankhoy Formation in the Tunka basins. The intense subsidence of basins started in the middle Pliocene, when coarse clastic material of the Anosovo Formation began to accumulate. The maximum thickness of the Cenozoic sediments in the central part of the Tunka Basin reaches 2700–2800 m [12]. With allowance for scarp height of the Tunka Range, which attains 2000 m near the Tunka Basin, the total amplitude of Cenozoic vertical displacements along the Tunka Fault and parallel fault segments within the basin may be greater than 4500 m.

Our preceding structural, geomorphic [2, 33, 43], and paleoseismological studies have shown that the transtensional regime that dominated in the Tunka system of basins from the Oligocene gave way to transpression in the late Quaternary. Strike-slip movements along the Tunka and Baikal–Mondy fault zones (the latter bounds the Tunka system of basins in the south) were predominant. Compressive deformations are localized at the block boundaries, whereas extension deformations are characteristic of the inner parts of the basins, which remain in the tectonic shadow in the process of left-lateral displacements along near-latitudinal faults [2].

The Tunka Range is also characterized by Holocene transpressional deformations expressed, for example, by reverse–strike-slip displacements along the Ikhe-Ukhgun Fault extending parallel to the Baikal–Mondy Fault to the north of the latter. As was shown in [1], both faults make up a common flower structure developing under NE-trending compression.

Older thrust faults oriented in the northeastern and more frequently in the northwestern direction are known in the Tunka Range [29]. Ruzhich [23] described the displacement of the Late Miocene–Pliocene basaltic dikes in the thrust fault zones reactivated in the Pliocene or Quaternary and pointed out the deformation of basaltic flows in the junction of the Yelovsky Spur—an intrabasinal uplift within the Tunka system—and the slope of the Tunka Range (rectangle A in Fig. 2). This deformation indicates compressive stress oriented in the northeastern direction.

The Tunka and Baikal–Mondy faults extend to the west in the form of the Ikh-Khoro-Gol–Mondy Fault that bounds the mountain massif of the Eastern Sayan in the south and separates it from the Hövsgöl and Darhat rift-related basins. This fault is localized at the foot of the Munku-Sardyk Range and also shows left-lateral strike-slip kinematics. The fieldwork conducted in the Ikh-Khoro-Gol–Mondy Fault Zone allowed us to estimate the last (late Quaternary) offset at 70 m in several valleys [3]. Outcrops of granitic rocks in the walls of one valley reveal dislocations. The fault strikes here at an azimuth of 90° E and dips at an angle of 70–80° to the north. As follows from the striation, left-lateral strike-slip and reverse movements are predominant. Given the kinematics of the fault, the W–E-trending Munku-Sardyk Range most likely is a pop-up structure, which is extruded under lateral compression oriented in the near-meridional direction. In this case, the reverse and thrust faults should develop at the frontal foot of the range that bounds the Oka Plateau. One such thrust fault displacing basaltic lavas dated at 2.6 Ma was described by Rasskazov [21] (rectangle B in Fig. 2). It cannot be ruled out that thrusting took place before 2.6 Ma as well. Structural observations show that uplift of the tectonic block that bounds the Oka Plateau near this thrust fault was combined with its shift to the north [21]. The offset calculated from boreholes was more than 300 m. It was concluded that thrusting was reactivated owing to increasing compression from the side of North Mongolia, which provoked hummocking of the Earth's crust. The dating of the basalts from the crest of the Munku-Sardyk Range and its northern slope made it possible to estimate the age of onset of rising and the rate of this process during the last 8.7 Ma [48]. It was shown that 8.7–6.9 Ma ago the rate of uplift of the Munku-Sardyk Range was 0.25 mm/yr; 6.9–2.8 Ma ago the rate was 0.06 mm/yr, and during the last 2.8 Ma the rate diminished to 0.03 mm/yr. Thus the last stage of mountain building, expressed in rising of the high ranges of the Eastern Sayan, started about 9 Ma ago [48]. The mass dating of basaltic lavas in the southwestern Oka Plateau has shown that the basaltic volcanism was active over more than 10 Ma and ceased 1.9 Ma ago.

The aforementioned data show that the active rise of mountain ranges in the south of the Eastern Sayan began in the late Miocene and was accompanied by long-term volcanic activity, which waned in the early Pleistocene. The Munku-Sardyk Range was formed along the southern boundary of the Oka Plateau as a pop-up structure over the last 8.7 Ma. The rate of vertical movements decreased in the Quaternary by an order of magnitude in comparison with the late Miocene. A rough estimate of the rate of left-lateral slip by 70 m along the southern foot of the Munku-Sardyk Range [3] yields ~0.7 mm/yr; this estimate is two times greater than the rate of vertical rise over the same period. The rate of horizontal offset was probably even higher, but in the absence of reliable data on the age of the displaced landforms, we cannot confirm this definitively. Judging from the good preservation of these landforms, they were formed in the late Quaternary.

The Late Cenozoic reactivation of mountain building in the Sayan, Khamar-Daban, and Hangay is supported by the data on the modified morphology of the dated lava flows [30, 31]. It was established that about 3 Ma ago the plateau-forming eruptions in the above regions were superseded by valley eruptions, indicating initial growth of the mountain system and the formation of the present drainage pattern. In the Eastern Sayan, the oldest valley basalts are dated at 2.8 Ma; in the Khamar-Daban, at 3.1 Ma; and in the South Hangay, at 2.9 Ma [31]. According to [38], the onset of valley eruptions in the Eastern Sayan is accepted at 5 Ma, and this date is regarded as the beginning of Cenozoic mountain building. Thus, the age of the last episode of mountain building is 9–5 Ma. This age is consistent with the period of active mountain building in the Gobi Altay and the Mongolian Altay, dated at 5 ± 3 Ma and regarded as a remote response to the Indo–Asian collision [42, 50]. The chronological coordination of the onset of active tectonic deformations in the Eastern Sayan, Gobi, and Mongolian Altay provides evidence for the same source of tectonic stress responsible for mountain building at that time. In our opinion, this source was the Indo-Asian collision.

To the northwest of the above-described deformations, the uplift of the southern wall of the Bii-Khem–Tissa Fault Zone is clearly expressed in the topography and attains 500 m near Lake Dozor-Nuur (rectangle C in Fig. 2) [8]. The rise took place in the post-Pliocene time, because the vertical separation was estimated as the difference between the elevation marks of the bottom of the broken Pliocene lava flows. Since the eastern segment of the Bii-Khem–Tissa Fault is not so evident in the topography as the western segment that terminates at the intersection of the fault with the Oka River valley, it may be suggested that eastward propagation of the Bii-Khem–Tissa Fault through the Oka Plateau occurred later.

