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Spatio-Temporal Patterns of the Development of Strong Seismic Activations (1999–2007) in the Northern Baikal Area

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Abstract—The development of strong seismic activations in the northern Baikal area in 1999–2007 is considered. Based on maps of earthquake epicenter density, it has been shown that each activation is a separate group of seismic shocks (a cluster), whose scale and spatio-temporal pattern depend strongly on the stress-strain state of the crust. Estimates of seismic-moment tensors for strong earthquakes within the clusters demonstrate that the most numerous groups of shocks form in the rift stress field. With moving away to the southeast from the conventional axis of the Baikal rift, this field changes under amplification of the compressional stresses in Transbaikalia. Simultaneously, we observe a decrease in the number of seismic events and in their energy level. Totally, the considered seismic activations prove the small-scale block structure of the crust in the northern Baikal area and reflect the main features of the modern geotectonic development of this area related to the adjacent morphostructural zone, where most of fragments are involved in rifting and the other are affected by the activation of positive-sign block movements. The obtained results should be taken into account in the assessment of the seismic hazard of the studied territory.

Keywords: seismic activations, clustering of earthquakes, seismic-moment tensor, fault-block structure of the crust

INTRODUCTION

The Northern Baikal region is located in the central part of the Baikal rift zone (BRZ) and characterized by high seismic activity (Fig. 1). Distinctive features of this rift area are: a honeycombed structure of the earthquake epicentral field and absence of stronger ($M_w \geq 6.5$) seismic events in a more than 60-year history of instrumental observations.

However, according to paleoseismological data (Kondorskaya and Shebalin, 1977; Solonenko, 1977; Khromovskikh et al., 1978; Solonenko et al., 1985; Chipizubov and Stolpovsky, 2003; Chipizubov et al., 2009; Smekalin et al., 2010, 2011), major fault structures that bound the Kichera, Upper Angara, and Barguzin basins have high seismic potential. Several ancient earthquakes aged from a few hundreds to tens of thousands of years ($M \sim 7$–8) are associated with these faults (Fig. 2).

Although the region is well studied by geological, geophysical, and geodetic methods (Krylov et al., 1981; Zamaraev et al., 1983; Pis'mennyi et al., 1984; Solonenko et al., 1985; Delvaux et al., 1995; Calais et al., 1998, 2003; Lesne et al., 2000; Suvorov et al., 2002; Yakovlev et al., 2007; Melnikova and Radziminovich, 2007; Seredkina et al., 2016; Seredkina et al., 2018; Seredkina and Solovey, 2018), it is still rather difficult to integrate the obtained results into one model that would explain the uniqueness of the earthquake epicentral field of the area due to information heterogeneity. This complicates any unbiased estimation of seismic hazards in the area, where critical civilian and industrial structures are located, among which the Baikal-Amur Mainline and ore mining and processing plants of the North Baikal ore district are of special importance (Fig. 1) (Nefed'ev, 2011; Gordienko et al., 2014). Thus, identification of seismic and geodynamic peculiarities of the Northern Baikal area still remains a topical problem. The solution of this problem may be facilitated by analysis of a regularly updated seismological database. Apparently, the data quality depends directly on the number of seismic stations and their instrumental equipment.

Over 20 seismic stations equipped with analog instruments were deployed in the Baikal and Transbaikalia region from 1962 to 1998. In 1977–1993, six additional local stations also with analog earthquake recording hardware were added to the observation network in the North Muya region. In 1998, re-equipment retrofitting of all the regional stations

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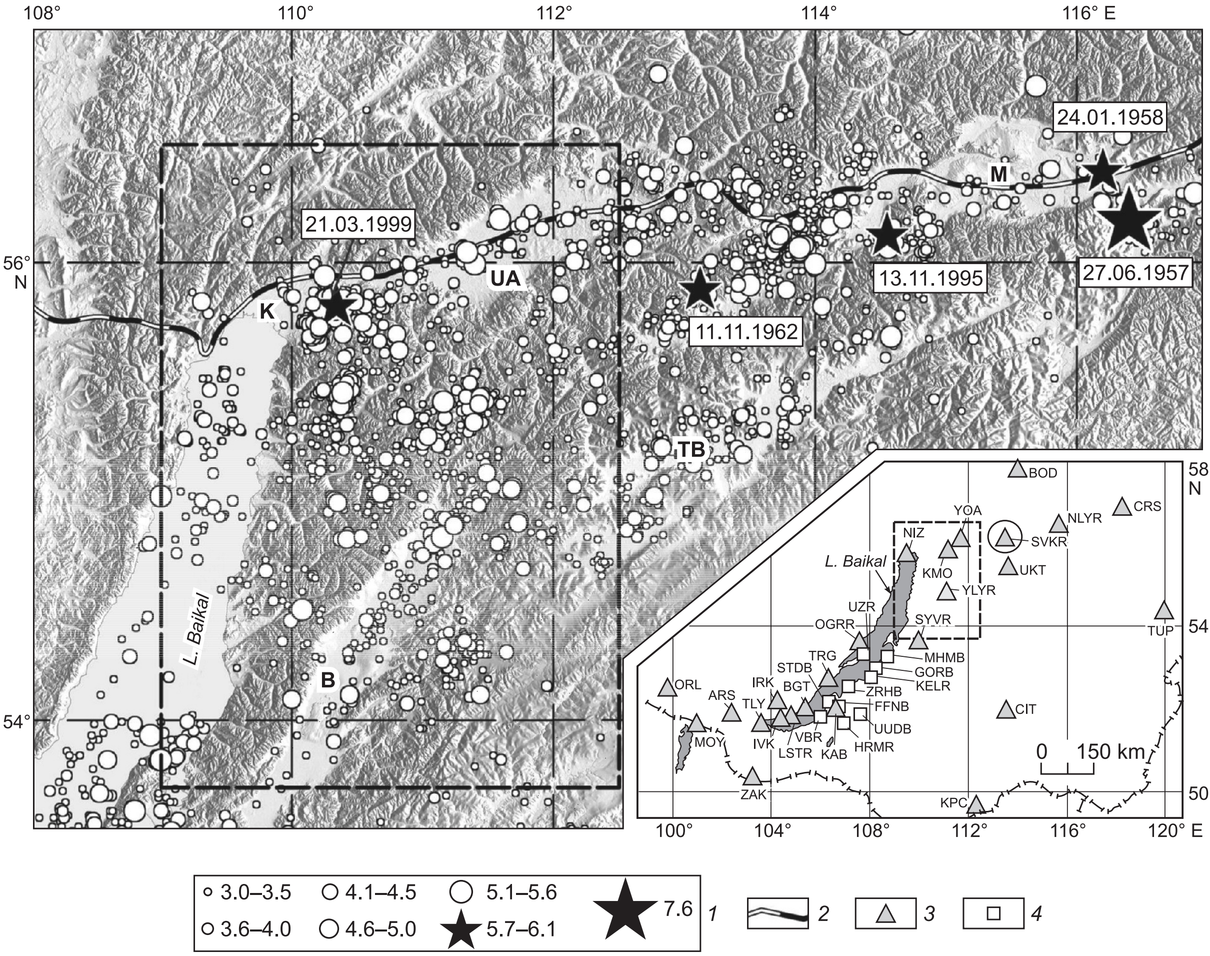


