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Active faults, seismicity and recent fracturing in the lithosphere of the Baikal rift system

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Abstract

A map of major active faults has been constructed for the Baikal rift system (BRS). Recent active faults are identified using seismological data. The BRS seismicity of the past 40 years is statistically analyzed. Areas of a "stable" concentration of epicenters are revealed. On this basis, a zone of recent fracturing of the lithosphere is identified and its relation to active and developing faults of the BRS is analyzed. The zone of the lithosphere fracturing is a major tectonic structure, which controls both the recent seismic process and the reactivation of ancient faults. It is demonstrated that the available seismological data can provide a basis for a detailed classification of faults by degree of their tectonic activity. Regularities in the distribution of strong earthquakes along the zone of the recent fracturing of the lithosphere are established, as well as regularities in the distribution of strong and weak seismic events relative to transform and other faults. The degree of the fault reactivation is determined by their spatial closeness to the axial zone of the recent rupturing of the lithosphere.

Keywords: Active faults; Fracturing of the lithosphere; Zone of fracturing; Seismicity; Earthquake epicenter field; The Baikal rift system

1. Introduction

Fracturing of the lithosphere is the disruption of its structural continuity. Geological objects, which manifest the lithosphere fracturing in the most distinct way, are fractures and faults that widely vary in hierarchic levels and time of formation. Their formation or reactivation are often accompanied by seismicity. Though most of seismic events are controlled by fault tectonics, they enhance, in their turn, the lithosphere fracturing (rupturing) and cause the formation of linear fracture zones. Thus, zones of the lithosphere fracturing are linear zones of increased fracturing and faulting characterized by the long-term spatially stable seismicity. Similar definitions were proposed by Benioff (1962), Gzovsky (1962), Sherman (1992), Papazachos et al. (1999), and some other authors. In fact, fracture zones represent one of the stages in the evolution of large deeply penetrating faults in the lithosphere in the Holocene. The recent seismicity of such faults is indicative of active tectonic process. In the hierarchy of the Holocene active faults, these faults should be at the highest age level corresponding to the recent tectonic activity.

Rift systems of the Earth, including the Baikal one, represent tectonic sites where fracture zones can be

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identified, mapped and studied. Most of the largest continental rift systems, such as the African, Baikal and Shanxi systems, develop on the pre-Paleozoic or early Paleozoic basement with a preexisting fault network. Rifting causes reactivation of some groups of the preexisting faults and formation of new faults. It is not always easy to distinguish between active and inactive tectonic faults using geological methods. This is especially true in respect to the BRS. The dated Holocene deposits are rare there, so active faults are recognized mainly by geomorphological and/or seismological indicators. Seismological data are the most reliable since they allow to distinguish the late Cenozoic faults, which are well manifested in the relief but tectonically passive, from the currently active faults. However, attempting to classify faults by seismological data, the researchers encounter another challenge.

The BRS is well studied in terms of tectonics and seismicity (Logatchev and Zorin, 1992; Doser, 1991a,b; Logatchev, 1993; Solonenko et al., 1997; Parfeevets et al., 2002). The most commonly used methodology which spatially correlates mapped faults and the earthquake epicenter field is not applicable to the case under study since the available instrumental data base on the distribution of earthquake epicenters in the BRS from 1961 to 2000 includes more over 120,000 records, and its mapped version looks like a compact ‘‘patch’’ (Sherman and Gladkov, 1999). When the number of earthquake epicenters is reduced by the exclusion of small energy events, linearly elongated fields of earthquake epicenter concentration occur on the BRS maps and they do not always correlate with the known faults of various hierarchy. Basing on this fact, some researchers claim that there is no stable relationship between fault tectonics and seismicity in the BRS (Golenetsky et al., 1993). It is clear, however, that a commonly accepted idea that an earthquake source is a rupture (Sobolev, 1993 and many others) cannot be simply ignored. The absence of evident spatial correlation between sesimicity and the faults found by geological (Sherman, 1992; Levi et al., 1997), geological and geophysical (Fault Map of the Southern East Siberia, 1988; Nedra Baikala, 1981) or geomorphological indicators may suggest that the latter are not necessarily the structures of that kind.

Instrumentally registered seismicity reflects the process of recent fracturing in the upper elastic layer of the lithosphere and, accordingly, cannot or should not be expected to always coincide with known faults. An earthquake epicenter field can be examined for solving a ‘‘reverse‘‘ problem, i.e., to reveal a zone of the recent fracturing of the lithosphere that can evidently involve the well known fault network, reactivate the faults or even develop in a relatively monolithic massive. Based on the above described concept, the authors analyze the recent seismicity as an indicator of recent fracturing zones in the BRS.

2. The Baikal rift system in the structure of Central Asia

The BRS stretches over 2000 km from the northwestern Mongolia through mountains in the East Siberia up to the South Yakutia. Its basement is a heterogenic and heterochronic fold belt that completed its development in the early Paleozoic. The orogenic complex of the territory formed from the end of the early Paleozoic to the Cenozoic included. Most of the BRS follows the lithospheric suture between the Siberian and Amur megablocks of the Eurasian plate. The suture started to form in the early Proterozoic and during the whole post-Archean period separated the structurally and evolutionary different lithospheric blocks (Mats et al., 2001). The suture has determined the recent S-shaped structure of the BRS, which is characterized by quite a regular fault network (Sherman, 1978, 1992; San’kov et al., 1997; Levi et al., 1997, 2000). By the scale of development and length, the BRS faults can be grouped to trans-regional (longer than 80 km), regional (35–80 km) and local (less than 35 km) faults. Their importance for the riftogenic stage of development of the given territory was also different.

