SEISMOLOGY

Tectonic Deformations and Subsequent Seismic Events in the Southwestern Flank of the Baikal Rift System Based on GPS Data

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Abstract—The measurement data obtained at the GPS network in the southwestern part of the Baikal Rift System for the period from 1994 to 2020 were analyzed. The spatial relationship between seismic events and tectonic strain rates was estimated. The field of modern horizontal motions and deformations was calculated for the Tunka, South Baikal, and Khubsugul depressions. The rotation pole of the Siberian block was defined. The general geodynamic setting on the western flank of the Baikal Rift System is characterized by low horizontal velocities in the range of $0.5-1.4$ mm yr^{-1}. Based on calculation of the relative deformations, the contrast zones of dilatation with narrow zones with the "non-Baikal" type of directions of deformation processes against the background tectonic extension regimes have been determined for the first time in the Bystraya and Khubsugul tectonic depression. Tectonic stresses are accumulated in these narrow zones and released in earthquakes.

The Tunka system of depressions is part of the Baikal Rift System (BRS) and unlike other northeastern depressions in this region, the Tunka system extends in the east direction.

As seen from the seismic data and reconstruction of paleostresses, the axis of extension in the central part of BRS has a northwest direction and is oriented perpendicular to the rift system axis; in the southwest direction, it is oriented obliquely to the strike of structures. Sherman and Dneprovsky [1] found different patterns of the formations in the Tunka system of depressions: as an initiating rift—rift transform system [2] with sinistral kinematics of displacements and a system of pool-apart basins [3–5]. There are data on paleoseismodislocations in the Tunka system that have strike-slip and overthrust—strike-slip kinematics [6]. We have recorded deformations in the Cenozoic formations (sediments and volcanics) that characterize strike-slip and overthrust—strike-slip stress regimes [7, 8]. The seismotectonic deformations calculated by V.I. Melnikova [9] based on the focal earthquake mechanisms in the southern flank show the prevalence of transpression and shear regimes of deformation at present.

The modern tectonic deformations were estimated earlier for the entire Baikal Region [10]. However, recent studies and the increased seismic activity of 2020−2021 made it possible to obtain more accurate amplitudes and directions of modern movements in the southwestern part of the BRS.

The Baikal−Mongolian GPS network includes about 150 stations, six of which are working in permanent mode. The western part of the geodynamic network covers the marginal parts of the Siberian Platform; the Oka, Khamar-Daban, and Trans-Baikalian blocks; and Lake Khubsugul (Fig. 1).

In addition, the atmospheric water content was calculated [11] to determine the effect of tropospheric delay on quality of signal [12].

The velocities and their increments of the GPS stations were estimated due to the measurement data processing using the GAMIT-GLOBK software [13]. The main stages and the philosophy of calculations are given in [14]. As the result were obtained three-dimensional coordinates, velocities, and increments expressed in ITRF2014 [15].