Fig. 1. Epicenter map for earthquakes with $M \geq 3$ ($K_R \geq 10$, according to T.G. Rautian) in the Northern Baikal area in 1953–2017. The studied area is shown by a dashed line. *1*, earthquake epicenters with different magnitudes, dates (day, month, year) are presented for the events with $M \geq 5.7$; *2*, Baikal–Amur Mainline; *3*, *4* (see the inset), regional seismic stations of the Baikal (*3*) and Buryat (*4*) Divisions of the GS RAS (the state of the network as of 2012), localization area of the local stations in the North Muya region is showed by a circle; rift-type basins: K, Kichera; UA, Upper Angara; B, Barguzin; M, Muya; TB, Tsypa-Baunt.

with digital short-period hardware started. It was also around the same time when the Buryat Division of the Geological Survey of the Russian Academy of Sciences (GS RAS) installed 10 digital seismic stations in the Central Baikal area. Thus, the total of 35 stationary digital seismic stations were used for recording regional earthquakes in 1999–2012 (see the inset in Fig. 1) (Masalskii et al., 2014). Coincidentally, it was in the years 1999–2007 when the strongest series of seismic shocks in the whole history of instrumental observations in the Kichera and Upper Angara basin areas and in the mountain chains of Barguzin and Ikat Ridges took place. This is illustrated by earthquake epicenter density maps (Fig. 3*a*, *b*) based on representative classes of seismic shock energy ($K_R \geq 7.0$) in 1962–1998 and 1999–2012, as well as by the seismic event recurrence plots (Fig. 4) that show a sharp increase in seismicity levels during the second time period.

The appearance of major seismic activizations in the Northern Baikal region made it possible to study their spatio-temporal evolution and the accompanying stress fields in detail. The goal of this study was to find out to which degree structural relationships and seismotectonic peculiarities of the junction area between the BRZ and its southeastern rim reflect the present-day seismicity that is important for assessing seismic hazards in this seismically active region.

GEOLOGICAL AND GEOPHYSICAL CHARACTERIZATION OF THE REGION

The crust in the Northern Baikal region was for a long time subjected to intense straining as a result of its confinement within the most active fragment of the marginal suture between the consolidated craton of the Siberian platform and the BRZ. Therefore, rupture faults play a significant part in the region's geological evolution. Most pre-Cenozoic faults with complex morphologies were activated in the Cenozoic having affected the formation of the present structure of the crust (Zamaraev et al., 1983). For example, the Kichera–

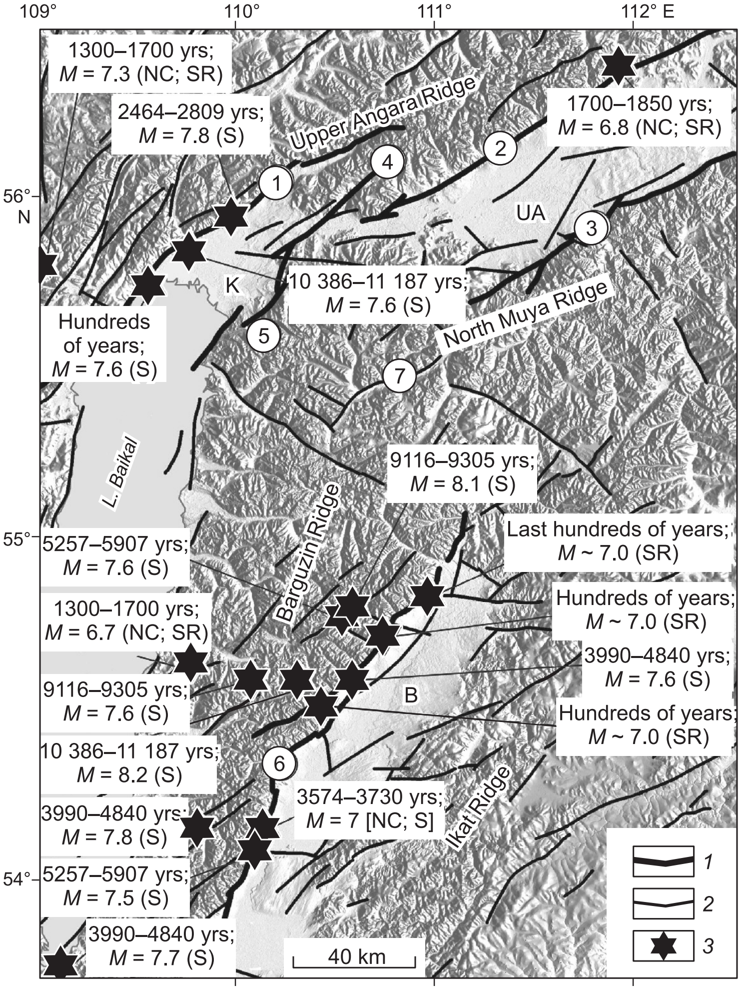


Fig. 2. Geological structural scheme of the Northern Baikal area after (Zamaraev et al., 1983; Lunina et al., 2010). Regional faults with Cenozoic activity: *1*, interblock faults (1, Kichera–Mama, 2, Upper Angara, 3, North Muya); *2*, intrablock faults (4, Dzelinda, 5, Akulikan; 6, Barguzin, 7, Svetlinskii); *3*, paleoearthquake epicenter with age, magnitude, and source (NC, (Kondorskaya and Shebalin, 1977); SR, (Solonenko, 1977); S, (Smekalin et al., 2011)). See the notation of rift-type basins in Fig. 1.

Mama, Upper Angara, Barguzin, and North Muya faults were among the pre-Cenozoic regional interblock first-order faults that reached significant lengths, primarily along the NE direction, and separated large crustal blocks, which were highly active in the Cenozoic. At a lower hierarchical level, Cenozoic activation also took place for most interblock regional faults with NE (Dzelinda) and NW (Akuli, Akulikan) strike directions (Fig. 2). Generally, the NE orientation of faults was associated with subhorizontal tension across the strike.

At the neotectonic evolution stage, the structures predominantly inherited the ancient plan most often observed in ruptures and folded deformations of different scales with NE strike directions (Zamaraev et al., 1979). Compared to the ones with NW strikes, they manifested themselves most actively in the early and middle Paleozoic, Mesozoic, and Cenozoic.

Thus, the present-day lithospheric destruction in the Northern Baikal region under rifting occurred based on the already existing rupture network with slight changes (Zamaraev et al., 1983). On the whole, junction areas of various morphological structures (basins and their rimming uplifts) are controlled by faulting driven by lasting tectonic evolution of the lithosphere and associated with tectonic displacements varying in nature and size that eventually form the block structure of the region. This structure is confirmed by gravimetry and electric logging, having indicated the presence of density irregularities in the upper part of the crystalline crust (Pis'mennyi and Alakshin, 1980; Pis'mennyi et al., 1984), as well as multidisciplinary geological and geophysical studies (Krylov et al., 1981) having shown that the crystalline bedrock underlying the thick loose sedimentary sequence was subjected to intense crushing. It was also found that, in addition to large bedrock clefts rimming the main structural fields, their interiors are dissected into isolated blocks by multiple smaller ruptures (Pis'mennyi et al., 1984).