The northern boundary of the Oka Plateau goes along the Oka–Zhombolok Fault that separates the plateau from the highest Kropotkin Range (Fig. 2). The kinematics of the Oka–Zhombolok Fault is determined as a left-lateral strike-slip displacement [8]. In the western direction, the Oka–Zhombolok Fault extends as the Azas–Sentsa Fault with documented reverse kinematics in the post-Pliocene time [8]. The northern face of the Ulug-Arga Range is uplifted along the Azas–Sentsa Fault for more than 700 m (rectangle D in Fig. 2). The study of plaleoseismodislocations in the

Oka–Zhombolok Fault provides evidence for its normal–strike-slip kinematics at the neotectonic stage [26]. Most restored stress fields within this fault zones characterize the regime of pure shear under conditions of transpression and northeastern orientation of the compression axis [20]. The stress field, which was restored from fracturing in the active deformation zone, is consistent with displacements of late Pleistocene–early Holocene landforms. To specify the kinematic characteristics of the Oka–Zhombolok Fault, we have performed structural, geomorphic, and paleoseismological studies, and their results are presented in the next section.

YOUNG DEFORMATIONS IN THE OKA–ZHOMBOLOK FAULT ZONE

The Oka–Zhombolok Fault of ancient origination is accompanied by a complex system of conjugate and near-parallel fractures with intensely developed cataclasis, foliation, mylonitization, and ductile deformation. The northern wall of the fault corresponds to the Kropotkin Range that towers above the Oka Plateau by 400 m on average. Both vertical and horizontal displacements variable in rate took place along this fault in the Late Cenozoic. The predominant reverse faulting gave rise to the rupture of the planation surface, the remnants of which are widespread on the Oka Plateau and on the Kropotkin Range as flat summits at various hypsometric levels. At first glance, the facets that are observed at the southern slope of the range point to the normal component of displacement; however, such facets are not characteristic of the entire extent of the Oka–Zhombolok Fault Zone and are localized only along its NE-trending segment in the lower part of the scarp in the Zhombolok River valley below the level of the Oka Plateau. This indicates that these facets are younger than the predominant reverse faulting that resulted in the rise of the planation surface. The formation of facets could have been facilitated by glaciers that filled the valley in the late Pleistocene.

Distinct signs of left-lateral kinematics are established for the near-parallel branches of the fault located somewhat north of the main scarp and at its foot. Thus, in the lower reaches of the Tashalur-Zhalga River (left tributary of the Zhombolok River), a left-lateral offset is observed along a branch of the Oka–Zhombolok Fault, which extends here at the contact between granite (northern wall) and marble (southern wall). Within the fault zone, the marble is brecciated; cataclastic and gouge zones are noted. The stream valley and the adjacent drainage divides reveal left-lateral offset along the fault zone (Fig. 3); the present-day valley is dammed by a block of crystalline rocks. The visible offset measured by displacement of the left wall of the Tashalur-Zhalga River valley is 150 m (Fig. 3c). The Late Pleistocene moraine in the right wall resting upon the deformed crystalline basement is displaced along the fault zone as well (Fig. 3d). As is seen in the satellite image, this offset is traced in the neighboring large valleys (Fig. 3a).

Because the landforms created as a result of long-term, largely vertical dislocations (large mature valleys and drainage-divide promontories) are involved in strike-slip displacements along the Oka–Zhombolok Fault, it may be suggested that the corresponding movements are younger. The offsets of the moraines constrain the age of strike-slip faulting to the late Pleistocene. The formation of clearly expressed facets in the Zhombolok River valley as evidence of local normal faulting is probably related to this stage.

The paleoseismological study of the Oka–Zhombolok Fault Zone allowed us to reveal an earlier unknown young seismic rupture at a slope of the tectonic scarp between the Bulag and Ubalzan-Zhalga rivers, the left tributaries of the Zhombolok River. This rupture is expressed in the topography as a linear flattening of the slope, which visually resembles a reverse scarplet trending parallel to the main fault zone at an azimuth of 55° NE and crossing the valleys of intermittent streams with left-lateral offsets (Fig. 4). The series of such valleys is displaced along the faults by a distance of 7.5 to 16 m. A trench five meters long and about 1.5 m deep was driven across the rupture in the locality marked by a rectangle in Fig. 4a. The trench crossed the near-vertical fractures with displacements of beds at different levels, which are related to two seismic events (Fig. 5).

The abruptly changing thickness of the members along the strike at the level of the ruptures is an attribute of the strike-slip component of the displacement due to a paleoearthquake [46]. It is not easy to estimate the vertical component because the visible vertical deformations may be a result of horizontal displacement along steeply dipping faults. Flattening of the slope at the intersection with the rupture may be a morphological manifestation of the reverse faulting, but no direct evidence for such deformation is revealed along the rupture.

Thus, at the initial stage of growth of the range, the deformations related to the Oka–Zhombolok Fault were characterized by a prevalence of vertical displacements and uplift of the northern wall relative to the southern wall by 400 m on average. The late stage (at least late Quaternary in age) is distinguished by left-lateral strike-slip offsets, which are crucial for boundary deformations in the Kropotkin Range. In the NE-trending segment of the fault, the strike-slip faulting is accompanied by locally developed normal faulting.

FAULT–BLOCK STRUCTURE AND DEFORMATION REGIME IN THE SOUTHEAST OF THE EASTERN SAYAN

On the basis of geological maps and the SRTM (Shuttle Radar Topography Mission) digital topogra-