Trans-regional faults clearly manifested in relief are the pre-Cenozoic deep structures revived in the Cenozoic. At the rifting stage, they controlled the positions of the rift basins and developed as normal faults in the central part and as faults with combined normal strike-slip movements in the flanks of the BRS. The about E–W-striking faults have the left-lateral strike-slip component, the NE (up to SE60°) faults have the right-lateral component, and the faults striking about 65° are typical normal faults.

Regional faults are more variable in kinematics and dominant strike. Among them, most abundant are normal faults striking parallel to the general strike of the rift system. Strike-slip faults with the normal component mainly occur at the flanks. There are also regional faults which are transversal to the rift basins. Taking into consideration the kinematics of displacements on the trans-regional E–W faults at the BRS flanks, the predominance of regional and local strike-slip faults and strike-slip faults with the normal component, as well as dominating strike-slip mechanisms of the earthquake foci, the E–W-trending flanks of the BRS are interpreted as transform faults (Sherman, 1978; Sherman and Levi, 1978) that developed along the pre-Cenozoic faults during rifting (Fig. 1).

Rifting commenced about 30–25 Ma ago and led to the reactivation of practically every fault in the basement within the limits of the rift basins and the bordering zones. Due to the lack of the well-developed Holocene and younger deposits (excluding the Baikal Lake itself), it is difficult to classify the BRS faults by age. It is believed that linear topographic scarps, deeply incised river valleys and other contrast geomorphophic features are active faults. In most cases, the fault nature of such forms in the BRS is confirmed by relevant structural and geological markers. Only some of the forms of the kind are characterized by seismic activity. This is why it is still very difficult in the BRS to reveal the faults of the Holocene age or reactivation out of the whole mass of various faults and to apply the conventional age scale to classify the active faults (Allen, 1975; Trifonov, 1985, 1999). Only in a few, easily accessible and well-studied rift basins, have detailed observations provided the information about the age of the Holocene paleoseismodislocations (McCalpin and Khromovskikh, 1995; Chipizubov and

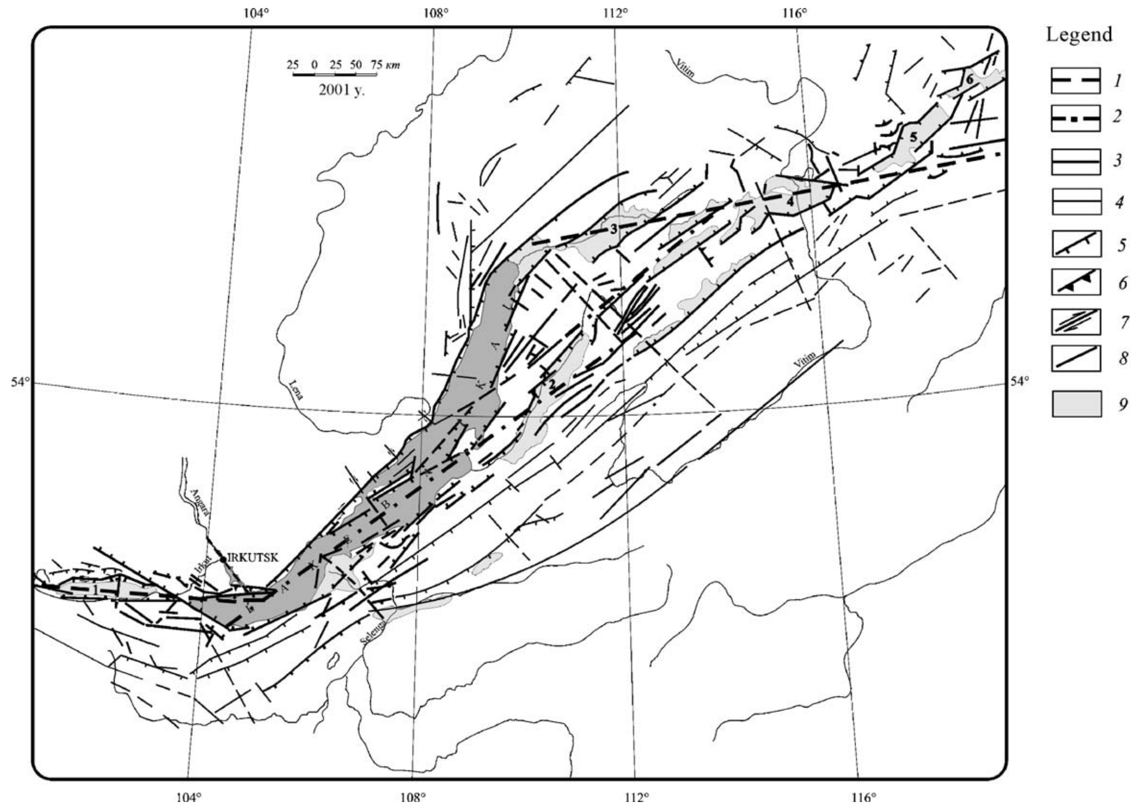

Fig. 1. Active fault map of the Baikal rift system. 1—The zone of recent fracturing of the lithosphere that includes transform faults; 2—the zone of the recent fracturing of the lithosphere; 3—seismically active faults; 4—active faults; 5—normal faults; 6—reverse faults and thrusts; 7—strike—slip faults; 8—faults of unidentified genetic type; 9—the Cenozoic basins (numbers refer to basins: 1 = Tunka, 2 = Barguzin, 3 = Upper Angara, 4 = Muya, 5 = Chara, 6 = Tokka).