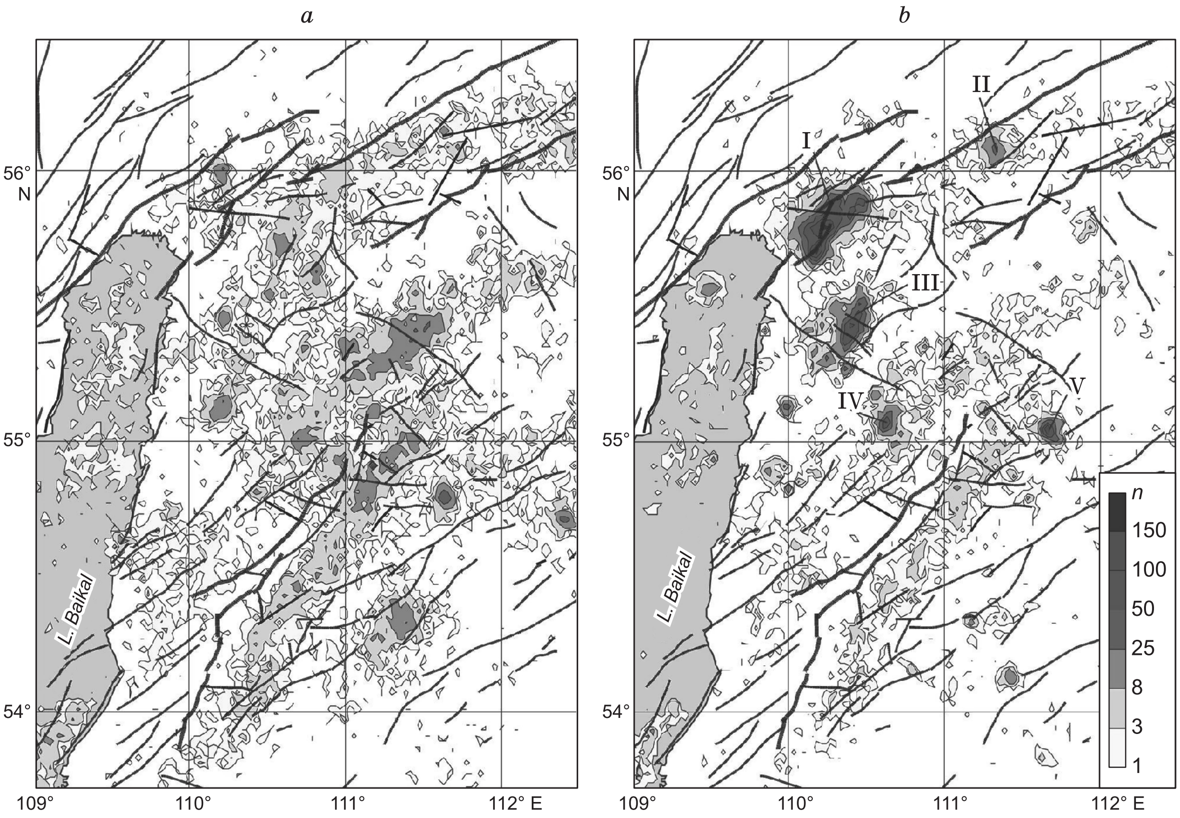


Fig. 3. Epicenter density maps for earthquakes with $K_R \geq 7.0$ in 1962–1998 (*a*) and 1999–2012 (*b*). *n*, the number of events per unit average area sized φ = 0.02° N and λ = 0.03° E. Roman numerals indicate the numbers of the seismic clusters identified by highest earthquake epicenters densities.

PECULIARITIES OF THE SEISMIC PROCESS

Seismological data obtained throughout the instrumental observation period make it possible to identify at least three earthquake belts with NE strike directions having increased epicenter densities in the Northern Baikal area (Fig. 1). These belts have discrete structures, and in 1999–2007 (as mentioned above) some of the fragments were represented by multiple and intense series of earthquakes (Fig. 3*b*) (Melnikova et al., 2007; Gileva et al., 2012, 2013).

To distinguish the areas of grouped seismic events (Fig. 3*a*, *b*), cluster analysis and the concepts of concentrated and scattered seismicity components were used (Aref'ev, 2003). As a result, the following five clusters were identified in the studied area: (I) Kichera–Akulikan in 1999 and 2006 (Melnikova et al., 2007; Gileva et al., 2012); (II) Kumora in 2003 (Radziminovich et al., 2009); (III) Tompuda in 2007 (Gileva et al., 2013); (IV) Ulyugna in 2003, and (V) Kovylinsky in 2002 (Fig. 3*b*). Nonequivalence of these clusters was clearly displayed in magnitudes of main shocks and total numbers of earthquakes, as well as their distribution in time (Fig. 5).

The clusters are separated on a spatio-temporal scale, and the seismically active blocks they occupy have different configurations and volumes. It is also known that most earthquake hypocenters in the Northern Baikal region are confined within the middle crust (h = 15–20 km), as they are throughout the whole rift zone (Gileva et al., 2000;

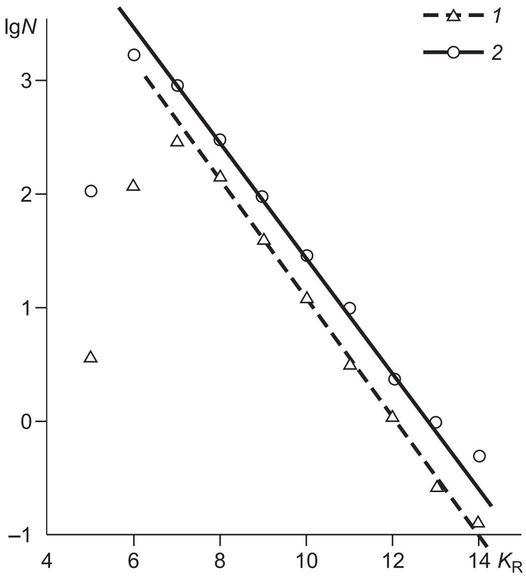


Fig. 4. Earthquake recurrence plots for the Northern Baikal area normalized by year. *1*, 1962–1998, γ = –0.53 ± 0.01; *2*, 1999–2012, γ = –0.51 ± 0.01. γ, angle index.

