ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2016, Vol. 52, No. 8, pp. 806–815. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © Yu.F. Kopnichev, I.N. Sokolova, 2016, published in Geofizicheskie Protsessy i Biosfera, 2016, Vol. 15, No. 1, pp. 57–72.

High *S*-Wave Attenuation Anomalies and Ringlike Seismogenic Structures in the Lithosphere beneath Altai: Possible Precursors of Large Earthquakes

Yu. F. Kopnichev[a], * and I. N. Sokolova[b], **

[a]*Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, 123242 Russia*
[b]*Institute of Geophysical Research, Ministry of Energy of the Republic of Kazakhstan, Almaty, Kazakhstan*
**e-mail: yufk777@mail.ru*
***e-mail: sokolova.inessa@mail.ru*

Abstract—This paper addresses inhomogeneities in the short-period *S*-wave attenuation field in the lithosphere beneath Altai. A technique based on the analysis of the amplitude ratios of *Sn* and *Pn* waves is used. High *S*-wave attenuation areas are identified in the West Altai, which are related to the source zones of recent large earthquakes, viz., the 1990 Zaisan earthquake and the 2003 Chuya earthquake. Associated with the Chuya earthquake, a large ringlike seismogenic structure had been formed since 1976. It is also found that ringlike seismogenic structures are confined to high *S*-wave attenuation areas unrelated to large historical earthquakes. It is supposed that processes paving the way for strong earthquakes are taking place in these areas. The magnitudes of probable earthquakes are estimated using the earlier derived correlation dependences of the sizes of ringlike seismogenic structures and the threshold values of magnitudes on the energy of principal earthquakes with prevailing focal mechanisms taken into consideration. The sources of some earthquakes are likely to occur near to the planned gas pipeline route from Western Siberia to China, which should be taken into account. The relationship of anomalies in the *S*-wave attenuation field and the ringlike seismogenic structures to a high content of deep-seated fluids in the lithosphere is discussed.

Keywords: lithosphere, attenuation, *S*-waves, ringlike seismogenic structures, large earthquakes, deep-seated fluids

DOI: 10.1134/S0001433816080077

INTRODUCTION

Studies of the last 10–15 years have revealed that zones with a high content of fluids are formed in the lithosphere before many of the large and great earthquakes (Husen and Kissling, 2001; Kopnichev and Sokolova, 2003; Ogawa and Heki, 2007; Wang et al., 2008). These zones correspond to zones of low velocities and high attenuation of short-period shear waves in the lower crust and upper mantle (Husen and Kissling, 2001; Kopnichev and Sokolova, 2003, 2007, 2010a–c, 2011, 2014b; Wang et al., 2008; Kopnichev et al., 2009). Also, they tend to be associated with ringlike seismogenic structures (Kopnichev and Sokolova, 2010c, 2013, 2014a, b). Therefore, data on *S*-wave attenuation and ringlike seismogenic structures may be used to determine the future location of large crustal earthquakes. To this effect, surveys were carried out in some regions of the Tian Shan (Kopnichev and Sokolova, 2010a, 2014a), Pamir-Hindu Kush (Kopnichev and Sokolova, 2011), and Baikal regions (Kopnichev and Sokolova, 2012b, 2014b). Importantly, if taken together, data on the short-period *S*-wave attenuation field and data on ringlike seismogenic structures allow the areas with a high probability for large crustal earthquakes to be determined more accurately; otherwise, false conclusions could be drawn. Moreover, the parameters of ringlike structures—with the most probable focal mechanisms taken into account—can be used to estimate the magnitudes of future large earthquakes using data in (Kopnichev and Sokolova, 2013).

This paper describes the results of analysis of the characteristics of the *S*-wave attenuation fields and seismicity in Altai.

HISTORICAL SEISMICITY

We consider a large area of Central Asia, between 45° N and 52.5° N and 82° E and 101° E (Fig. 1). Eight rather large earthquakes have been registered there in the last 250 years, including five earthquakes with $M \geq 8.0$ (Table 1, Fig. 1).