Smekalin, 1999) and seismically active faults (Deverchere et al., 1993). Their spatial location and association with the faults of the pre-Cenozoic reactivation support the above described criteria of fault activity in the BRS. At the same time, instrumental data on seismicity can significantly help to identify faults of the recent activity among the active faults.

The distribution of earthquake epicenters is used to identify currently active faults or zones of the recent fracturing of the lithosphere.

3. The method of analyses of the earthquake epicenter field and identification of zones of the recent fracturing in the lithosphere

With the aim of recognizing seismically active faults or zones of the recent fracturing of the lithosphere, an algorithm has been designed to process the seismological data. Over 4000 seismic event occur annually within the BRS limits. By now, the instrumental database includes over 120,000 records. In the first approximation, earthquake epicenters are scattered chaotically. From the huge database, it is necessary to reveal regions of the relatively stable concentration of earthquake foci in time and space, i.e., the regions of relatively stable fracturing of the lithosphere. It is agreed that a criteria of the seismic process stability can be provided by spatially stable, non-random concentrations of earthquake epicenters, their density values being higher than two standard errors, 2σ from the average background value of earthquake epicenter distribution within the BRS limits. Initial data have been selected from "The Catalog of Earthquakes of North Eurasia" which uses a surface wave magnitude M_{LH} as an indication of earthquake magnitude recorded instrumentally. They were combined with the data on $2.5 \leq M < 3.5$ earthquakes and new data from the regional catalog of the Baikal Experimental Seismological Expedition of the Institute of the Earth's Crust. In cases when the magnitude has not been instrumentally determined, we calculated M_{LH} using the statistical equation (commonly used in Russia) $K = 4 + 1.8M_{LH}$, where K is energy class.

For the whole BRS, the final database included 30.000 earthquakes with $2.5 \leq M \leq 7.6$ that occurred from 1961 to 1999. Densities of epicenters are evaluated for each $0.2 \times 0.3°$ square unit, with a step equaling the sliding box size. Based on the obtained evaluations, an average density of epicenters in the BRS is calculated.

Statistical patterns of events that took place within the sliding box show either migration or "spatial stability" of seismicity inside or outside the areas of dynamic influence of faults (Sherman et al., 1983). Fig. 2 shows the areas with the density of earthquake epicenters 2σ higher than the average density. Anomalous clusters of epicenters are bordered by density curves with values above $2\sigma = 105$. With high reliability, several areas of stable high concentration of epicenters are revealed. These areas make up three zones of steadily increasing seismic activity, which are the E–W Tunka and Baikal–Muya zones and the NE-striking South Baikal–Muya zone. The stability of locations of sections with high earthquake density can be regarded as an integral value of the seismic state within the given coordinates of space and time; it shows active fracturing of the lithosphere. The recent fracturing takes place along the axial line of the BRS and occupies a broken S-shaped, linearly elongated zone. At the BRS flanks, the zone coincides with the transform faults. In the BRS central part, it combines the well-known major and regional faults and thus makes a large independent geotectonic structure (see Fig. 1). Some indications of this structure have been revealed earlier and termed as the developing Baikal–Chara fault (Sherman, 1978).

The above described pattern of the stable locations of the areas of seismic activity gives grounds to identify an actively developing zone of the lithosphere fracturing in the BRS. Its formation and the area of dynamic influence predetermine the current seismic activity of the BRS. The zone of the recent fracturing of the lithosphere correlates well with the transform faults; however, it does not always agree with the well-known major and regional faults in the BRS (see Fig. 1).

Thus, in the BRS, the revealed zone of the recent fracturing of the lithosphere, being the zone of the recent faulting and/or reactivation of ancient faults, is controlled by the previously existing transform faults in the flanks. Between the transform faults, in the central part of the rift system, it is controlled by the stable earthquake epicenter concentrations that reflect the active process of elongation and merging of the