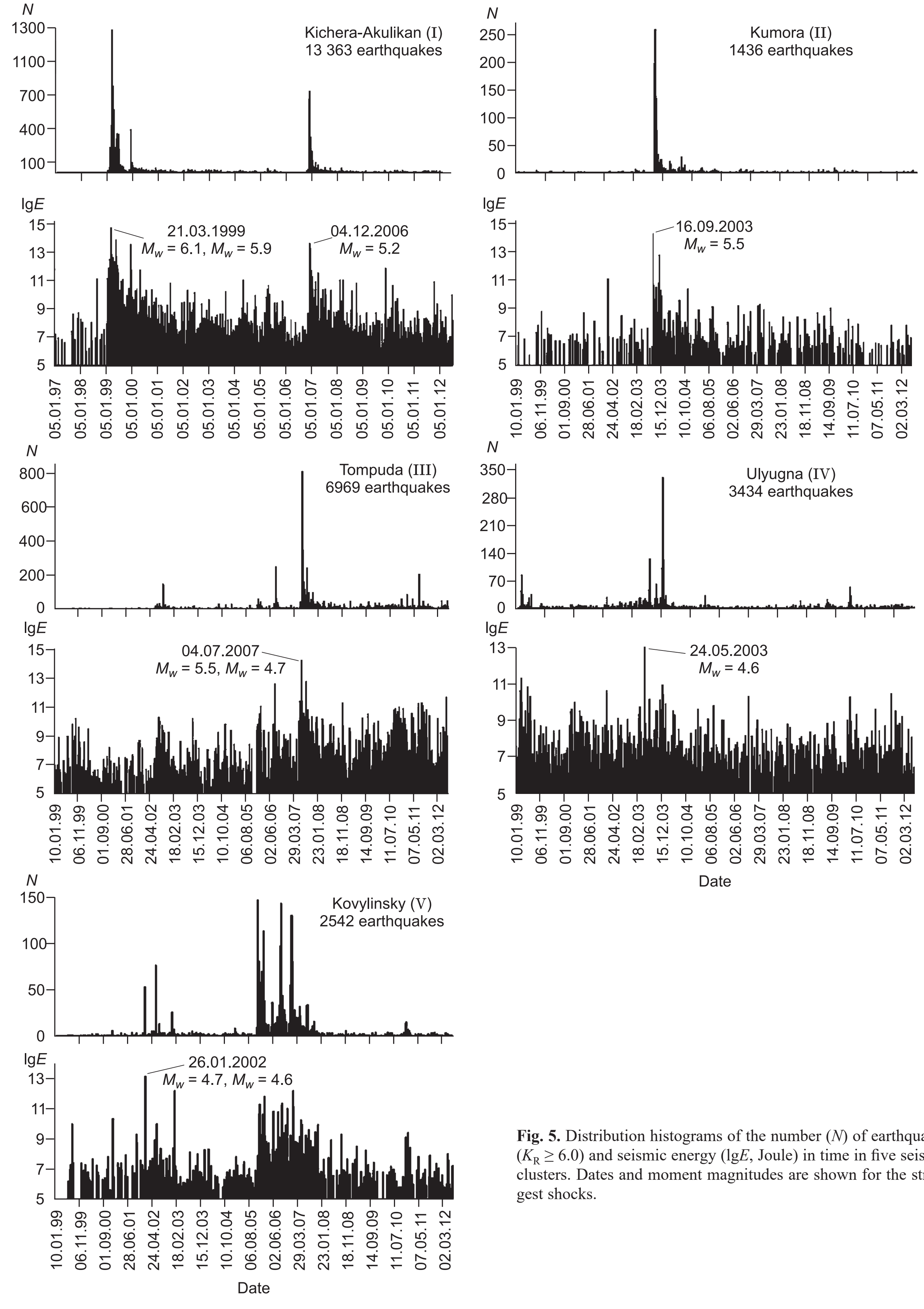


Fig. 5. Distribution histograms of the number (*N*) of earthquakes ($K_R \geq 6.0$) and seismic energy (lg*E*, Joule) in time in five seismic clusters. Dates and moment magnitudes are shown for the strongest shocks.

Déverchère et al., 2001; Radziminovich, 2010). It should be noted that series of earthquakes combined into clusters may be represented by strong individual events with aftershocks (the second strongest shock following the main one) and swarms (two or more strong events with close or equal magnitudes). Different manifestations of seismic activity reflect the uniqueness of destructive processes in individual seismically active blocks and stress relaxation patterns in complex geological media (Solonenko and Solonenko, 1987). For example, according to (Pis'mennyi and Alakshin, 1980; Pis'mennyi et al., 1984), relatively strong earthquakes ($M \geq 6.0$) are associated with the areas of evolving granitoids that facilitate the accumulation of large stresses, while swarm events are associated with the contacts of granites and sedimentary-metamorphic formations. In terms of rheological properties, contact areas are considered to be the weakest zones of the crust, which favor slight displacements.

EARTHQUAKE FOCAL MECHANISMS AND STRESS FIELD TYPES

At the regional observation scale (epicentral distances of $\Delta \leq 10^{\circ}$), where almost all seismic stations are equipped with short-period instruments (firstly analog and then digital), focal mechanisms for most earthquakes with moderate magnitudes of $3.0 \leq M \leq 5.0$ ($9.4 \leq K_R \leq 13.0$) were determined using the standard technique (Misharina, 1972) based on signs of P-wave first arrival polarities. Here, a focus was determined as a point seismic source described by the double-couple model (e.g., Honda, 1962; Vvedenskaya, 1969). In this case, reliability of the obtained solutions depends on the clarity and correct identification of the used seismic wave phases, representativeness of the data on signs in various azimuths from the epicenter of the seismic event, etc. This technique has provided satisfactory focal mechanism solutions for numerous events from the considered clusters (Melnikova, 2001; Melnikova et al., 2007; Radziminovich et al., 2009; Gileva et al., 2012, 2013). However, it is known that the most complete characteristic of earthquake sources is provided by seismic moment tensor (SMT), which is determined on a timely basis by international seismological agencies (Global CMT, NEIC, USGS), but only for relatively strong seismic events ($M_w > 5.0$). This information is also found occasionally in published papers (Doser, 1991; Emmerson et al., 2006). Since the amount of these earthquakes in the studied region is relatively small (about 1%), a special research has been performed recently, which made it possible to determine SMTs for seismic events in a wider magnitude range ($M_w \geq 4.2$) (Seredkina and Melnikova, 2013, 2014, 2018).

A reliable estimation of focal parameters for the strongest earthquakes from the studied series was of critical importance, which is why in the present study it was done for 8 seismic events using advanced seismological data processing and inversion techniques (Table 1). Surface waves records of selected earthquakes that were obtained by the broadband channels of the IRIS, GEOSCOPE, and GEOFON seismic stations were used as the initial data for our calculations. In total, the records from 49 seismic stations were used (Fig. 6). Their positions were chosen in a way that they were located in different azimuths from the earthquake epicenters. Amplitude spectra of fundamental modes of Rayleigh and Love waves were calculated for each station using frequency-time analysis (Levshin et al., 1986) while processing the records of an individual seismic event. The final period range for the whole set of earthquakes was 30–105 s.

The SMT (in double-couple approximation) and hypocentral depth were calculated from the obtained amplitude spectra of surface waves (Bukchin, 1989). To unambiguously identify earthquake focal mechanisms, the P-wave first arrival polarities from regional and remote seismic stations were taken into account (Lasserre et al., 2001). Nodal plane parameters (NP: strike is a strike azimuth, dip is a dip angle, slip is a slip angle) and focal depth (h) were determined during inversion by searching in a 4D parametric space, while the seismic moment (M_0) was calculated by the least square minimization of residuals between the observed and the calculated amplitude spectra of surface waves. Moment magnitude values (M_w) were calculated based on seismic moment values calculated during the inversion in accordance with (Hanks and Kanamori, 1979). The peculiarities of the applying chosen SMT calculation technique to earthquakes in the Baikal region are considered in detail in (Seredkina and Melnikova, 2013, 2014).