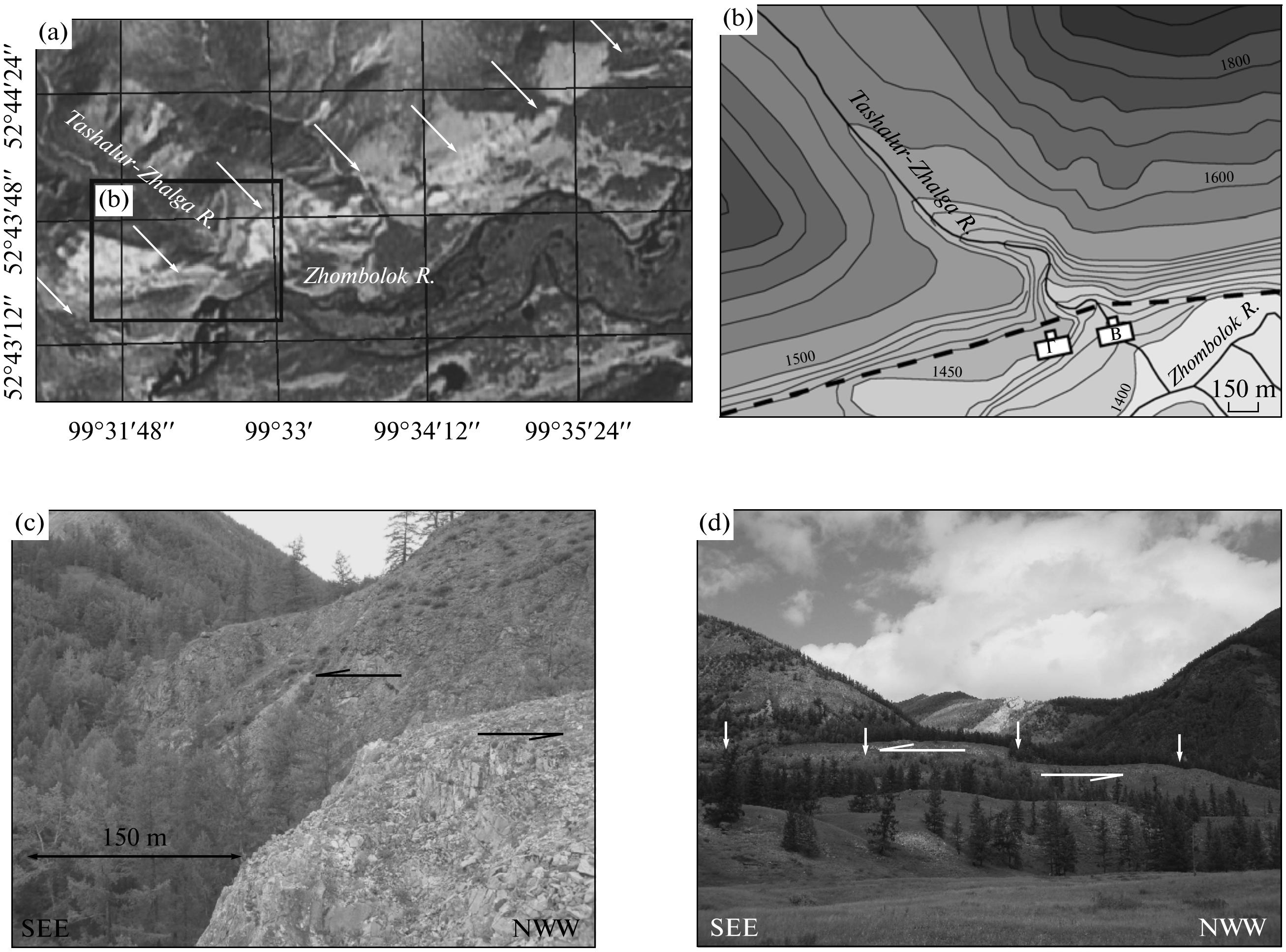


Fig. 3. Left-lateral offsets along the Oka–Zhombolok Fault: (a) a close-up of the Landsat image; the arrows indicate a segment of the Oka–Zhombolok Fault with strike-slip offsets described in the text; (b) morphology of the Tashalur-Zhalga River valley at the intersection with the Oka–Zhombolok Fault; (c) left wall of the valley shown in Fig. 2b displaced along the fault; (d) Late Pleistocene moraine displaced along the Oka–Zhombolok Fault.

phy model and using the technique of revealing block structures from the topography [19], the scheme of the fault–block structure, as well as the geological–structural scheme, have been created for the southeastern part of the Eastern Sayan (Figs. 6a, 6b). The scheme of the fault–block structure was prepared by contouring blocks with different absolute heights. The recommended minimal difference in height for young mountain systems is 200 m. To select blocks, the reference heights not cardinally distorted by denudation were chosen, e.g., elevation marks of drainage divides, tectonic steps, and plains; slopes and river valleys were not taken into account. The demarcation of blocks was conducted by the foots of slopes, straight segments of river valleys, inflections of slopes separating tectonic steps, and linear arrangement of saddle-shaped inflections or scarps on several drainage divides. In parallel, the faults, which were active during the formation of the mountain system and thus clearly expressed in the topography, were traced. The conjugation of the sites differing in height and coinciding with the revealed faults are the boundaries of tectonic blocks. The boundaries of the blocks, which do not coincide with the faults, were probably formed as a result of erosion.

As follows from the scheme of the fault–block structure (Fig. 6a), vertical movements were important in the formation of the relief of the Eastern Sayan. The vertical displacement of blocks relative to the Siberian Platform (absolute heights of 700–800 m near the Eastern Sayan) varies from 1400 m in the lowermost part of the Oka Plateau to 2400 m in the highest Tunka, Kitoi, Kropotkin, Munku-Sardyk, and Greater Sayan ranges. Within the Sayan Massif, the difference in the present-day hypsometric levels of the ancient planation surface retained on the Oka Plateau and partly on the summits of the Kropotkin Range is 400 m on average.

The intermontane Oka Plateau that occupies the central part of the studied territory is less uplifted relative to the framing mountain ranges. The eastern and

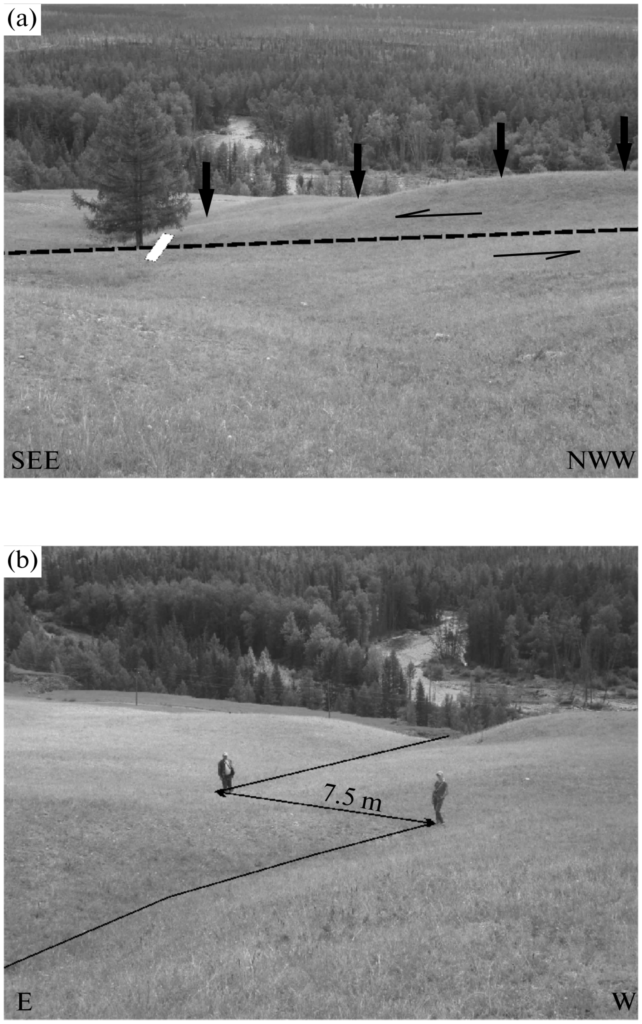


Fig. 4. Reverse scarplet and left-lateral offset of an intermittent stream in the zone of seismic rupture.

western blocks, which are distinguished in the topography of the plateau, are divided by a tectonic line striking in the northwestern direction. This boundary extends along the Oka River valley and appears as a fault in the topography (Fig. 7). Nevertheless, it has not been shown in maps and described in the literature, as might be expected for faults of such a rank. Its distinct morphological attributes (a chain of linear landforms and different heights of the blocks divided by this line) allow us to identify it as the Oka Fault. The eastern block of the Oka Plateau is generally uplifted relative to the western block. The difference in heights is especially evident for the highest summits, which occur at a level of 2514–2522 m in the western block and at a level of 2700–2900 m in the eastern block; the highest elevation mark therein is 2905 m. The uplift of the eastern block by more than 300 m relative to the western block partly explains the fact that the latter is more dissected by erosion. Another cause of this difference is a greater tilt of the eastern block, which provides faster development of the drainage pattern. Furthermore, the drainage pattern of the eastern block was not blocked by glaciers during the Late Pleistocene glaciations, whereas moraines surround the western block. The standing of the valley glaciers raised the base level of erosion in the western block and thus decreased the intensity of erosion.