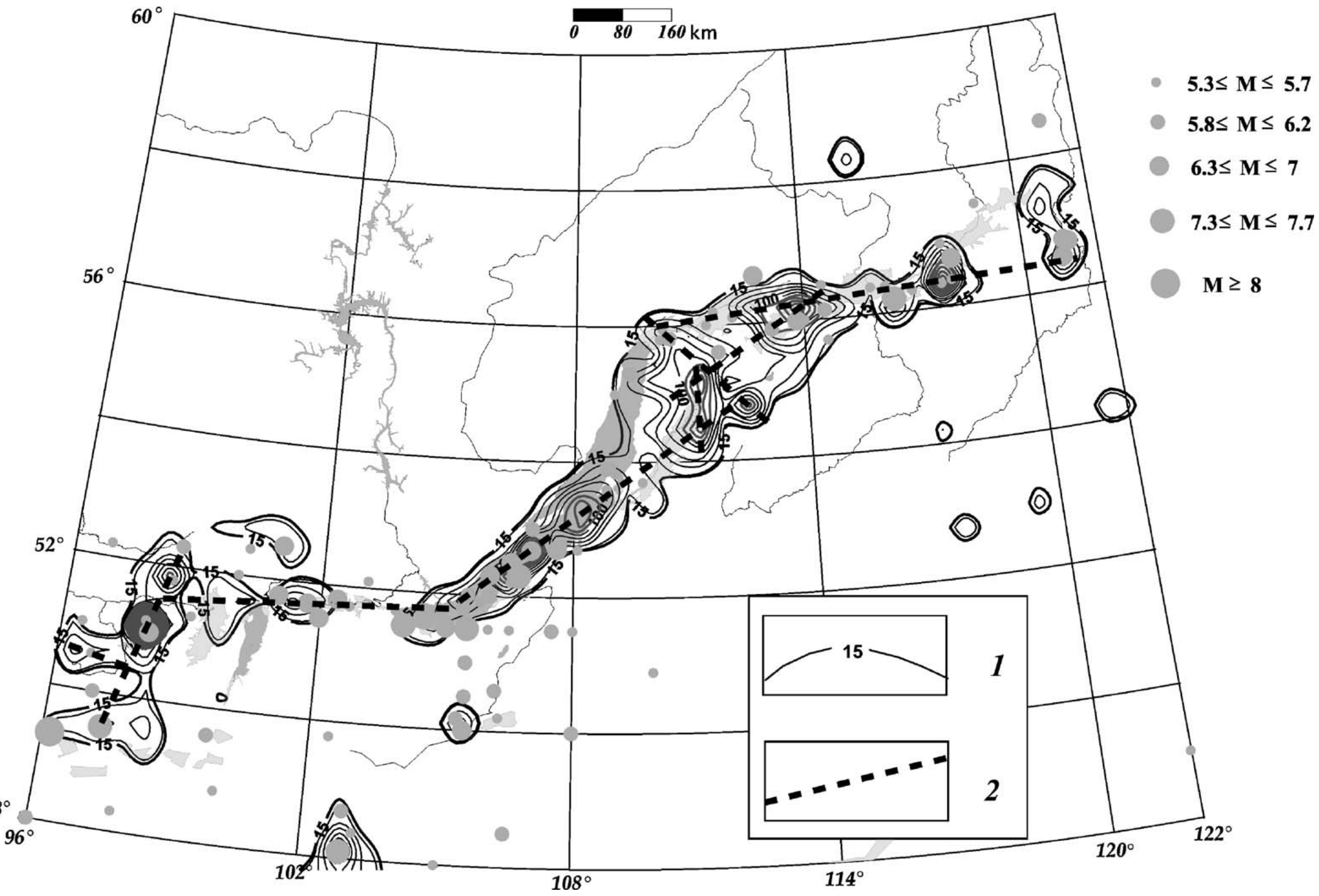

Fig. 2. Epicenter density map of the Baikal rift system. 1—epicenter density isolines (numbers refer to densities of events); 2—the zone of the recent fracturing of the lithosphere.

existing faults and the occurrence of new ones at various scale levels at the recent stage of the BRS development that is accompanied by seismicity.

4. Some geological and geophysical parameters describing the zone of the recent fracturing of the lithosphere

Rundkvist et al. (1999) apply computerized geographic information systems to carry out spatial analyses of seismic activity of the most important faults in the BRS. Seismic activity is evaluated by seismic moment, M_0 as given by the equation $M_0 = 1.5M_{LH} + 9.14$. On both sides of every fault under study, 20-km-wide buffer zones are constructed, and all the earthquakes within the limits of such zones are considered associated with the given fault. A summary seismic moment is calculated for every event with respect to the fault length (a specific seismic moment). The cartographic analysis of the obtained results shows that the highest specific seismic moments are typical of the faults located in the vicinity or in the axial line of the zone of the recent fracturing of the lithosphere. With distance from the axial line, a seismic moment decreases by one or more orders. This suggest the decrease in the energy potential of seismicity, the decline in the relative degree of fracturing across the strike of the zone and shows the decrease in the relative current seismic activity of faults located at distances from the axial line of the zone of the recent fracturing of the lithosphere.

The distribution of earthquake hypocenters in the crust's cross-section is of considerable importance for evaluating depths of fracturing of the lithosphere. The most recent investigation in BRS (Gileva et al., 2000) carried out at 25 stationary seismic stations show that the largest depths of earthquake foci are registered at stations Arshan (20–25 km in average, 30–35 km in maximum), Ulyunkhan (20–25 km in average, 40 km in maximum), Uakit (15–20 km in average, 25–30 km on maximum) and Chara (15–20 km in average, 25–30 km in maximum). These stations are located in succession from the southwestern flank through the central part to the northeastern flank of the BRS, i.e., in the axial part of the zone of the recent fracturing of the lithosphere. Their data indicate that fracturing and faulting penetrate down to depths of 35 km. With distance across the axial line, depths of earthquake foci decrease. It is more clearly evidenced at station Tyrgan (the Primorsky fault, the western shore of Lake Baikal) where the average depths are up to 10–15 km.