The 1761 Mongolian earthquake ($M = 8.3$) was associated with the large-scale northwest-striking Ar-Hutel fault. The $M_w = 8.5$, July 9, 1905, Tsetserleg earthquake and the $M_w = 8.4$, July 23, 1905, Bolnay

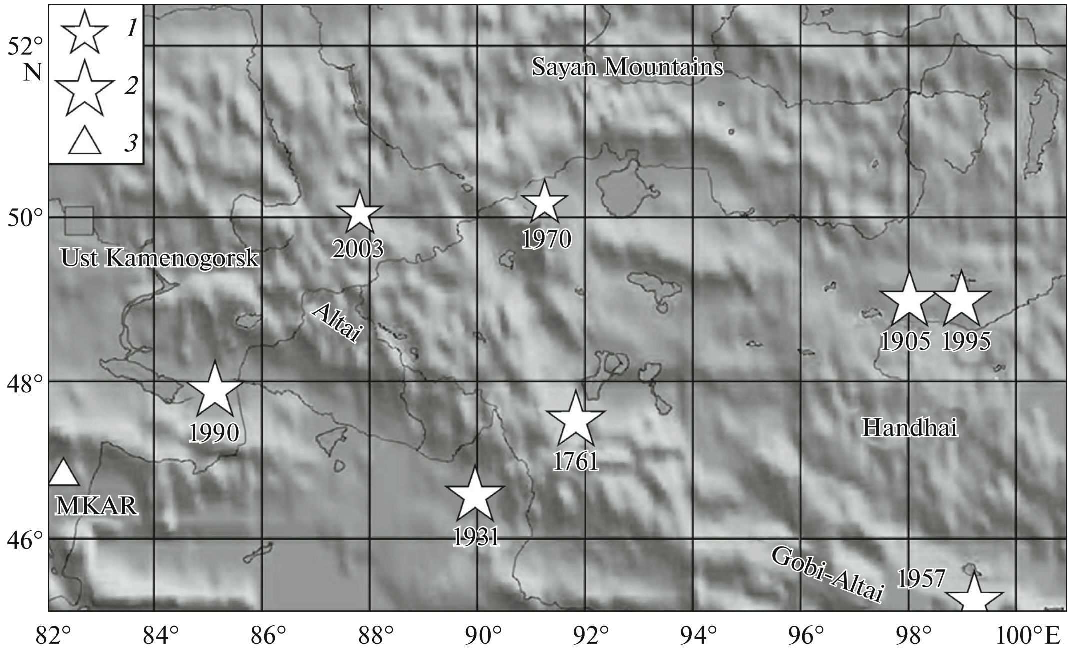

Fig. 1. Map of the area under study and epicenters of large earthquakes *1* and *2;* magnitudes of events: (*1*) $M = 6.6–7.3$; (*2*) $M \geq 8.0$; (*3*) seismic station.

earthquake were some of the largest earthquakes in Azia since 1900 (Engdahl and Villasenor, 2002). The rupture zones of the two earthquakes, which had left-lateral strike-slip focal mechanisms, were confined to the sub-latitudinal Bolnay fault; the total length of seismic dislocations was several hundred kilometers. The 1931 Mongolian-Altai earthquake ($M_w = 7.9$) resulted in surface ruptures about 200 km long. The $M_w = 8.1$, April 12, 1957, Gobi-Altai earthquake with left-lateral strike-slip focal mechanism was caused by slippage along the sublatitudinal Bogdo fault; dislocations were observed over an area about 270 km long by ~30 km wide. The May 15, 1970, Ureg-Nur earthquake ($M = 6.7$) was rather strong; the aftershock area was 90 × 40 km^2. The $M_w = 6.6$, June 14, 1990, Zaisan earthquake was the strongest in Eastern Kazakhstan in history. The rupture zone of this earthquake was on the Ulengur-Zaisan fault; aftershocks were observed over an area of about 45 × 15 km^2. The $M_w = 7.3$, September 27, 2003, Chuya earthquake had its focus extended in a northwest–southeast direction; aftershocks were recorded over an area of ~75 × 30 km^2 (Strong ..., 2004).

MATERIALS AND RESEARCH TECHNIQUES

Mapping of Inhomogeneities in the S-wave Attenuation Field in the Lithosphere

The *S*-wave attenuation field was studied using recordings of crustal earthquakes with epicentral distances Δ ranging from 300 to 1450 km; the recordings were made by the Makanchi seismic station (MKAR)

Table 1. Large earthquakes in the Altai region

Date	Coordinates		*M*	Name
	φ,° N	λ,° E		
09.12.1761	47.5	91.8	8.3	Mongolian earthquake
09.07.1905	49.00	99.00	8.5	Tsetserleg earthquake
23.07.1905	49.00	98.00	8.4	Bolnay earthquake
10.08.1931	46.57	89.96	7.9	Mongolian-Altai earthquake
04.12.1957	45.18	99.22	8.1	Gobi-Altai earthquake
15.05.1970	50.17	91.23	6.7	Ureg-Nur earthquake
14.06.1990	47.87	85.12	6.6	Zaisan earthquake
27.09.2003	50.04	87.81	7.3	Chuya earthquake