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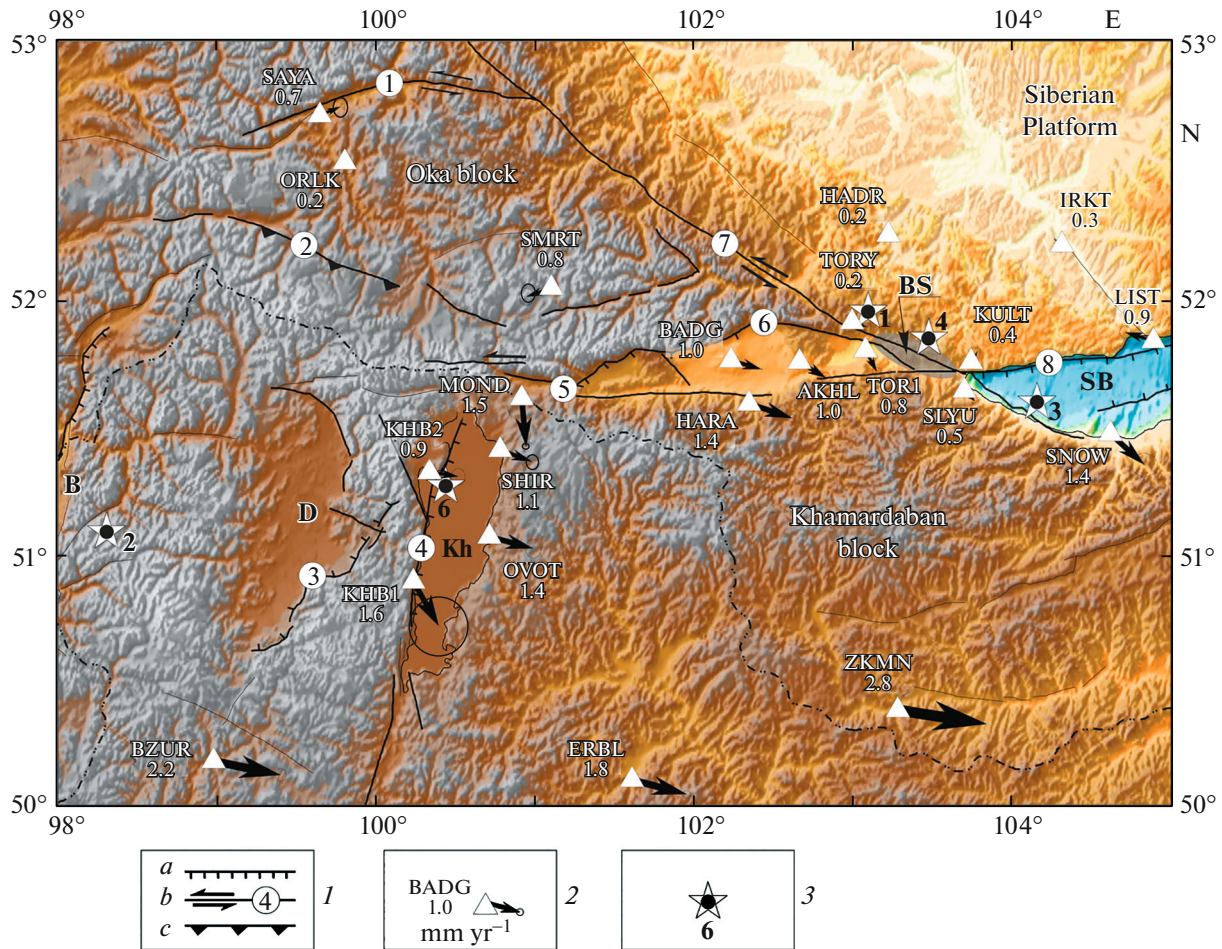**e-mail: loukhnev@crust.irk.ru*

Fig. 1. The strain rate field of modern horizontal motion of the Earth's surface on the southwestern flank of the Baikal Rift System (BRS), according to GPS data for the period of 1994−2020, relative to the Siberian block. (*1*) Active faults ((*a*) faults, (*b*) strike-slip faults, (*c*) thrust faults); (*2*) vectors of modern horizontal movements with 95% probability (mm yr^{-1}); (*3*) earthquake epicenters for the period of GPS measurements ((1) June 29, 1995, M_w = 5.8; (2) April 27, 2005, M_w = 5.3; (3) August 27, 2008, M_w = 6.3; (4) September 21, 2020, M_w = 5.4; (5) December 9, 2020, M_w = 5.5; (6) January 11, 2021, M_w = 6.7). Letters indicate rift depressions: B, Busingol; D, Darkhat; Kh, Khubsugul; SB, South Baikal; and BS, Bystraya. Numbers indicate active faults: (1) Oka−Zhombolok, (2) South Oka, (3) Darkhat, (4) Khubsugul, (5) Baikal−Mondy, (6) Tunka, (7) Main Sayan, (8) Obruchev, (9) Primorskii.

The horizontal motion velocities of the GPS stations (Fig. 1) are presented relative to the Siberian block (BAYA; ORLK; IRKT; HADR; KSTU; NVSK). We have defined the following parameters of the rotation pole: latitude 53.107° ± 0.068°, longitude 99.793° ± 0.024°, ω = 0.249282° ± 0.000114°/Ma.

The main kinematics for this area are GPS site movements in southeastern direction relative to Siberian block. In Transbaikalia, the horizontal motion velocities reached 2.3−2.8 mm yr^{-1} (Fig. 1). The relative displacements in the Main Sayan Fault ranges from 0.1 mm yr^{-1} (SLYU-KULT) to 0.3 mm yr^{-1} (TORY-TOR1) in the sinistral strike-slip. The extension across the central part of the Tunka fault zone is 0.8−1.4 mm yr^{-1}.