Therefore, both the transform faults at the flanks (the Tunka and Muya–Chara faults) and the BRS central part where the faults and fractures of various hierarchic levels are actively merging and growing, are involved in recent fracturing. Fracturing occurs throughout almost the whole thickness of the crust.

Fracturing and active faulting of the lithosphere contribute to convective heat mass transfer. There is no uniform regional heat flow anomaly in the BRS. Most of the thermal sources are located near the axial part of the zone of the recent fracturing of the lithosphere (Lysak, 1998). Out of the three tectonic components of the BRS, i.e., the central part and two flanks, the central part is the most heated one (Southern Baikal–Barguzin). The situation in northeastern flank is complicated by the Baikal–Chara transform fault which controls the high heat flow and thermal springs outlets in its westernmost termination. Registered phenomena confirm that crustal depths are highly heated in the center of the BRS flanks and in the BRS central part itself, i.e., in the zone of the Southern Baikal—the Barguzin basin—the North-Muya basin. Increased deep heat transfer is one of the typical indications of convective heat mass transfer in the intensely fracturing medium of high permeability.

The above described additional geological and geophysical characteristics of processes associated with the zone of the recent fracturing of the lithosphere give grounds to consider it as a developing uniform tectonic structure (Sherman et al., 1992). The formation of the structure under study is taking place within a geological time interval which is evidently longer than the period of instrumental observations of seismicity. Thus, it is possible to conclude that the zone of the recent fracturing of the lithosphere has occurred earlier, several thousands of years ago. This is evidenced by paleoseismodislocations mapped in the Tunka fault zone which borders the Tunka basin in the north, in the Major Sayan fault zone, along the western shore of Lake Baikal (Chipizubov and Smekalin, 1999) and in some other places. By now, it has already formed as an active fracturing zone which, in its turn, changes the local stress field and influences the seismic process. Below the seismic process is discussed to reveal its other space–time regularities in relation to the identified fracturing zone.

5. The zone of fracturing of the lithosphere is the leading structure controlling seismicity

The zone of fracturing of the lithosphere as the recent active tectonic structure in the BRS produces considerable influence on the distribution of earthquakes in space and time. For the first time in the BRS, it appears possible to establish a hierarchic relationship between the linear dimensions of the zone of fracturing on the surface and magnitudes of earthquakes, which are controlled by the zone. Three examples are discussed below.

5.1. Distribution of seismic events in the strike of fracture zone. Seismic events of 7.7≥M≥6.0

All strong seismic events which have been instrumentally registered and historically recorded (including 27 events with $M \geq 6.0$) occurred in the vicinity of the axial line of the revealed zone of fracturing of the lithosphere (see Fig. 2). They are associated with the transform faults in the BRS flanks and in the southwestern termination of the zone of fracturing in the South Baikal basin. For the purposes of our investigation, the zone of fracturing is represented by the straight line along the BRS strike, and the distribution of seismic events is analyzed with respect to this zone within the framework of the available historic and modern data (Fig. 3).

The analysis is carried out for 27 events since 1760 that are characteristic of the linearly elongated zone of about 1700 km in length. Only three events had M=7.3, of which two were historically recorded. The set of events under study is not numerous and provides only a general view on the migration of events along the strike of the zone of fracturing. Other 24 events have M=6.0–7.0. Due to higher occurrence, they migrate more intensely from the southwest to the northeast and backward along the strike of the zone of fracturing. Strong evidences are found to confirm the migration of seismic events between the fault terminations that has been already well established at many seismically active faults (Kasahara, 1981; Ma Jin et al., 1988). However, the recurrence of events is variable in different parts of the BRS.

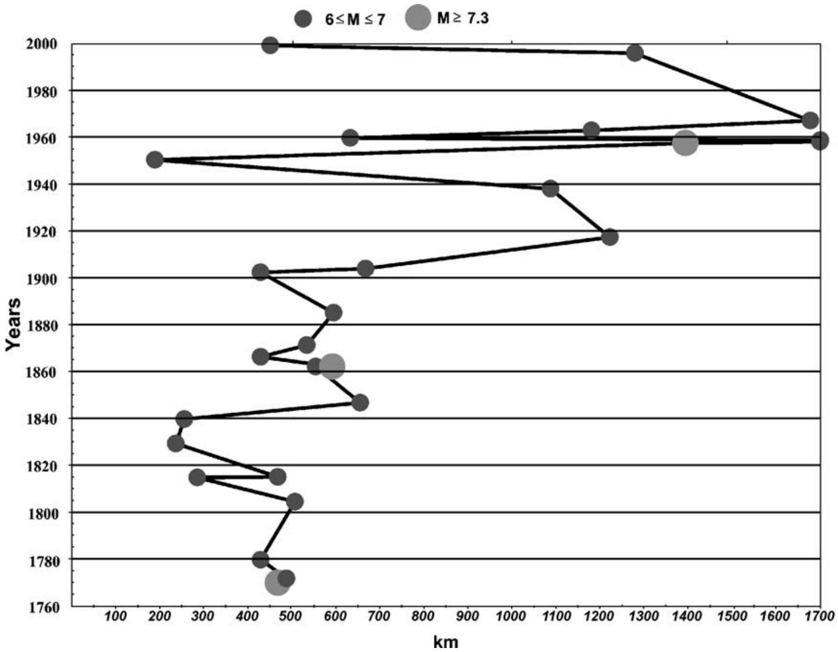

Fig. 3. Space–time migration of seismic events of $M \geq 6$ along the strike of the zone of the recent fracturing of the lithosphere.