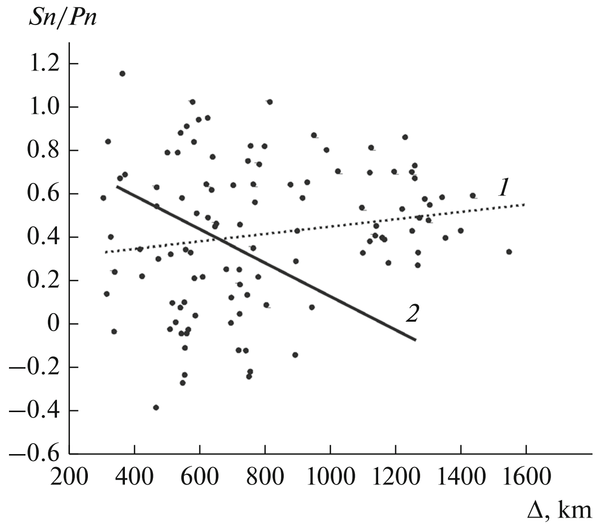

Fig. 2. Parameter Sn/Pn versus Δ, based on MKAR data. Regression lines: (*1*) for the Altai Region; (*2*) for the Central Tien Shan and Dzungaria.

between 1995 and 2013 (see Fig. 1). More than 300 recordings of earthquakes with $M = 3.5$ to 5.5 were analyzed.

The ratio of the peak amplitudes of waves *Sn* and *Pn,* or parameter $\log(A_{Sn}/A_{Pn})$, hereafter referred to as Sn/Pn, was used to map the shear wave attenuation field in the lithosphere. Based on all available data, it was concluded that group *Sn* comprises shear waves reflected from numerous sub-horizontal boundaries in the upper mantle (Kopnichev and Arakelyan, 1988). In this case, when recordings of a single station are used, the level of group *Sn* serves as a measure of attenuation of *S* waves in the lower crust and upper mantle in the vicinity of earthquake epicenters (Molnar and Oliver, 1969; Kopnichev and Sokolova, 2010a, b, 2011; and Kopnichev et al., 2012). Parameter Sn/Pn is used for normalization because waves *Sn* and *Pn* propagate along near paths.

The distance that *Sn* waves travel in the lower crust is several tens of kilometers; it is almost independent of Δ (Kopnichev and Arakelyan, 1988; Kopnichev and Sokolova, 2010a, b, 2011). Therefore, changes in parameter Sn/Pn with distance are primarily due to variations in shear-wave attenuation in the upper mantle. Since the attenuation of seismic waves substantially depends on their frequency, the vertical components of the recordings were preliminarily filtered by a band-pass filter with a center frequency of 1.25 Hz and 2/3-octave bandwidth (Kopnichev, 1985).

Analysis of Ringlike Seismogenic Structures

We used earthquake catalogs received by the National Earthquake Information Center (NEIC), United States, since 1973.

The technique of the delineation of ringlike seismogenic structures is as follows:

(1) Seismicity parameters are analyzed for a period of 40 years, which corresponds to the maximum values of *Tn (*the time ringlike structures take to form).

(2) The seismicity parameters are reviewed for two depth ranges: from 0 to 33 km and from 34 to 70 km, where ring structures are formed. For each of these depth intervals, events are selected whose magnitudes are no less than the threshold ones (*Mn*1 and *Mn*2, respectively); these magnitudes are usually two or three units less than the magnitude of principal earthquakes. Thereby we exclude weaker events with epicenters within the ringlike structures, whose total energy is considerably less than that of the events occurring on the edges of the structures.

(3) The threshold values of magnitude *Mn* are gone over with a step of 0.1 (for the two depth intervals) to determine the optimal values of *Mn* at which ringlike structures are most clearly discernible.

(4) Ringlike seismogenic structures are generally approximated by ellipses; they are outlined in such a way that relatively weak events are shared approximately equally between both sides of the ellipses. We assume that an elliptical ring formed by earthquake epicenters is a ringlike seismogenic structure if its maximum width, which is a sum of the largest deviations of the epicenters inside and outside the ellipse from the ellipse itself, is no more than 1/4 of the minor axis of the ellipse (structure quality criterion).

(5) Then, ringlike structures with the highest possible threshold values of *Mn*1 and *Mn*2 are picked out. Ceteris paribus, a structure with maximum major axis of the ellipse (*L* and *l* for the shallow and deeper rings, respectively), is selected.