In our opinion, the uplift of the eastern block is caused by the reverse kinematics of the Oka Fault during the late Pliocene mountain building. This interpretation is sensible because the Oka Fault is nearly parallel to the thrust front extending along the southwestern boundary of the Oka Plateau. The western rigid block remained almost undeformed, whereas the eastern block rose by more than 300 m along the Oka Fault Zone.

Despite its internal divisibility, the Oka Plateau stands out against the background of the surrounding mountain ranges as a single large block, which is disturbed by faults to the least extent. This applies not only to the relief-controlling faults but also to the ancient faults untouched by Cenozoic reactivation. The Oka Plateau is a salient of Archean–Proterozoic sedimentary and volcanic rocks, whereas the framing ranges are composed largely of Paleozoic rocks (Fig. 6b). The Oka Plateau is a peculiar backstop providing compressive deformation expressed in the development of reverse and thrust fault zones in its high-mountain framework.

The highest mountain ranges in the southeast of the Eastern Sayan were formed along the W–E- and NW-trending faults bordering the Oka Plateau (Fig. 6a) and giving evidence for long-term compressive stresses and lateral shortening of the crust with extrusion of the rock massifs at the boundaries of the rigid block in the meridional and northeastern directions. This is supported by the geometry of the tectonic blocks: the main mountain ranges are elongated across the direction of the principal compressive stress.

Horizontal movements in the central part of the Sayan mountain massif were expressed in the left-lateral offsets along the near-latitudinal faults, which, being conjugated with the Main Sayan Fault, accommodated the slip along the latter.

The combination of Pliocene–Quaternary thrust and strike-slip faults corresponds to the transpressional regime of deformation, while the geometry and kinematics of the faults point to meridional and northeastern orientation of compressive stress. The transtensional deformation in the Oka–Zhombolok Fault Zone, as well as the area of subsidence at the junction of the Oka and Oka–Zhombolok faults (call it the Oka domain of extension) are the only structural elements that disagree with this scheme. The uplift of the latitudinal high-mountain Kropotkin Range relative to the Oka Plateau requires compression in the meridional direction. The Oka Plateau was also involved in rising but at a lower rate than the surrounding mountain ranges. The ranges of the southern and western frame-

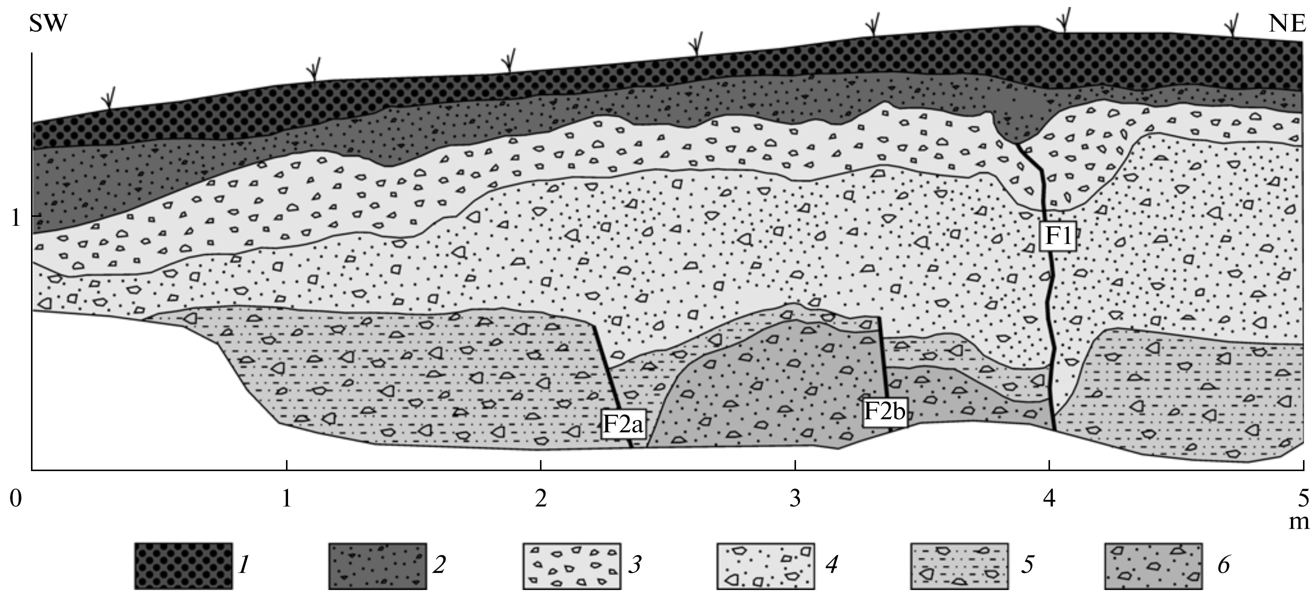


Fig. 5. Northwestern wall of the trench crossing a renewed segment of the Oka–Zhombolok Fault. (*1*) Soil; (*2*) soil with sand and grus; (*3*) carbonated sand, grus, and gravel; (*4*) gravelstone with fine-grained carbonated matrix; (*5*) gravelstone with sandy–clayey matrix; (*6*) gravel and sand. Heavy lines are faults: F1, the fault formed during a younger seismic event corresponding to deposition of layer 2; F2a and F2b, the faults that mark an older event corresponding to deposition of layer 4.