The areas of predominantly NW−SE extension in the South Baikal depression in the field of relative deformation rates reaching 3.3 × 10^{-8} yr^{-1} are distinguished (Fig. 2). In the zone of coseismic and postseismic manifistaion in the Kultuk earthquake area, relative extension velocities have increased reaching (4−7) × 10^{-8} yr^{-1} in the submeridional direction. In the eastern part of the Tunka depression system, the NW-trending extension is combined with the NE compression. The evident prevalence of horizontal compression is observed in the northern and southern parts of the Khubsugul depression. In general, there is an apparent trend towards a reversal of the compression axis from the N−NE strike in the western part of area to a northeasterly one in the east. Within the inner parts of the blocks, the deformation rates are usually reduced to 10^{-9} yr^{-1}.

The previous calculations of the deformation parameters in the area of the Bystraya depression [12]
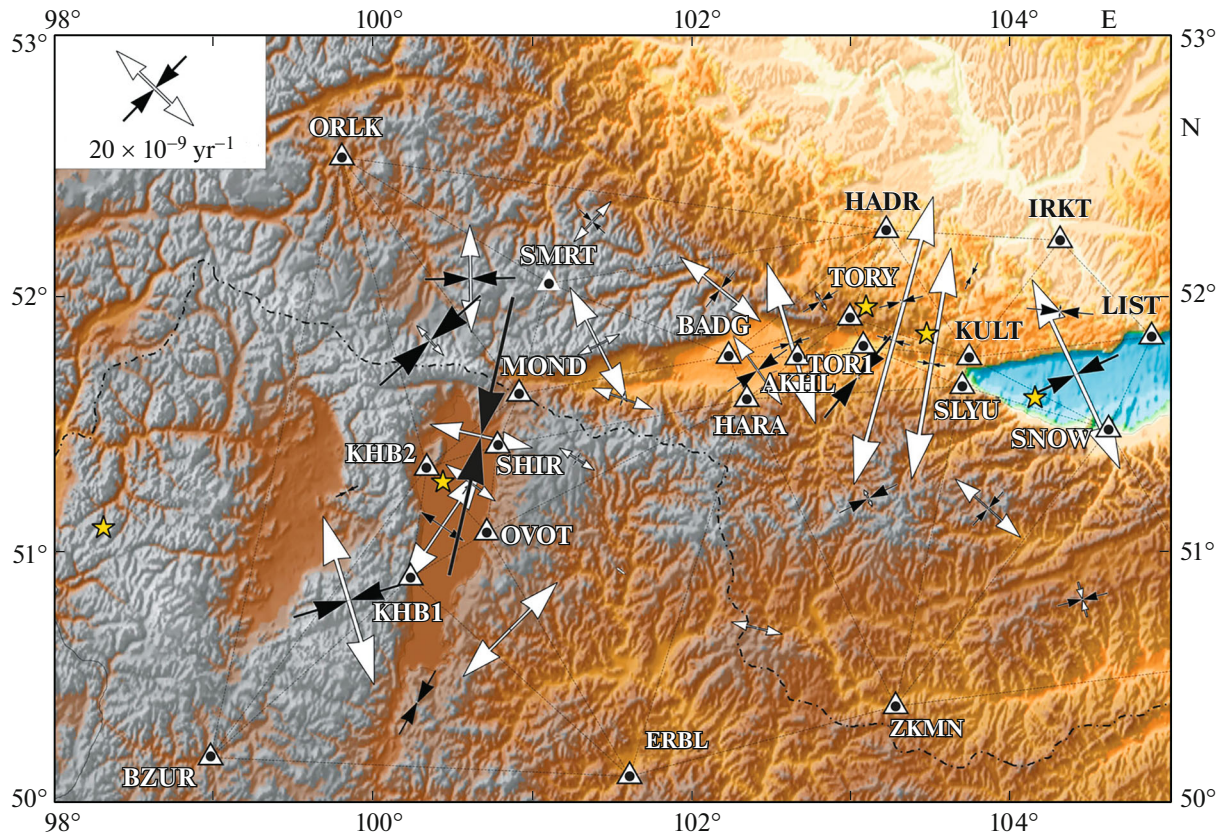
Fig. 2. The strain rate field of relative motions of the Earth's surface on the southwestern flank of the Baikal Rift System (BRS), according to the GPS data for the period of 1994−2020. Black arrows show shortening axes; white arrows, elongation axes. The asterisks show earthquake epicenters ($M_w \geq 5.3$) over the entire period of the GPS measurements.

revealed oblique compression in the northeasterly direction with respect to the Main Sayan Fault ($\varepsilon_1 = 11.3 \pm 5.4$; $\varepsilon_2 = (-21.3 \pm 3.7) \times 10^{-9}$ yr^{-1}; $\theta = 29.9° \pm 5.7°$). It is possible that the change of deformation modes in this area led to the accumulation of tectonic stresses that were realized in the seismic event on September 21, 2020.