(6) Seismicity parameters should be regularly monitored (at least every 6 months), because sometimes new ringlike structures with much larger *Mn* get revealed one or two years before an earthquake, for example, the structures that were discovered before the Great Tohoku Earthquake on March 11, 2011 (Kopnichev and Sokolova, 2012a).

DATA ANALYSIS

Mapping of S-wave Attenuation Field

Figure 2 shows parameter Sn/Pn versus epicentral distance (based on MKAR data). In the figure, most points correspond to the average data for small areas several tens of kilometers long, as a rule. Although data averaging lessens the dependence of parameter Sn/Pn on the directional characteristics of waves *Sn* and *Pn*, there is large spread of data nevertheless. The regression line was formally calculated by the least-square method, though the correlation coefficient for Sn/Pn (Δ) is very low. As follows from Fig. 2, in the region under study the average values of Sn/Pn calculated from MKAR data do not decrease with distance, in contrast to other

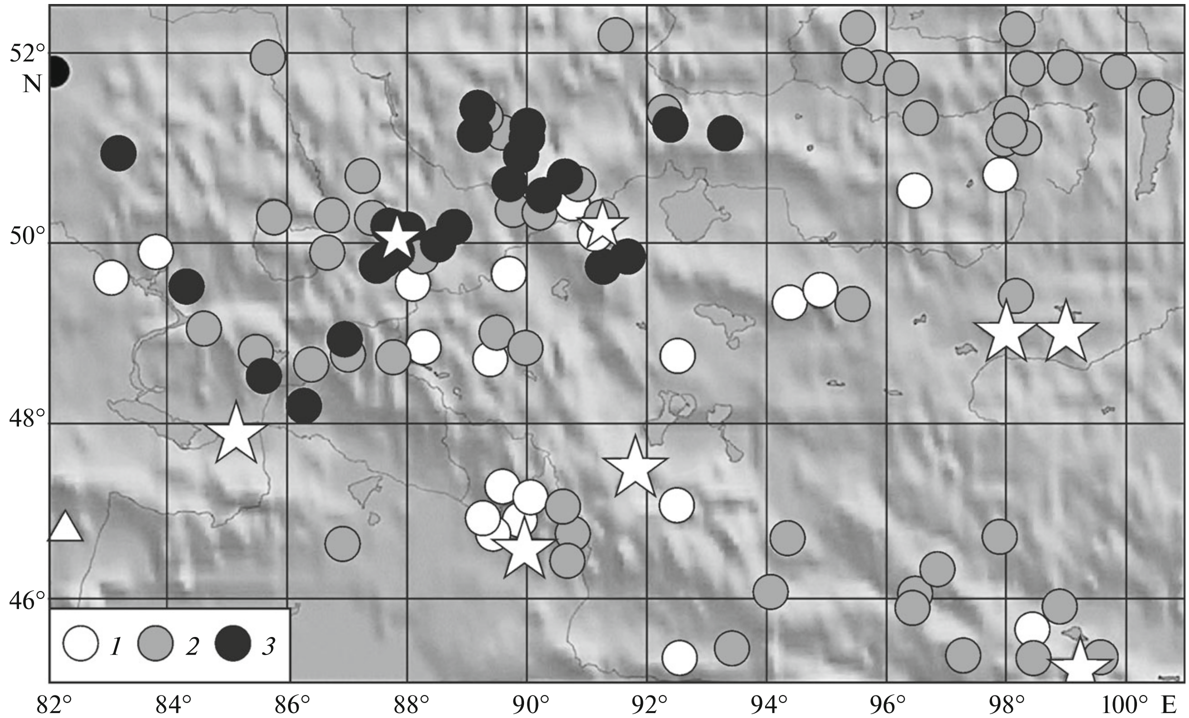

Fig. 3. Map of *S*-wave attenuation field in Altai. Attenuation: (*1*) low; (*2*) intermediate; and (*3*) high. For legend see Fig. 1.

regions of Central Asia (Kopnichev and Sokolova, 2010a, 2011, 2014b; Kopnichev et al., 2012). This is primarily due to the large contribution of relatively low Sn/Pn (<0.2) at distances of up to 1000 km. A comparison of these data with those obtained from the MKAR recordings for the Central Tien Shan and Dzungaria (Kopnichev and Sokolova, 2010a) shows that the average values of Sn/Pn for $\Delta > \sim 700$ km are significantly higher in the Altai region (at $\Delta \sim 1000-1300$ km, differences reaching ~0.30–0.60 log. un.)