The quality control of the obtained solution was performed using the normalized residual function (ε) (Lasserre et al., 2001). This function characterizes the deviation of the calculated amplitude spectra from the observed ones and indicates the relationship of the number of the first arrival polarities contradicting the obtained radiation diagram to the total number of polarities. In addition, a partial normalized residual function was determined during the inversion, which made it possible to better understand the resolution of the sought parameters (for example, depth ε_h).

The structure of the crust below the seismic stations was assigned using the 3SMAC model (Nataf and Ricard, 1996) and in the neighborhood of the earthquake focus – using 3SMAC or CRUST 2.0 models (Bassin et al., 2000), depending which of them provided a smaller value of the normalized residual function. To characterize the upper mantle and calculate the attenuation of surface waves, the spherical symmetric PREM model was used (Dziewonski and Anderson, 1981).

As a result, we obtained focal mechanisms, hypocentral depths, scalar seismic moments and moment magnitudes for the studied earthquakes (see the Table). It should be noted that focal parameters calculated using various methods agree well for the earthquakes with SMT solutions available in catalogs of international seismic agencies (Global CMT, NEIC) and other sources (Braizer and Nyblade, 2003; Em-

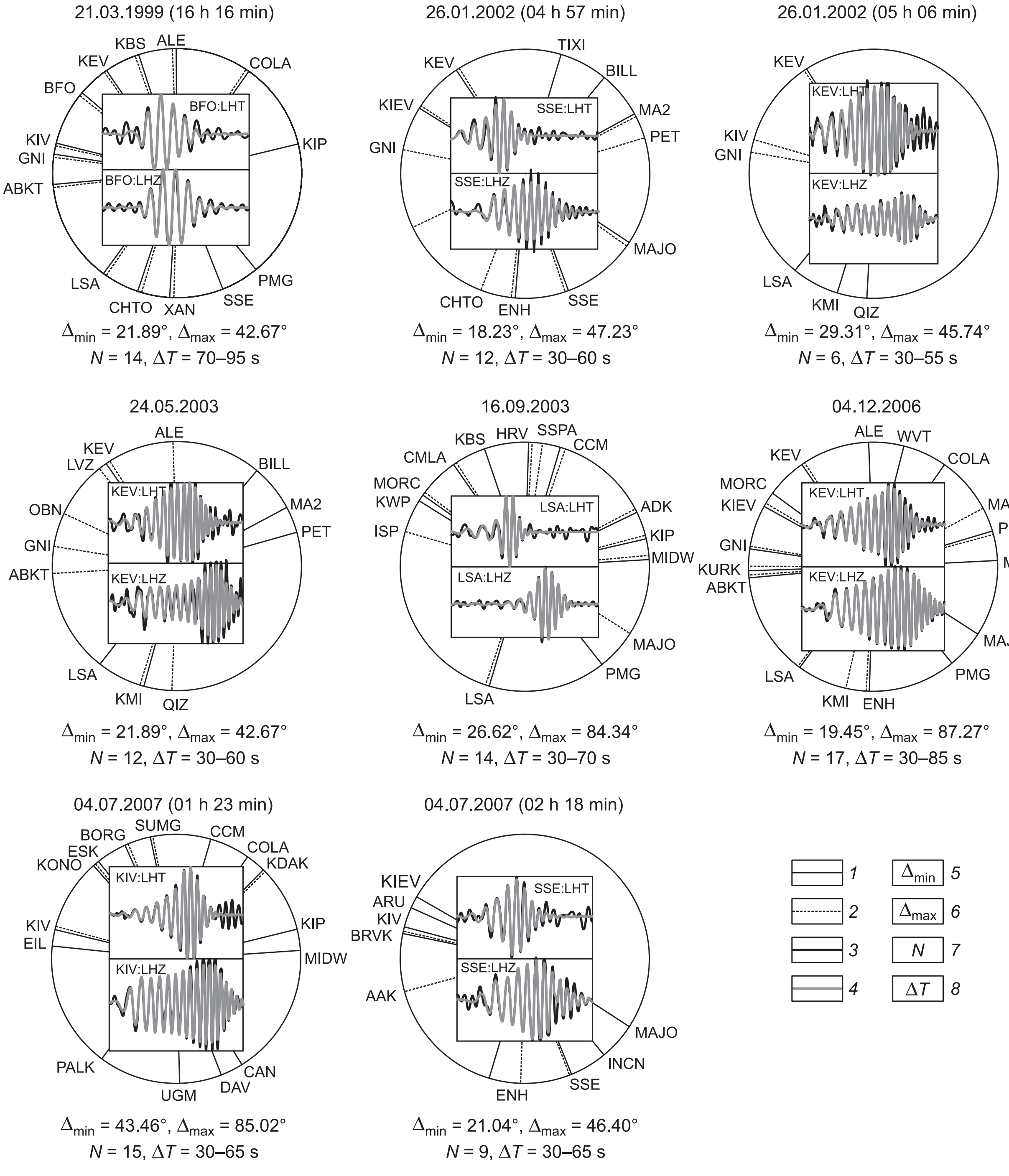
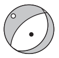
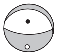
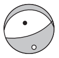
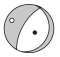
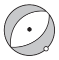
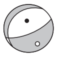
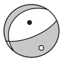
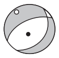
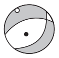
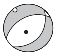
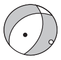
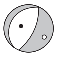
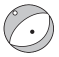


Fig. 6. Azimuthal distributions of seismic stations with respect to the epicenters of the studied earthquakes with examples of filtering of the records. Station codes are in conformance with the international standard. *1*, Rayleigh waves; *2*, Love waves; *3*, initial records; *4*, filtered records; *5*, minimum epicenter distance; *6*, maximum epicenter distance; *7*, number of seismic stations used; *8*, studied period range.

merson et al., 2006) (Table 1), the only exception being the earthquake on March 21, 1999 (16 : 16). In the latter case, the available focal mechanisms showed significant differences in fault plane parameters. The solution obtained in the present paper is supported by a small normalized residual function value (ε = 0.293), and also by the fact that both rather long-period (surface waves) and short-period (first arrival polarities) seismic oscillations were taken into account in the calculations. Thus, the obtained focal mechanism reflects not only the main but also the initial faulting phase in the focal area. We were unable to identify the fundamental mode of surface waves for the earthquake on March 21, 1999