The prevailing values of the shortening axis ($\varepsilon_2 = (-59.9 \pm 5.3) \times 10^{-9}$ yr^{-1}) over the elongation axis ($\varepsilon_1 = (22.1 \pm 6.8) \times 10^{-9}$ yr^{-1}) and the direction to the northeast $\theta = (12.9° \pm 2.9°)$ were established in the northern part of the Khubsugul depression (MOND-KHB2-SHIR). In contrast, the shortening axis in the southern part of the depression has minimum values $\varepsilon_2 = (0.3 \pm 2.5) \times 10^{-9}$ yr^{-1}, and the elongation axis is characterized by a northeassterly orientation $\theta = 34.2° \pm 3.9°$ at $\varepsilon_1 = (29.6 \pm 10.13) \times 10^{-9}$ yr^{-1} (KHB2-OVOT-KHB1). The values of the shortening axis in the northern part are comparable to those of the elongation axis in the southern part of the Khubsugul depression. Such an opposite position of the axes leads to accumulation of tectonic stresses and, as a result, the seismic relaxation that occurred on January 11, 2021.

The shortening axis in the South Baikal depression has a northeasterly direction: $\theta = 65.1° \pm 2.0°$ at mean values of $\varepsilon_2 = (-19.7 \pm 1.9) \times 10^{-9}$ yr^{-1} (LIST-KULT-SNOW). The elongation axis dominates with a magnitude of $\varepsilon_1 = 43.7 \pm 4.0$ (Baikal-type). A sharp change in the directions of the elongation axes towards the northeast is characteristic of the Bystraya depression, where earthquakes with $M_w > 5$ occurred on June 29, 1995, and September 21, 2020. It should be noted that the elongation axes values are an order of magnitude higher than those in the adjacent territory, reaching $\varepsilon_1 = (62.7 \pm 7.6) \times 10^{-9}$ yr^{-1} at the azimuth $15.4° \pm 3.1°$.

The dilation rates were calculated based on the velocities of horizontal motion (Fig. 3). The analysis showed that the areas with maximum rates of extension are confined to the closure of the South Baikal depression, the central part of the Khubsugul depression (closer to the western side), and the western edge of the Tunka valley. The maximum dilation rates are also observed in the Bystraya depression.