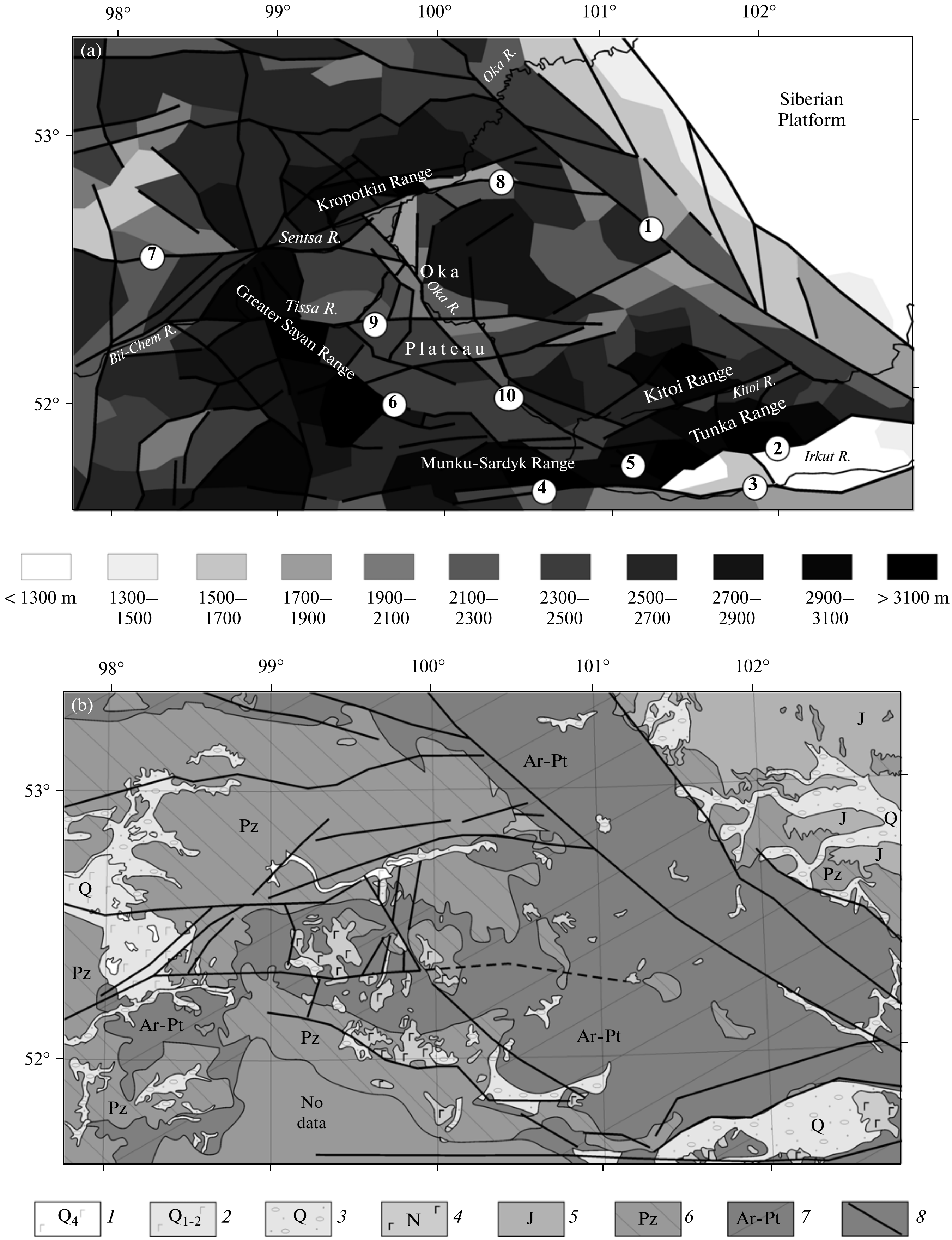
works were thrust over the Oka Plateau; thrusting at the boundary with the Kropotkin Range is not clearly manifested in the topography. Under compression, this range, bounded on both sides by parallel W–E-trending faults, must be formed as a pop-up uplift. Most likely, this actually took place in the late Miocene and Pliocene. It is quite probable that the steep Oka–Zhombolok Fault dips northward at a depth and may be regarded as a reverse fault. The movements along this fault led to the difference in height between the Kropotkin Range and the Oka Plateau. The remnants of the planation surface at the summits of the Kropotkin Range are likely fragments of the planation surface covering the most part of the Oka Plateau. Strike-slip displacements mostly developed at that time in the west along the near-latitudinal Azas–Sentsa and the Bii-Khem–Tissa faults conjugated with near-meridional thrust faults at the boundary of the Oka Plateau (Fig. 8).

The available morphostructural data are insufficient to estimate the duration of active thrusting. It can be only stated that the left-lateral Oka–Zhombolok Strike-Slip Fault with the normal component in one of its segments was especially active in the late Quaternary. The same is evident for the Oka extension domain expressed in the present-day topography and bounded in the north by the normal–strike-slip segment of the Oka–Zhombolok Fault.

We suggest that at the last stage of neotectonic evolution of the studied territory, the orientation of the maximum compressive stress shifted to the east-northeast, probably due to redistribution of tangential stresses at the boundaries of the geoblocks. The oblique pressure from the southwest led to the reactivation of shear along the near-latitudinal faults and eastward propagation of the Azas–Sentsa and Bii-Khem–Tissa faults (Fig. 9). Thereby, the Azas–Sentsa Fault connected with the Oka–Zhombolok Fault, so that the offsets formerly accommodated in the meridional thrusting at the boundary with the Oka Plateau were transmitted further to the east along the Oka–Zhombolok Fault. The Bii-Khem–Tissa Fault propagated up to intersection with the weakened zone along the meridional segment of the Oka River valley. To the east of this zone, the strike-slip displacement was transmitted to the Oka–Zhombolok Fault, as in the case of the Azas–Sentsa Fault. The eastern continuation of the Bii-Khem–Tissa Fault proper did not have a focused master suture. In the zone of transition from the Bii-Khem–Tissa Fault to the Oka–Zhombolok Fault, the redistribution of stresses resulted in the formation of a meridional depression with subsidence of particular blocks down to 800 m relative to the surface

→

Fig. 6: (a) Scheme of fault–block structure of the southeastern part of the Eastern Sayan; numerals in circles are major relief-controlling faults (see Fig. 2); (b) structural–geological scheme of the studied area. (*1*) Holocene basalts; (*2*) Pleistocene basalts; (*3*) Quaternary sediments; (*4*) Neogene basalts; (*5*) Jurassic sedimentary rocks; (*6*) Paleozoic sedimentary and volcanic rocks; (*7*) Archean and Proterozoic sedimentary and volcanic rocks; (*8*) major Cenozoic faults.


98°
99°
100°
101°
102°
53°
52°
(a)
Oka R.
Siberian Platform
Kropotkin Range
Sentsa R.
Oka
Oka R.
Tissa R.
Greater Sayan Range
Bii-Chem R.
Plateau
Kitoi Range
Kitoi R.
Tunka Range
Irkut R.
Munku-Sardyk Range
1
2
3
4
5
6
7
8
9
10
< 1300 m
1300–1500
1500–1700
1700–1900
1900–2100
2100–2300
2300–2500
2500–2700
2700–2900
2900–3100
> 3100 m
(b)
Ar-Pt
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Q
No data
Q_4 1
Q_{1-2} 2
Q 3
N 4
J 5
Pz 6
Ar-Pt 7
8

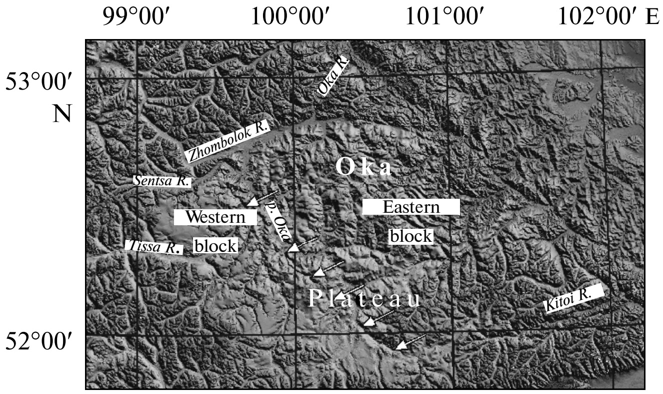

Fig. 7. Topography of the Oka Plateau. The boundary between the eastern and western blocks is indicated by arrows.

of the Oka Plateau. As is illustrated by the inset to Fig. 9, the Oka Depression is formed in the area of an S-shaped bend of the northern and northwestern boundaries of block B moving to the east. Normal faulting locally combined with strike-slip offsets in this segment of the Oka–Zhombolok Fault is related to the northeastern strike of the segment and the predominance of extension in the depression zone.