Table 1. Focal parameters of the studied earthquakes

Earthquake	M_0 10^{17}, N m	M_w	*h*, km	NP			Stereogram of focal mechanism	Reference
				strike	dip	slip		
				deg				
1	2	3	4	5	6	7	8	9
21.03.1999, 16:16 55.83°N, 110.34°E	18.00	6.1	15	68 187	87 7	–84 –151		ε = 0.293
	8.50	5.9	15*	27 227	29 62	–107 –80		GCMT
	4.60	5.7	10*	91 282	68 22	–94 –80		NEIC
		5.7	3	70 267	69 22	–96 –74		(Emmerson et al., 2006)
			6*	19 209	21 69	–99 –86		(Braizer, Nyblade, 2003)
21.03.1999, 16:17 55.85°N, 110.26°E	8.40	5.9	15*	50 223	47 44	–86 –94		GCMT
	3.10	5.6	10*	49 200	57 35	–77 –109		NEIC
		5.8	3	66 222	72 20	–82 –113		(Emmerson et al., 2006)
26.01.2002, 04:57 55.03°N, 111.68°E	0.09	4.6	28	160 278	50 61	140 48		ε = 0.328
26.01.2002, 05:06 55.04°N, 111.69°E	0.12	4.7	20	30 208	30 60	–88 –91		ε = 0.182
24.05.2003, 21:49 55.01°N, 110.68°E	0.08	4.6	16	280 29	70 48	–45 –153		ε = 0.288
16.09.2003, 11:24 56.05°N, 111.34°E	2.50	5.5	12	254 30	67 30	–70 –130		ε = 0.300
	3.06	5.6	15*	251 35	56 39	–68 –119		GCMT
	2.20	5.5	17	253 40	55 40	–69 –116		NEIC
		5.5	15	245 38	53 40	–73 –111		(Emmerson et al., 2006)
04.12.2006, 09:14 55.67°N, 110.19°E	0.83	5.2	4	29 230	71 20	–97 –70		ε = 0.328
	0.86	5.2	14	32 210	55 35	–89 –92		GCMT
04.07.2007, 01:23 55.44°N, 110.44°E	1.90	5.5	14	25 219	70 21	–95 –77		ε = 0.317
	1.39	5.4	12	32 199	55 36	–82 –101		GCMT
	1.10	5.3	20	54 230	30 60	–87 –92		NEIC
04.07.2007, 02:18 55.40°N, 110.39°E	0.12	4.7	14	45 170	76 23	–71 –143		ε = 0.290

Note. 1, date (day, month, year), GMT time at the origin, earthquake epicenter coordinates according to GS RAS; 2, scalar seismic moment; 3, moment magnitude; 4, focal depth; 5–7, nodal plane (NP) parameters: (strike—strike azimuth, dip—dip angle, slip—slip angle; 8, stereogram of focal mechanism, lower hemisphere projection (emergence of compression and extension axes are shown by black and white dots, respectively); 9, source (normalized residual function values (ε) are presented for the solutions obtained in the present paper).
* Fixed depth.

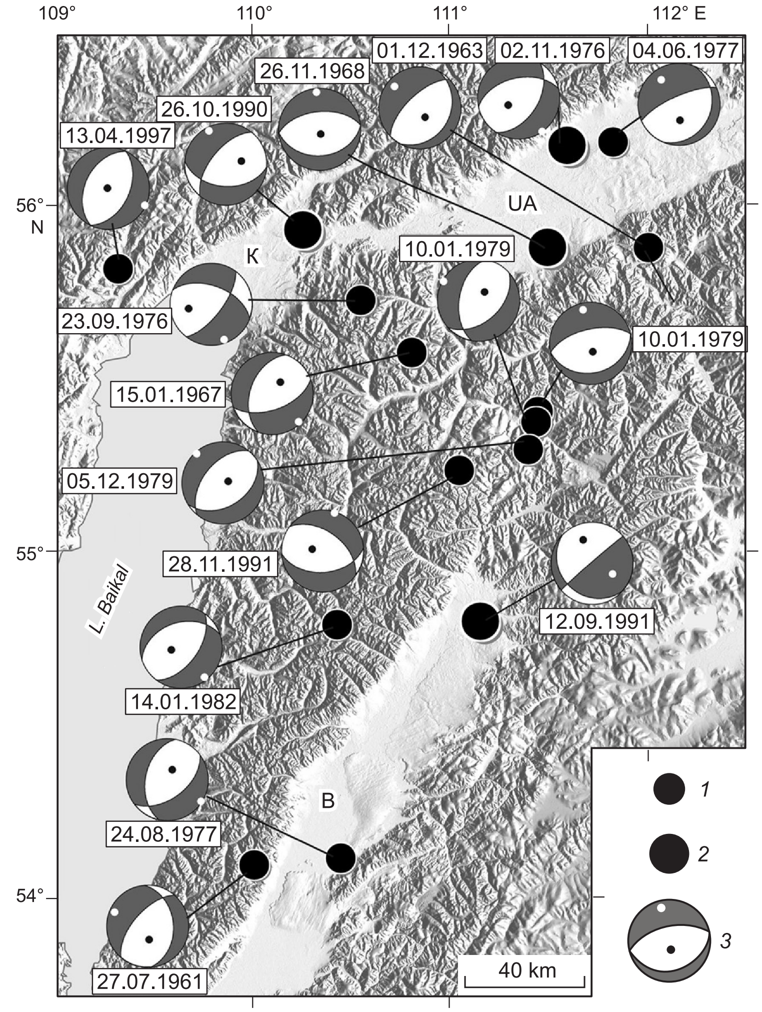


Fig. 7. Focal mechanisms of earthquakes with $K_R \geq 13$ ($M \geq 5.0$) in the Northern Baikal area in 1962–1998. *1* and *2*, epicenters of earthquakes with $K_R = 13$ and $K_R = 14$, respectively; *3*, stereogram for focal mechanisms (see description in the table). See the notation of rift-type basins in Fig. 1.

(16 : 17) recorded a minute after the main shock with enough confidence and, therefore, to perform the further inversion. However, the estimates of focal parameters of this event presented in GCMT and NEIC catalogs indicate that its formation was affected by the syn-rift stress field (Table 1).

It is known that the data on earthquake focal mechanisms are a critical piece of information on the stress-strain state of the Earth's interior, and the Northern Baikal region is well researched in this sense. In total, there are both individual and group solutions available for over 1000 seismic events with $M \geq 1$ (Melnikova, 2001). Statistical processing of these data showed the NW–SE trending subhorizontal extension to be the prevalent seismotectonic crustal deformation regime in the area, which is also a basic characteristic of stress fields throughout the most part of the BRZ zone (Melnikova and Radziminovich, 2007). These features of the stress-strain state of the medium echo morphokinematic types of main faults in the studied area and are clearly manifested in focal mechanisms of the stronger ($M \geq 5$) earthquakes (Figs. 7, 8).

It is worth noting that the present-day evolution of the region, which represents the junction area between the BRZ and its southeastern rim, is associated not only with the syn-rift stress field but also with non-rift processes caused by the activity of positive-sign block displacements (Dem'yanovich, 1978). It is reflected by a wider variety of stress implementations in local earthquake foci usually with $M \leq 5$. The areas of the studied major earthquake series are different in terms of tectonic positions and have the necessary number of focal mechanism solutions available (Melnikova et al., 2007; Gileva et al., 2012, 2013), which allows us to trace the spatio-temporal evolution of various stress fields in this adjacent morphostructural zone.