Figure 3 shows a map of the field of *S*-wave attenuation in the lithosphere beneath the region under consideration (based on MKAR data). All values of Sn/Pn are divided into three groups: lower attenuation ($Sn/Pn \geq 0.70$), intermediate attenuation ($0.25 < Sn/Pn < 0.70$), and high attenuation ($Sn/Pn \leq 0.25$). Here, in contrast to (Kopnichev and Sokolova, 2010a, 2011, 2014b; Kopnichev et al., 2012), we have not applied a correction for distance, since the average values of Sn/Pn do not decrease with Δ. Each point in the map corresponds to the center of a small zone for which the values of Sn/Pn are averaged. Clearly, relatively weak *S*-wave attenuation is observed over most of the territory. Linear structures of high attenuation stand out against this background. First and foremost, it is a V-shaped belt of high and partly intermediate attenuation in the northwestern part of the region located between 82° E and 89° E (wider in the east and relatively narrow in the west). The eastern branch of this belt is extended in a northeast direction, crossing the high mountainous areas of Altai. The western branch, extending in a northwestern direction, runs along the edge of Rudny Altai. Interestingly, the minimum values of parameter Sn/Pn (−0.38 to −0.03) are mostly observed in the northwestern edge of the V-shaped belt and in the focal zone of the 2003 Chuya earthquake. Also, there is a linear structure to the west of Ubsu Nur Lake, between 89° E and 92° E. This structure is oriented toward the northwest. Another small spot with low values of Sn/Pn is found to the north of Ubsu Nur Lake. Generally, the zones of high *S*-wave attenuation occupy a relatively small area; all of them are located west of 94° E, between 48° N and 52° N. The rest of the territory is mainly characterized by intermediate and partially lower *S*-wave attenuation.

It is found that the areas of low and intermediate *S*-wave attenuation correspond to the focal zones of large earthquakes that occurred before 1990, including those with $M \geq 8.0$. This also applies to the zone of the 1970 Ureg-Nur earthquake, which is found in the low-Sn/Pn belt extending in a northwestern direction. The Chuya earthquake focus is in the eastern part of the V-shaped high-attenuation belt. The focal zone of the 1990 Zaisan earthquake is at a distance of several tens of kilometers from the southern edge of the belt (southwest of it). With allowance for the deflection of seismic rays in the Earth's crust, which is ~40–50 km if the sources are located in the upper crust and the *M* discontinuity is at a depth of ~50 km (Kopnichev and Arakelyan, 1988; Kopnichev and Sokolova, 2010a, 2011; Kopnichev et al, 2012), this also indicates that there is a high *S*-wave attenuation zone in the upper mantle below the earthquake source.

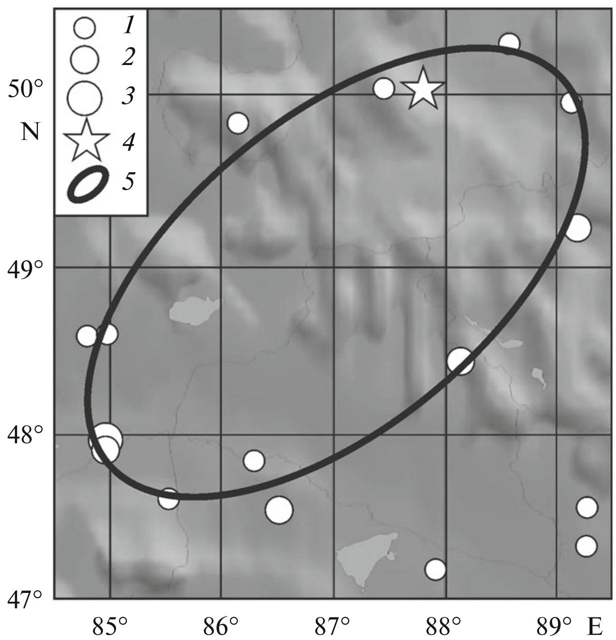

Fig. 4. Ringlike seismogenic structure before Chuya earthquake ($Mn1 = 4.3$). *1–4,* Magnitudes of events: (*1*) $M < 5.0$; (*2*) $5.0 \le M < 6.0$; (*3*) $M \ge 6.0$; (*4*) epicenter of Chuya earthquake; and (*5*) shallow ringlike structure.