Thus, after propagation of the Bii-Khem–Tissa Fault up to the Oka Fault Zone, both are combined into a common structural assembly with the Oka–Zhombolok Fault; as a result, the left-lateral strike-slip displacement along the latter is reactivated. The cumulative amplitude of the slip in one of its segments is 150 m (see above). At the same time, the transition zone between the Bii-Khem–Tissa and Oka–Zhombolok faults started to subside and to transform into a domain of extension with numerous normal faults bounding the subsiding steps. The Holocene transtensional deformation in the Oka–Zhombolok Fault Zone [26] is confined precisely to this domain of fault-line extension.

The area of volcanic activity—the Azas volcanic plateau and volcanoes of the Khi-Gol Depression—in the west of the described territory (Fig. 10) is the same fault-line extension domain. This domain is deformed under extension or transtension, facilitating opening of magma conduits along the deep faults. The Orosoy Fault bounding the Kropotkin Range in the northwest is such a feeder. This fault is conjugated with the Oka–Zhombolok Fault in the southwest and gradually wanes in the northeast. According to [18], in the late Quaternary, the southwestern segment of the fault was a conduit for basaltic lava. Some cinder cones of

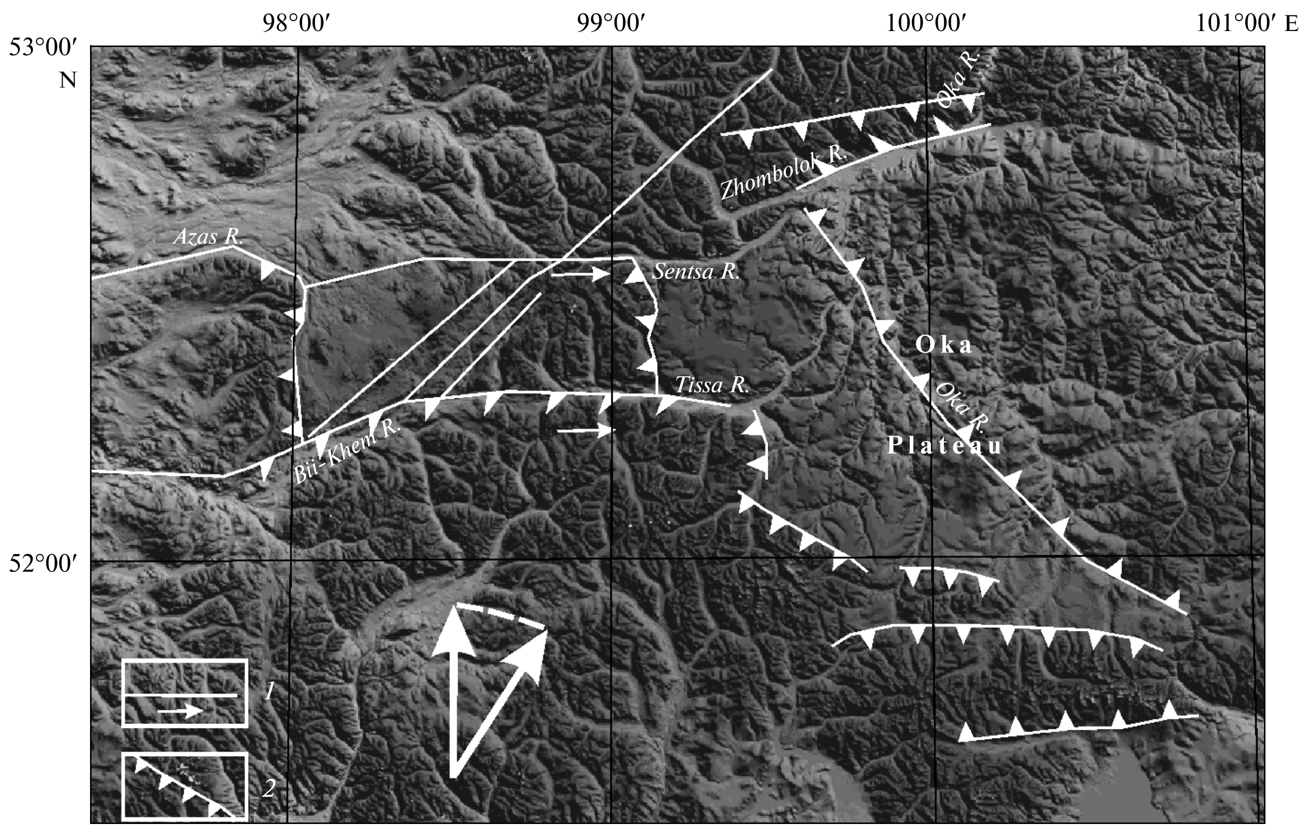

Fig. 8. Kinematics of major faults in the southeastern part of the Eastern Sayan at the early stage of mountain building (since late Miocene). (*1*) Strike-slip faults; (*2*) reverse and thrust faults. Heavy arrows indicate the directions of the principal compressive stress.