In the narrow zones between low (from -5×10^{-9} yr^{-1}) and high (up to 25×10^{-9} yr^{-1}) dilatation values along the Bystraya depression (Fig. 3, profile B), in the conjunction zone of the Tunka and Main Sayan faults, the
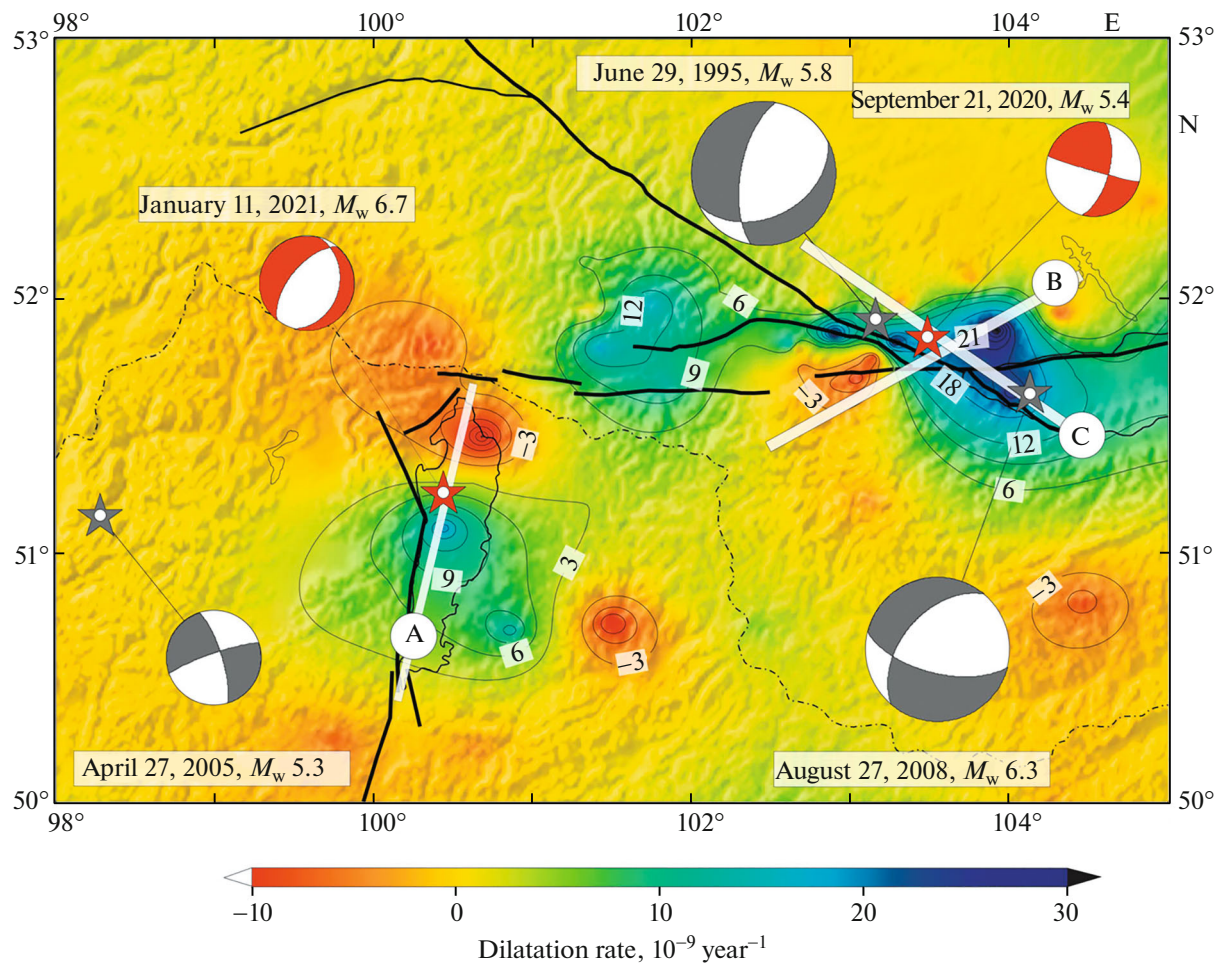
Fig. 3. The dilatation rate of the Earth on the southwestern flank of the BRS according to the GPS data over the period of 1994–2020. White–gray hemispheres show the source mechanisms of earthquakes preceding the seismically active period of 2020; white–red hemispheres, sensible earthquakes in late 2020–early 2021 (earthquakes solution are from USGS [16]); A, B, C, dilatation profiles.

elongation axes change their orientation to the northeast ($\theta = 9°–15°$) at the maximum values of the shortening ($\varepsilon_2 = -7.3 \pm 1.3$) and elongation ($\varepsilon_1 = (62.7 \pm 6.6) \times 10^{-9}$ yr^{-1}) axes (KULT-TOR1-TORY).

The long measurements of the SLYU and KULT stations located on different planes of the Main Sayan Fault have shown that they moved at the same rate. Differentiated movements between them were noted during and after earthquakes. The coseismic and postseismic motions caused by an earthquake formed an anomalous deformation zone with a submeridional maximum elongation axis (Fig. 2). The focus of the Bystraya earthquake on September 21, 2020 ($M_w = 5.4$), was formed on the periphery of this zone.

A characteristic feature of the arrangement of the large earthquake epicenters ($M_w > 5$) like Kultuk, Bystraya, and Khubsugul in 2020–2021 is their confinement to narrow zones between the maximum and minimum values of dilation (Fig. 3).

One can assume that the sharp transition from positive to negative values in a narrow zone served as a trigger for a seismic event of this class. This resulted in the accumulation of significant stresses in the upper part of the lithosphere over a relatively short period when the Earth's crust "did not have enough time" to adapt to deformation strains. It means that brittle deformations were not followed by ductile ones.

The less pronounced dilatation parameters are observed in the Khamardaban block, south of the Bystraya depression, in the southern part of Lake Khubsugul, south of the Irkutsk amphitheater of the Siberian Platform, and in the Transbaikalian block.

Against the background of the general extension in rift troughs, narrow zones with the "non-Baikal" type of deformation processes and accumulation of tectonic stresses are distinguished. To some extent, the stress relaxation was the reason for the seismic events.

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