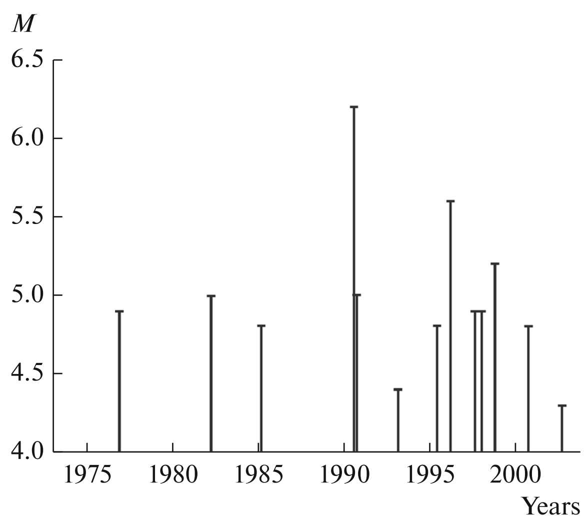

Fig. 5. $M(T)$ for ringlike structure in Western Altai before the 2003 Chuya earthquake.

Ringlike Seismogenic Structures

Taking the earlier results (Kopnichev and Sokolova, 2010a, 2014b; Kopnichev et al., 2009) into account, we considered the ringlike seismogenic structures in the areas characterized by high S-wave attenuation and in their immediate vicinities.

Figure 4 shows the characteristics of shallow seismicity in the Western Altai for the period from January 1, 1973, to September 26, 2003, before the Chuya earthquake ($Mn1 = 4.3$). A very large ringlike structure ($L \sim 390$ km) elongated in a northeastern direction was formed between 1976 and 2003. The border areas of Kazakhstan, Russia, China, and Mongolia are within the bounds of this structure. The highest magnitude within this seismogenic ring is related to an aftershock of the 1990 Zaisan earthquake ($M = 6.2$).

Note that the sum of the magnitudes of the events that occur during time interval ΔT can serve as a rough measure of the rate of seismotectonic strain within ringlike seismogenic structures. As follows from Figure 5, a sharp increase in the rate of seismotectonic strains occurred between 1990 and 2003. The Chuya earthquake epicenter was located within the ringlike structure at a distance of about 20 km from its northern edge, which is much less than the structure's major axis length. The eastern branch of the V-shaped high-attenuation belt is found inside the seismogenic ring.

Figure 6 shows data on relatively deep focus seismicity (h = 34–70 km) in the area under study. The fact that such events, though very few, occurred in Altai is confirmed by a detailed study of the focal zone of the large 1990 Zaisan earthquake (Nurmagambetov et al., 1996). Altogether, five events (M = 4.2–6.6) were registered during this period; four of them were either on the edge of a shallow ring structure or within it. Interestingly, the epicenters of the 1990 Zaisan earthquake and one of its aftershocks (hypocenter depths are 57 and 37 km, respectively) are confined to the southwestern edge of this ring structure. Note that only nine events ($M \ge 3.5$) with relatively deep foci were registered here after the Chuya earthquake; seven of them, which occurred between 2005 and 2015 at a depth of 35–45 km, form a compact spot ~50×60 km^2 confined to the source zone (see Fig. 6b). Judging from available data, the vast majority of relatively deep earthquake sources in this region are at depths of no more than 50 km, which corresponds to the lower layers of the Earth's crust.

Figure 7 illustrates the characteristics of seismicity east of the rupture zone of the 2003 Chuya earthquake. Here, in Western Mongolia, a large ringlike seismogenic structure ($Mn1 = 4.2$, $L \sim 220$ km) oriented in an east-west direction was formed from 1974 to 2010. The highest magnitude within this seismogenic ring corresponds to the 1988 event ($M = 5.9$). Interestingly, in the west (at about 89.2° E) this structure adjoins the structure that was formed before the 2003 Chuya earthquake. Note that the ringlike seismogenic structure crosses the southeastern edge of the high-attenuation belt extending in a northwestern direction.

Figure 8 shows a magnitude-time plot for earthquakes in this area. It has a U-shaped form; the highest rates of seismotectonic strain were between 1974 and 1988 and between 1998 and 2010.

Figure 9 shows data on seismicity in the vicinity of the border between Russia and Mongolia, to the north