5.2. Seismic events of M=5.0÷5.5

Earthquakes of the given energy type migrate in time along the zone of fracturing. Due to the lack of statistical data on earthquakes, it is difficult to reveal the scale of sections of the zone of fracturing that controls the events under study. By the scale of the structural control, they are in between the two hierar-

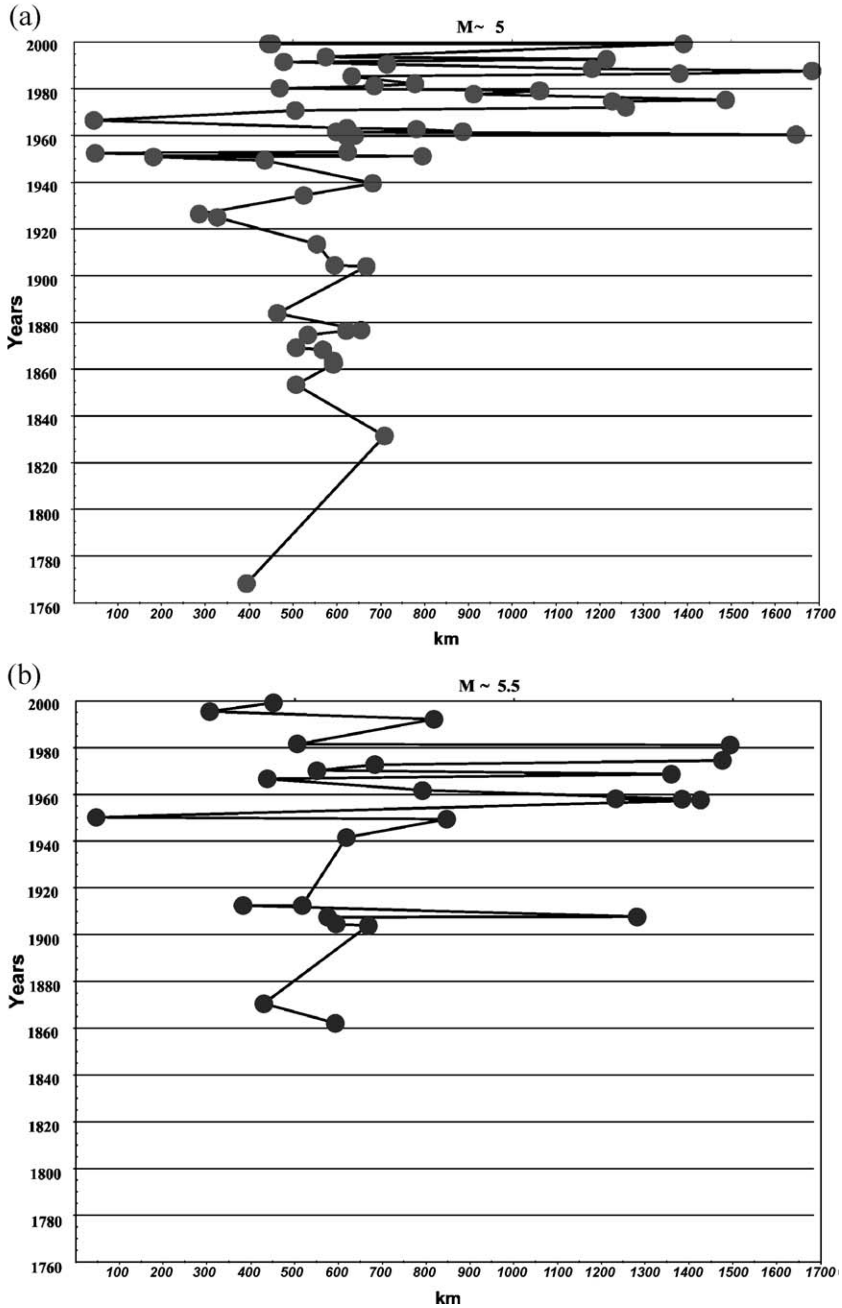

Fig. 4. Space–time migration of seismic events along the strike of the zone of the recent fracturing of the lithosphere: a—$M \approx 5$; b—$M \approx 5.5$.

chical ranks of structures, i.e., between the whole zone of fracturing itself, as it was stated for events of $M \geq 6.0$, and its three components (flanks and the central part). Judging from the distribution of events in space and time (Fig. 4), the second suggestion is preferable. The ambiguity in evaluating the rank of the structural control provides another confirmation that the relationship between the two complex processes in the elastic lithosphere of the BRS, i.e., between faulting and seismicity, is complicated.

Spatial relationships between areas of increased seismic activity and structures of the lower orders, transform and regional faults, are analyzed. Rare events of M>7.0 are excluded from the analysis.