EVOLUTION SCENARIOS OF SEISMIC CLUSTERS

To uncover certain patterns specific for the studied earthquake clusters, we consider the spatio-temporal evolution scenarios for every one of them. For example, the epicenter

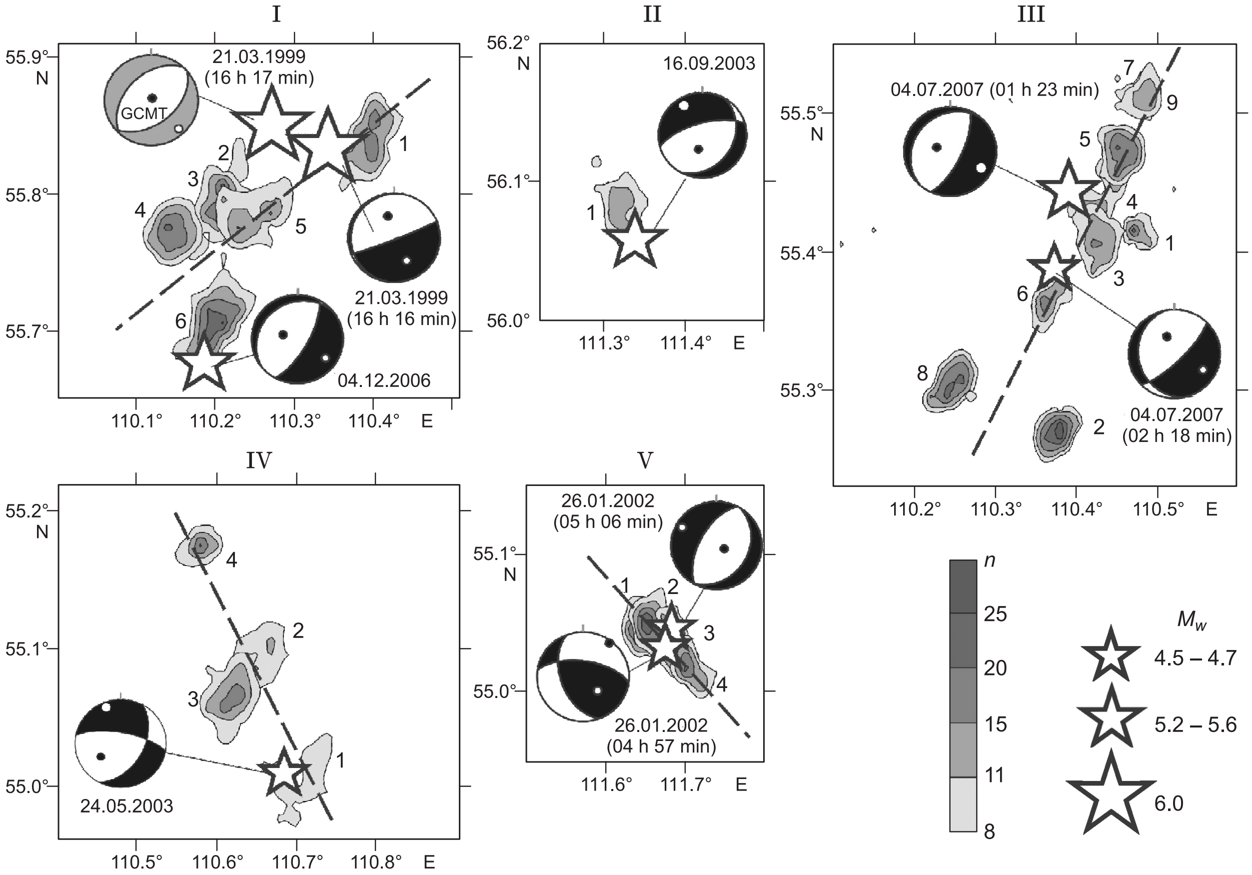


Fig. 8. Spatio-temporal distribution of earthquake epicenter density in five seismic clusters (I–V) and focal mechanisms of the main shocks. Dashed line indicates the formation direction of the main cluster composed of individual fragments, with the sequence of their appearance indicated by numbers. Dates (day, month, year) are shown for the main shocks, with the epicenters indicated by stars. *n*, see Fig. 3; focal mechanism, see Table 1.

field of the most representative Kichera–Akulikan cluster (I) was firstly localized in the Kichera basin and in the years to come occupied a part of the southeastern mountainous rim (Melnikova et al., 2007; Gileva et al., 2012). In total, over 13,000 seismic events with $K_R \geq 6.0$ occurred here in a span of several years (Fig. 3). Moreover, moment magnitudes of the strongest shocks came close to $M_w = 6.1$ for the first time in the history of instrumental observations. In 1999, most earthquake epicenters localized in the Kichera basin fragmentarily traced the NE–SW direction of the crustal destruction. Here, stress unloading in the source of the main events (March 21, 1999, 16:16, $M_w = 6.1$ and 16:17, $M_w = 5.9$) was exclusively implemented in the form of normal fault (Table 1, Fig. 8). Despite the focal mechanisms of numerous aftershocks indicating the presence of local ruptures with different orientations (Melnikova et al., 2007), focal displacements in most of them were controlled by a major NE-trending riftogenic fault, which bounded the southeastern edge of the Kichera basin. Thus, the studied earthquakes occurred under NW–SE directed subhorizontal tension (stretching) as a prevalent seismotectonic regime. The mountainous rim of the southeastern edge of the Kichera basin became active in the same (rift) stress field in 2006–2010. Here, earthquake epicenters indicated submeridional direction of crustal destruction, which agreed with the trends of focal fault planes not only for main shocks (Fig. 8), but also for the majority of earthquakes with determined focal mechanisms (Melnikova et al., 2012; Gileva et al., 2012).

Compared to the Kichera–Akulikan cluster (I), cluster II formed in the Upper Angara basin by the Kumora series of seismic events in 2003 (Fig. 3*b*) is less representative, i.e., only about 1500 shocks with $K_R \geq 6.0$ were recorded here before 2012. The strongest shock ($M_w = 5.5$) occurred on September 16, 2003, and was characterized by a rift-type focal mechanism (Table 1), while the aftershocks demonstrated a wide variety of focal mechanisms (Radziminovich et al., 2009). It is most likely that stress unloading during the aftershock process was associated with the activity of secondary structural faults. This was reflected by the aftershock field geometry, where we can see the NW–SE trend that does not agree with the focal fault plane trends of the main shock and main faults (Fig. 8).

Cluster III is represented by the epicentral area covering numerous shocks of the Tompudinsk series (about 7000 shocks with $K_R \geq 6.0$), the maximum concentration observed on NW slopes of the Barguzin Ridge in 2007 (Fig. 3*b*) (Gileva et al., 2013). The analysis of spatio-temporal development of the seismic process in this series showed the activity of small crustal blocks aligning with time along the NE–SW direction (Fig. 8). Migration of individual seismically active zones with high epicenter density from the center to the periphery was a distinct evolutionary feature of this discrete epicentral field. It should be noted that most fault planes in the earthquake foci including the main shock (Fig. 8) showed the NE trend (Gileva et al., 2013). On the whole, deformation of the seismically active volume, in which the Tompuda series of earthquakes was localized occurred under subhorizontal extension in the NW–SE trending.