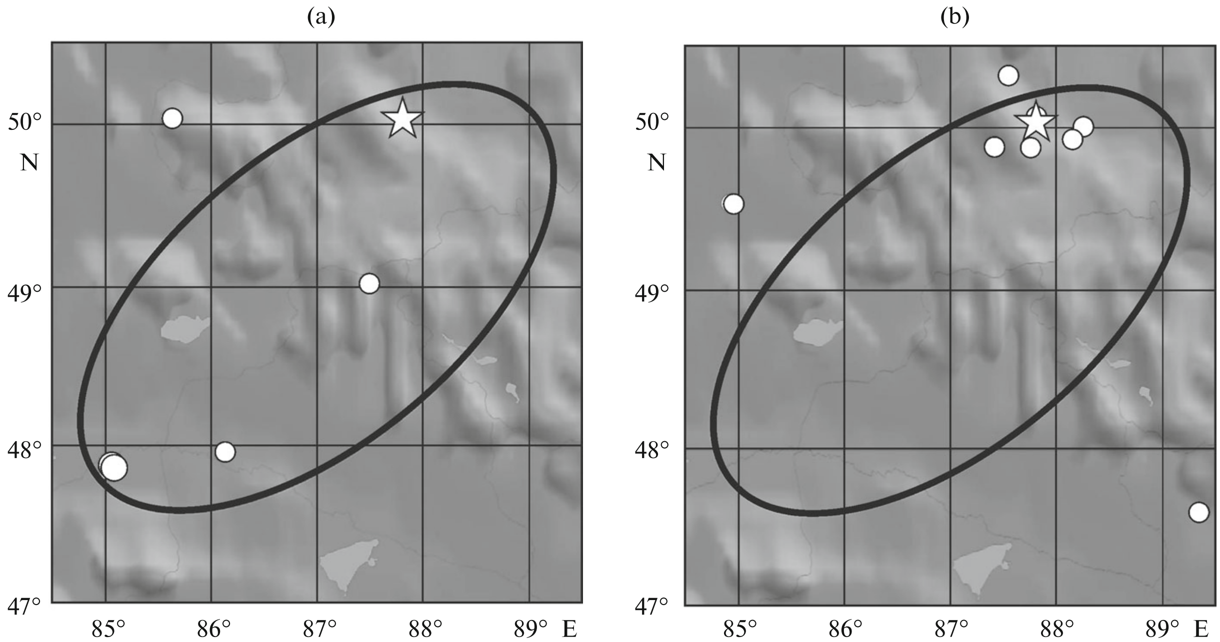

Fig. 6. Deep-focus seismicity before (a) Chuya earthquake ($M = 4.2–6.6$) and after (b) ($M = 3.6–4.4$).

of the above-described structure. A much smaller ringlike seismogenic structure ($Mn1 = 4.3$, $L \sim 120$ km) was formed here between 1974 and 2008, also oriented in a sub-latitudinal direction. The strongest events were recorded in the area of the ringlike structure in 1974 and 1995 ($M = 5.5$). The highest rates of seismotectonic strain were observed in 1974 and between 1988 and 1995 (Fig. 10). Note that the two ringlike structures adjoin at ~49.9° N. The seismogenic ring crosses the eastern belt of high attenuation between 90° E and 91° E. According to available data, only three relatively deep-focus events (in 2008, 2009, and 2013, $h \sim 35$ km) occurred in the area of the two ring structures, confined to the northwest high-attenuation belt.

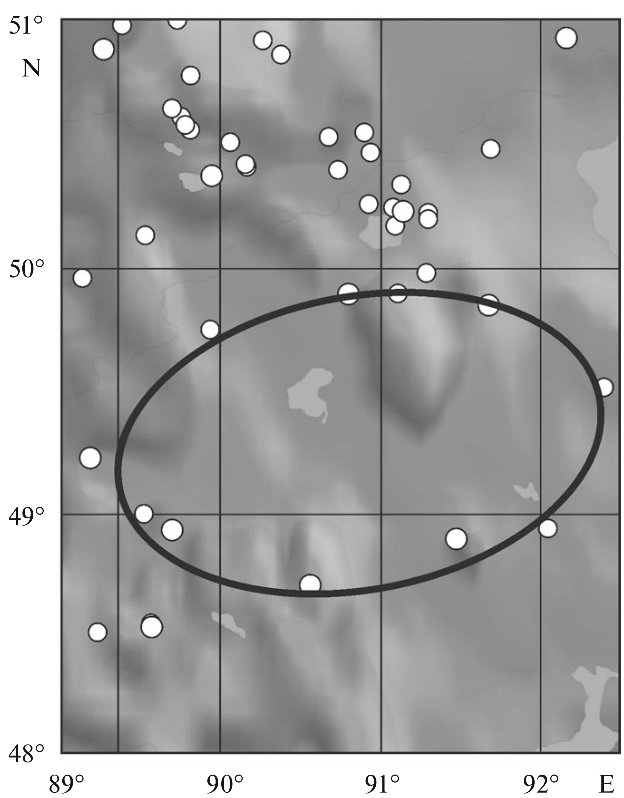

Fig. 7. Ringlike seismicity to the east of the Chuya earthquake center ($Mn1 = 4.2$). For legend see Fig. 4.