5.3. Distribution of seismic events in the southwestern flank of the BRS. Seismic events of 6.0≤M≤7.0

Much data is available for the southwestern flank of the BRS. The zone of fracturing of the lithosphere

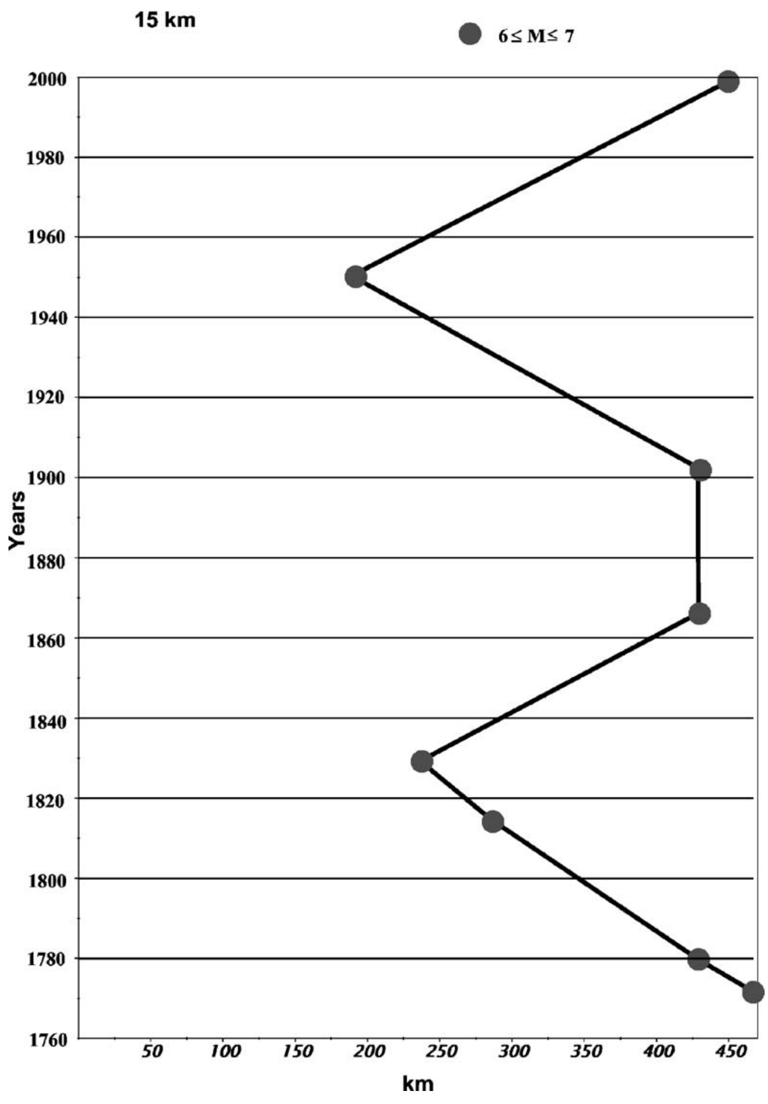

Fig. 5. Space–time migration of seismic events of $6 \leq M \leq 7$ along the strike of the zone of Tunka transform fault (SW branch of the recent fracture zone of the lithosphere).

develops in agreement with the well known Tunka transform fault (Sherman, 1992; Sherman and Levi, 1978). The summary width of the zone of dynamic influence of the fault is 15 km; the fault's axial line is marked on the map. Fig. 5 shows that seismic events of $M = 6.0 \div 7.0$ migrate along the axial line from west to east. Paleoseismo–geological and historical data since 1760 have been used to construct the plot (Golenetsky et al., 1993). The migration of strong events is strongly confirmed along almost the whole axial line of the Tunka transform fault which controls the zone of fracturing in the given BRS flank. As shown by other more detailed studies, the regional faults, especially the Tunka one bordering the Tunka rift basin in the north, are recently reactivated, though its seismic events are relatively less strong and dense. Seismic events are even more rare in the South Tunka fault which borders the Tunka basin in the south; however, there are no doubts that the given faults was reactivated in the post-Holocene time and has low tectonic activity currently.

5.4. Seismic events of $3.5 \leq M \leq 4.5$

In the same flank, the distribution of seismic events of $3.5 \leq M \leq 4.5$ in space and time is discussed for two values of the width of the area of dynamic influence of the transform fault or the zone of fracturing (in the given case, they are similar). Fig. 6a,b is constructed from instrumental data for the past 40 years and shows analytical results for the widths of 15 and 30 km. In principle, the plots are similar and give grounds to suggest the following. From year to year, seismic events of $M \approx 3.5 \div 4.5$ occur within the limits of specific fragments of the zone of fracturing that are from 50 to 100 km long. Clearly manifested lateral (and, partly, transverse, as seen from the plots) migration of earthquake epicenters