The Ulyugna (IV; $N = 2542$ with $K_R \geq 6.0$) and Kovylinsky (V; $N = 3434$ with $K_R \geq 6.0$) earthquake clusters in the Barguzin and Ikat Ridges respectively are significantly lacking both in number of seismic events and the total seismic energy release compared to the clusters mentioned above (Fig. 5). Moreover, the source of the strongest shocks (January 26, 2002, 04:57, $M_w = 4.6$ and 05:06, $M_w = 4.7$), is buried deeper compared to the other clusters (Table 1), which is likely due to the thicker crust, compared to the axial part of the rift (Suvorov et al., 2002). The fact that seismic events trace the NW–SE crustal destruction trend may be considered a common trend in spatio-temporal evolution of their epicenter field. It is known that faults along this direction are attributed to a lower hierarchical level of the geological structure in the region (Zamaraev et al., 1979). It is worth noting that fault planes with this strike direction are also found in the foci of the main seismic events characterized by shear and reverse-fault displacements (Fig. 8).

DISCUSSION

Hierarchical division of the upper part of the lithosphere into systems of blocks is regularly mentioned in literature (Sadovskii et al., 1987; Shebalin et al., 2002; Makarov, 2007). In the Baikal and Transbaikalia regions, the fault-block structure of the crust is confirmed by topographic amplitudes, fault density (Seminskii, 2008), and geophysical data (Pis'mennyi and Alakshin, 1980; Krylov et al., 1981; Pis'mennyi et al., 1984; Lysak, 2002), but the structure of the earthquake epicenter field is considered the decisive argument (Misharina and Solonenko, 1990a,b; Melnikova and Gilyova, 2017). The Northern Baikal region is the most illustrative example in this sense, since the spatio-temporal evolution of its seismic clusters confirms the divisibility of the crust into blocks with different ranks. The activations responsible for cluster formation are usually associated with tectonic nodes, where structural elements with different orientations intersect. Most often, these include faults with NE (first order) and NW (second order) strike directions (Fig. 2).

Geophysical studies showed the presence of rock crushing zones in granite bases of the Kichera and Upper Angara basins, where the most representative clusters (I and II) are localized (Pis'mennyi and Alakshin, 1980; Zamaraev et al., 1983). When overlapped with differently oriented faults, these zones expand significantly in areas and according to the field observations facilitate the unloading of tectonic stresses in the form of relatively strong earthquakes ($5.6 \leq M_w \leq 6.1$), accompanied by numerous shocks of small and moderate energies. Thus, structural features of the geological medium in the studied region develop prerequisites for earthquake clustering. At the same time, it is not the only possible cause for development of these seismic activations. The type of seismotectonic deformation of the medium and stress increase rate depending on the rate of the main tectonic process are major factors as well.

Despite the complexity of the relationship between seismicity and tectonic processes, it is worth noting that the strongest contrast between the recent vertical tectonic displacements in the Northern Baikal region is observed in highly seismic zones of the Kichera and Upper Angara basins and in the northern part of the Barguzin Ridge. Here, velocity gradients reach $(0.6–1.0) \times 10^{-8}$ yr^{-1}, which is higher by an order of magnitude, than, for example, in marginal areas of Transbaikalia $(0.3–0.5) \times 10^{-9}$ yr^{-1} (Solonenko et al., 1985). If we consider the velocity field for the present-day horizontal crustal movements calculated from the satellite geodetic data for 2001–2007 (Ashurkov et al., 2011), then the extension rate of the BRZ in the northern part of Baikal (1.25 mm/yr) will be lower, than in the south (2.3 mm/yr). This may be considered as indirect evidence for longer accumulation period of critical stresses in the north of the lake, than in the south, which agrees quite well with increased compartmentalization of the geological medium in the Northern Baikal region. Thus, it takes time to consolidate and generate a relatively strong earthquake, during which the lower-rank fault surfaces may merge, especially in the lower crust (Pshennikov, 1964). Development of a rupture in this medium takes a lot of energy that, under certain conditions, may be comparable to the amount needed to generate a strong seismic event.

When it comes to recurrence of strong earthquakes ($M \geq 6.0$), it seems impossible to obtain unbiased data in our case because we possess neither the long enough observation period (hundreds of years for historical events and thousands of years for paleoearthquakes), nor the statistically representative quantity of these seismic events. It is only known that a seismic event similar to the strong Kichera earthquakes of 1999 ($M_w = 6.1$, 5.9) took place in the studied region in 1931 ($M \sim 5.9$) (Solonenko, 1977), while the preparation of the strongest earthquakes ($M \geq 7.5$) approximately took hundreds or thousands of years (Fig. 2).

As we assessed the stress-strain state of the crust in the Northern Baikal area based on earthquake focal mechanism data, it should be mentioned that it reflects the uniqueness of the present-day evolution of morphostructural elements in the junction zone between the BRZ and its southeastern rim. The interaction of the two following stress fields, i.e., subhorizontal extension on the side of the BRZ accompanied by vertical, primarily downward, block displacements, and subhorizontal compression on the side of the Transbaikalia block-wave zone associated with positive-sign block movements, was clearly manifested in this area before and after the appearance of major seismic activity concentrations (clusters) (Dem'yanovich, 1978).

Riftogenic displacement activity is gradually attenuated from the center of the Baikal rift towards the southeastern periphery, which is clearly manifested in the configuration of the earthquake epicenter field, the total seismic energy released, and focal mechanisms of the studied clusters (Melnikova and Gilyova, 2017) (Fig. 8). For instance, unloading of tectonic stresses corresponding to the largest clusters (I, II, III) reflects the present-day evolution of rift basins, while for the smaller clusters (III and IV) it reflects a complex differentiated structure of the transitional zone, where block displacements with different signs are present.

CONCLUSIONS

The results of the detailed study of major seismic activizations that took place in the Norther Baikal area in 1999–2007 have shown that the seismicity reflects the key features of the present-day geotectonic evolution of the region belonging to the adjacent morphostructural zone, with most fragments involved in the rift-type evolution, while the rest are subjected to changes with positive-sign block displacements. These tectonic evolutionary conditions facilitate a small-scale block structure of the crust and stress relaxation along numerous smaller-scale low-rank faults. In terms of seismicity, this is manifested in lengthier preparation periods of strong ($M \geq 6.0$) seismic events and earthquake clustering. It is also apparent that the prevalent effect of the rift stress field decreases gradually from the conventional axis of the Baikal rift to the southeast, which leads to decrease in energy levels of the clustering seismic events and reduction in their quantity. This fact should be taken into account, when estimating the seismic hazards in the studied area.

It has been found that significant changes in the stress field may even be observed in the Ikat Ridge area, where subhorizontal extension on the side of the BRZ interacts strongly with subhorizontal compression on the side of the Transbaikalian block-wave zone. According to the geological observations, it is the approximate area, where the northeastern lateral boundary of the rift zone is located, which does not display a pronounced linearity, which is confirmed by the obtained seismological data.

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