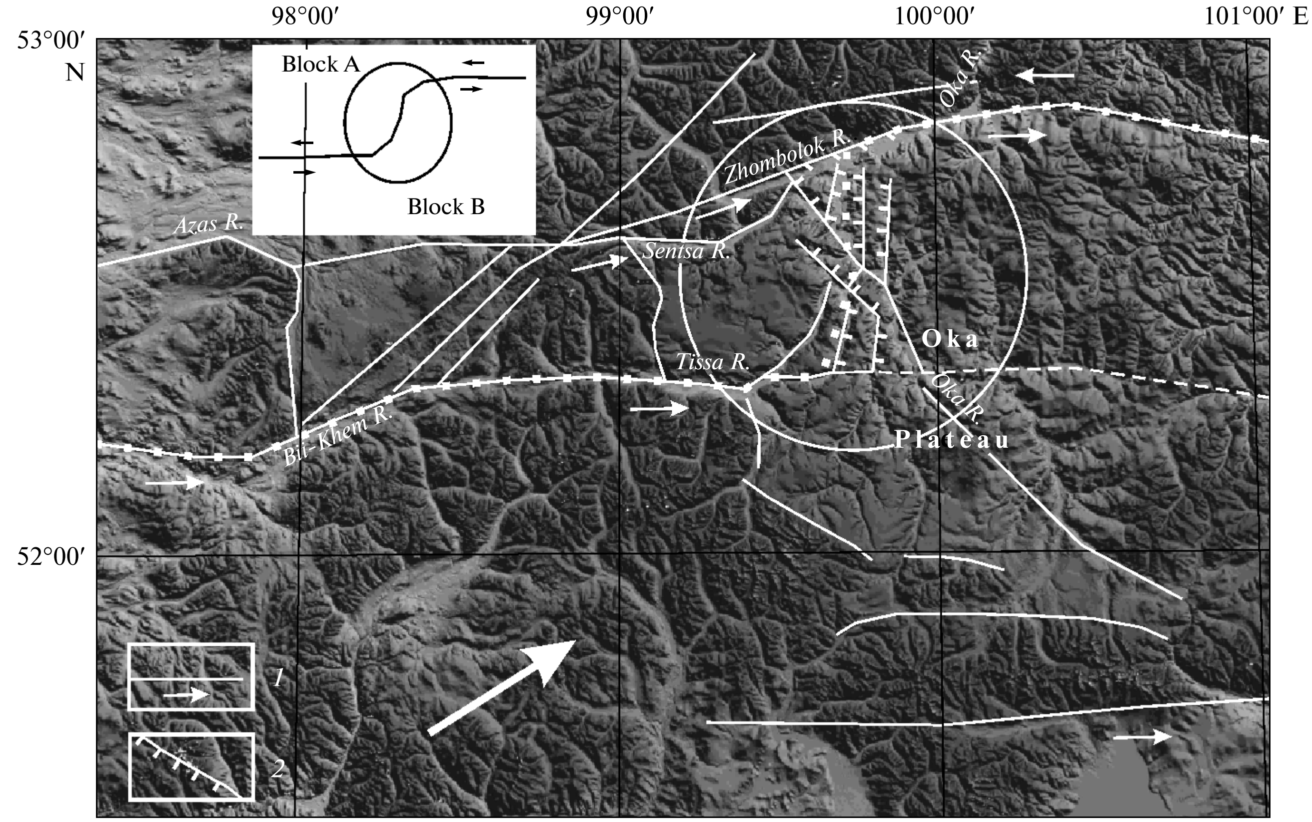

Fig. 9. Kinematics of major faults in the southeastern part of the Eastern Sayan at the Late Quaternary stage of mountain building. (*1*) Strike-slip faults; (*2*) normal faults. The heavy arrow indicates the directions of principal compressive stress; the dotted line indicates the boundary between blocks A and B (see inset).

Holocene volcanoes in the Khi-Gol Depression of the Eastern Sayan are localized in the axial zone of this fault.

The system of parallel faults dissecting the Azas Plateau is the southwestern continuation of the Orosoy Fault (Fig. 10). This volcanic plateau started to form in the Miocene and developed up to the late Pleistocene [22, 25, 32]. The faults control a series of volcanic edifices formed during this period. It is noteworthy that the centers of lava eruptions on the Azas Plateau are related to auxiliary NE-trending fractures oblique with respect to the master near-latitudinal faults bounding the tectonic blocks. Groswald [8] noted that the northeastern strike of magma conduits is consistent with the orientation of tension cracks that arise as splays of left-lateral strike-slip movements along the near-latitudinal faults. The latter, in combination with thrust faults, could be induced by lateral compressive stresses oriented at an acute angle to the strike of the faults. Signs of such compression are observed in the volcanic fields. For example, in the Dula-Khol-Tonma River valley on the Azas Plateau, the presumably Pliocene sequence of boulders, pebbles, and sand is deformed into gentle folds plunging at an azimuth of 210°SW [7] (square D in Fig. 2). In other words, indications of Late Cenozoic compression in the northeastern direction are observed not only at the boundaries of the Oka Plateau as a backstop for propagation of deformation from the side of North Mongolia, but also in the areas of magma conduits, which are regarded as domains of predominant extension. Thus, beginning from the late Miocene, compression and transpression in the Eastern Sayan became of regional importance, whereas extension was local and confined to the faults oriented along the direction of principal compressive stress or at an acute angle to this direction (Fig. 11). The regional character of transpressional deformation is confirmed by reconstructions of local stress fields in the Sayan rock massif, Tuva Rise, and southwestern flank of the Baikal Rift Zone [24]. The authors of the above-cited publication drew the conclusion that beginning from the late Miocene the given territory was characterized by a transpressional stress field first with the NW- and then the NE-trending compression axis.

An attempt to estimate the direction of principal compressive stress from the orientation of the dikes in the volcanic Azas Plateau was undertaken in [9]. It was concluded that the strike of the dikes commonly oriented along the direction of compressive stress changed with time. The dikes dated at 1.2–0.7 Ma were oriented mainly in the NNE direction scattered

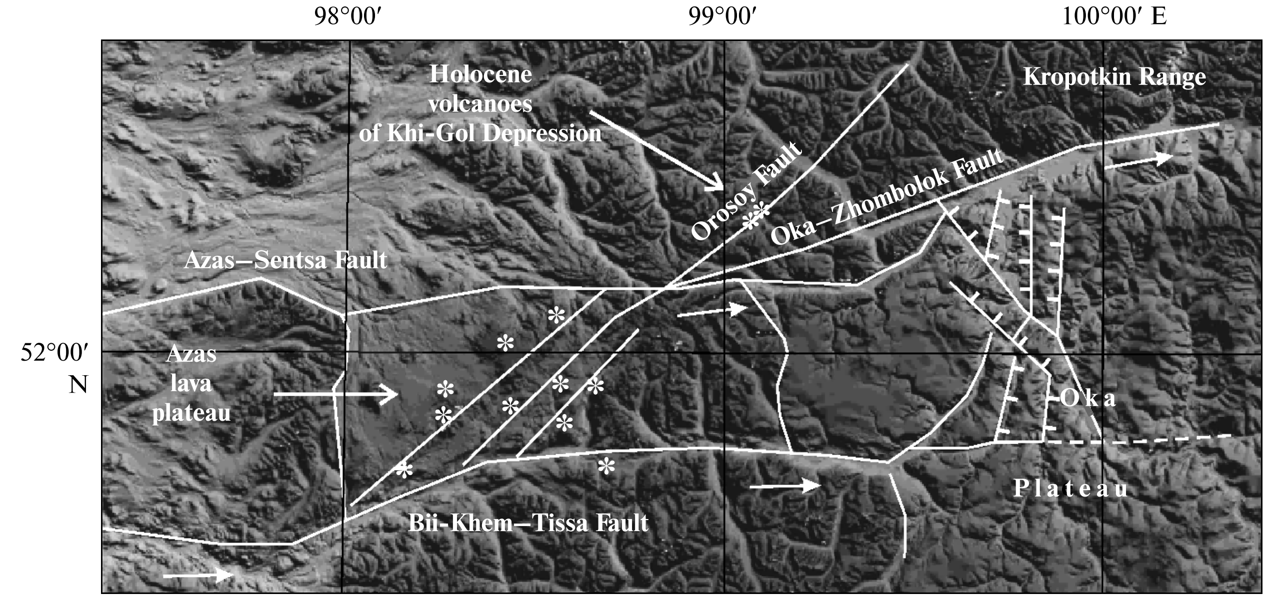

Fig. 10. Volcanic activity on the Azas lava plateau and Holocene volcanoes of the Khi-Gol Depression. Main volcanic centers are shown by stars.