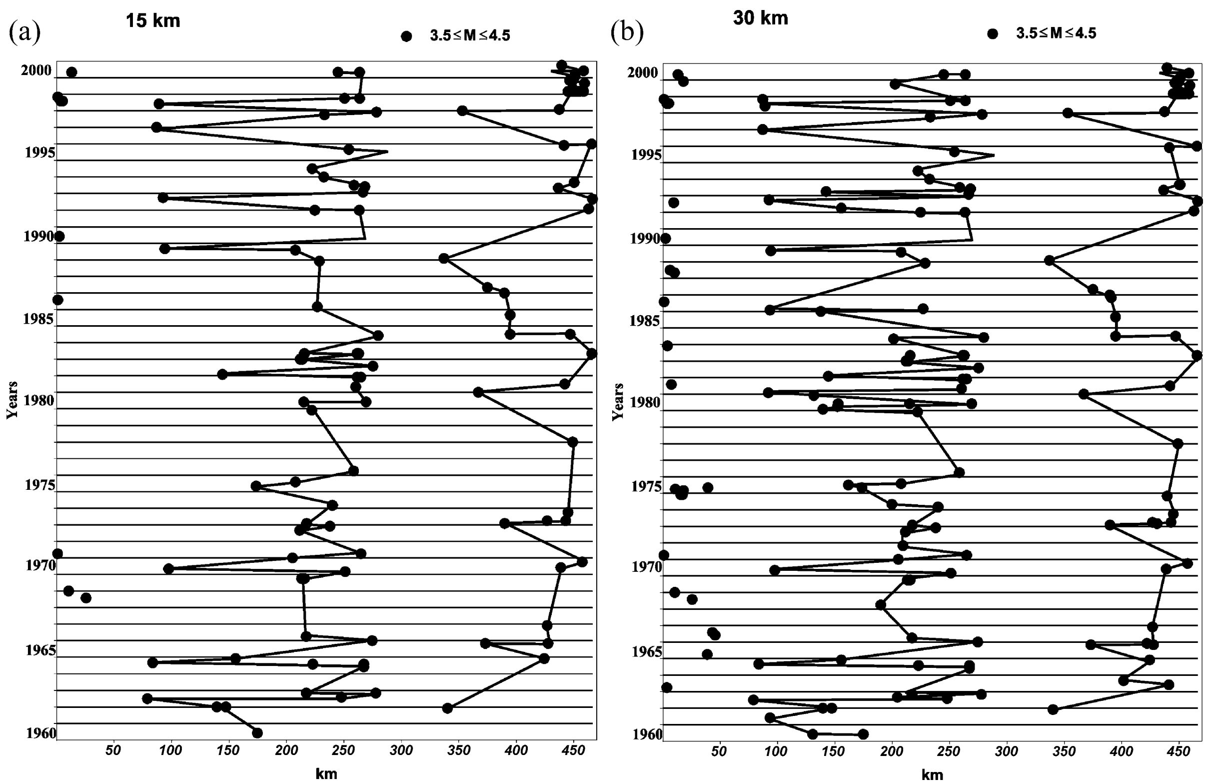

Fig. 6. Space–time migration of seismic events of $3.5 \leq M \leq 4.5$ along the strike of the zone of Tunka transform fault (SW branch of the recent fracture zone of the lithosphere); the width: a—15 km; b—30 km.

is established within these limits, the maximum deviation being ± 50 km. In the zone of fracturing, section of relatively high seismic activity alternate with section of lower seismic activity which are about 200 km in length. As the result, the whole seismically active zone of fracturing in the southwestern flank of the BRS is split into alternating seismically active and less active sections of different lengths. In terms of tectonics, it means that by the more detailed mapping, the Tunka transform fault which was undoubtedly active in the Holocene can be subdivided into sections of relatively higher and lower recent tectonic activity.

The above presentation allows the authors, for the first time for the BRS, to conclude that seismic events of various magnitudes that accompany the recent process of rifting are controlled by the zone of fracturing of the elastic lithosphere. This genetic relationship is determined by various structural ranks in the organization of processes.

6. Conclusion

Most of the BRS faults, irrespective of their age, are tectonically active. Their geomorphological, geological and seismological indications which are used to classify active faults are variable. Geomorphological indications are typical of the faults of almost all the ranks that are involved in rifting. However, they cannot solely provide for a standard identification of obviously active faults since the formation of the relief in the territory under study is related with the Meso–Cenozoic reactivation. The limited occurrence of young deposit in shoreline zones of Lake Baikal does not allow to reveal any faults of the Holocene or recent reactivation. Only high seismic activity of the territory in combination with the fault tectonics studied in detail show that most of the faults are seismically active. This allows the authors, firstly, to identify the zone of the recent fracturing of the lithosphere as a single tectonic structure, secondly, to demonstrate its impact on the relative activity of the BRS faults, and, thirdly, to reveal spatial and temporal regularities in the migration of seismic activity in the zones of dynamic influence of tectonic structures of various ranks, i.e., the zone of fracturing and accompanying faults.

The discreteness and migration of seismic events and their rank association with faults of various hierarchic levels show general regularities of fracturing of the lithosphere under corresponding geodynamic regimes of the lithosphere development. Faulting and seismicity are multilevel synergetic processes of fracturing of the lithosphere. Relationships between fault tectonics and seismicity should be evaluated at comparable levels of destruction of the lithosphere, i.e., rare strong seismic events reflect stages of development of the whole zone of fracturing, whereas weak events are related to its specific segments. Trans-regional and regional active faults in the BRS reflect the structure of the upper part of the lithosphere and predetermine only local variations in the earthquake epicenter field in space and time. The physical mechanism of migration of epicenters correlates with experimental results and modern concepts of physical mesomechanics on multilevel stages of the formation of dislocations in the geological mediums of various volumes and synchronous phenomena.

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