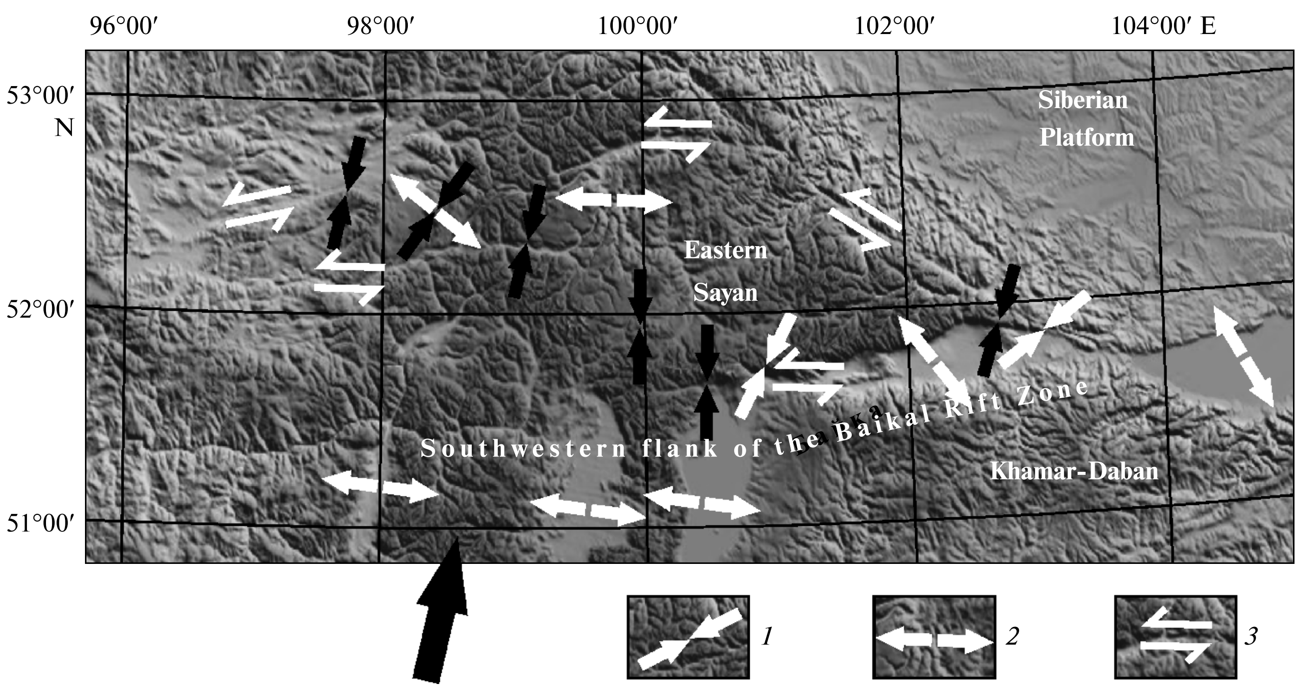

Fig. 11. Deformation regime in the southeastern part of the Eastern Sayan and the adjacent territory. Location of (*1*) compressive and (*2*) tensile structural elements described in the literature and direction of local compressive and tensile stresses (Pliocene and post-Pliocene deformations are indicated by black arrows and Late Quaternary deformation by white arrows); (*3*) Late Quaternary strike-slip faults. The large heavy arrow shows the direction of regional compression.

from NW to NE. In the last 0.6 Ma, the direction of the dikes changed to ENE. These results broadly confirm our suggestion that the direction of compressive stress changed with time and that the predominance of the ENE-trending compression in the late Quaternary determined the left-lateral strike-slip movements along the near-latitudinal faults. During the early stage, the direction of compressive stress varied from NE- to N–S and even NW. As a result, the NE- and W–E thrust faults were formed.

Thus, the data presented above may be regarded as evidence in favor of the remote influence of collision on compressive deformations in the southeast of the Eastern Sayan since the late Miocene. Tensile deformations develop locally in the zones of major relief-controlling faults (Oka–Zhombolok, Tunka, Bii-Khem–Tissa), which are eastern endings of large latitudinal strike-slip faults that extend westward beyond the limits of the Baikal Rift. The displacement of the southern walls along left-lateral strike-slip faults under transpression results in the development of reverse–strike slip deformation along the near-latitudinal faults (Baikal–Mondy, Ikhe-Ukhgun, etc.) and in extension along the transverse faults (Azas volcanic field and Oka domain of extension). The blocks moving along the left-lateral strike-slip faults undergo clockwise rotation approaching the Main Sayan Fault because the latter is also a left-lateral strike-slip fault [28].

CONCLUSIONS

The morphotectonic analysis of the Pliocene–Quaternary deformations in the studied territory has shown that in general the present-day mountain ranges of the Eastern Sayan were formed in the transpressional regime with a predominance of vertical or horizontal displacements along the major faults during certain periods.

The reactivation of ancient thrust faults in the Tunka Range (in the post-Miocene time) and at the southern boundary of the Oka Plateau (beginning from the late Miocene) started to develop under conditions of northeastern compression. This period corresponds to reactivation of mountain building in North Mongolia [42, 50], which is regarded as a result of the remote influence of the Indo-Asian collision, also responsible for the growth of mountains in the Gobi and Mongolian Altay by the late Miocene–early Pliocene. The simultaneous mountain building in the Sayan region and the ranges of North Mongolia indicates a common source of tectonic stresses related to the Indo-Asian collision.

In our view, the domains with a prevalence of Quaternary extension in the Eastern Sayan are unrelated to the active rifting in the Baikal Rift Zone. The localization and geometry of subsided blocks and magma conduits show that they are formed as local structural elements of fault-line extension, whereas the regional strike-slip faults are crucial in the development of the southeastern part of the Eastern Sayan.

The geometry and kinematics of the major faults in the studied territory bear evidence for the northeastern (in general) direction of compression, which is consistent with the vector of deformation related to the Indo-Asian collision. This stress field facilitates the development of reverse–strike-slip deformations along the main relief-controlling faults. At the early stage of mountain building, which started in the late Miocene, the orientation of compression varied from the near-meridional to northeastern directions. As a result, the N–S- and NW-trending thrust faults declined to the east-northeast bearings and the left-lateral strike-slip offsets became dominant along the near-latitudinal faults. The deformation along the strike-slip faults leads to clockwise rotation of blocks approaching the NW-trending Main Sayan Fault and the development of left-lateral strike-slip and reverse–strike-slip displacements along this fault zone known at its southeastern ending [28].

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