Figure 11 shows the characteristics of seismicity in the vicinity of Ubsu Nur Lake and to the north of it. Here, in South Siberia, an indistinct ring structure elongated in a sub-latitudinal direction ($Mn = 3.7$, $L \sim 100$ km) was formed by January 1, 2015. The strongest earthquake ($M = 5.3$) in the area of this structure occurred in 2013. Relatively high rates of seismotectonic strain were observed here between 1985 and 1994 and between 2008 and 2013 (Fig. 12). The high-attenuation zone to the north of Ubsu Nur Lake is associated with the seismogenic ring. Note that no deep-focus events with $M \geq 3.5$ have been registered in this area since 1973.

Estimation of the Magnitudes of Earthquakes Related to Ringlike Structures

In (Kopnichev and Sokolova, 2013), the correlation dependences are given, relating the size of ringlike structures and threshold magnitudes to the energy of large inland earthquakes with different focal mecha-

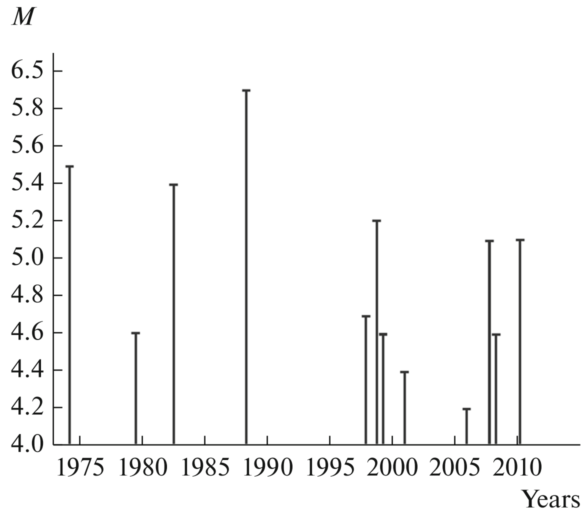

Fig. 8. $M(T)$ for ringlike seismogenic structure to the east of Chuya earthquake rupture zone between 1973 and 2010.

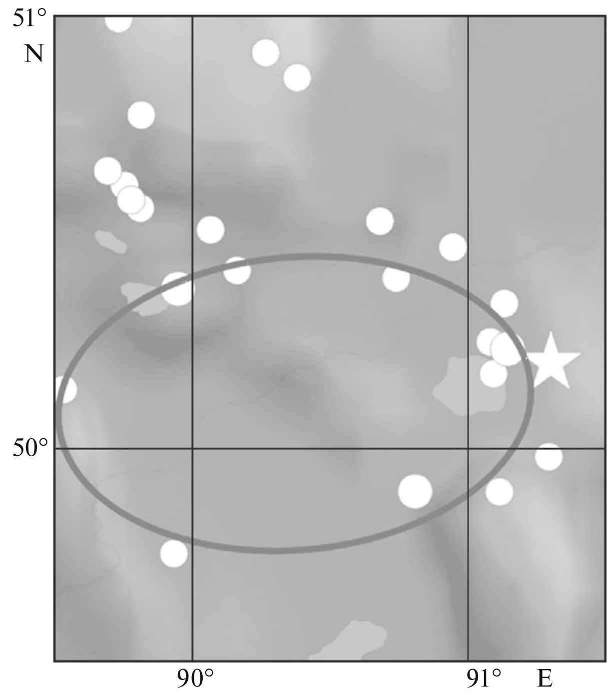

Fig. 9. Ringlike seismicity on the border between Mongolia and Russia ($Mn1 = 4.3$); * Ureg-Nursk earthquake epicenter. For legend see Fig. 4.

nisms. For shear-type focal mechanisms, which are typical of large earthquakes in Altai (Strong..., 2004), these dependences are expressed by the formulae

$$\log L \text{ (km)} = -1.12 + 0.49M_w, r = 0.94, \quad (1)$$

$$Mn1 = -0.17 + 0.64M_w, r = 0.67, \quad (2)$$

where r is the correlation coefficient.

Using these formulae, we estimated the magnitudes of large earthquakes that could be related to the above-described ringlike seismogenic structures in Altai (Table 2). It follows from Table 2 that the event with $M_w = 7.3 \pm 0.3$ could be associated with the seismogenic ring formed before the Chuya earthquake. The other three ringlike structures are correlated with probable events with $M_w = 7.0 \pm 0.2$, 6.8 ± 0.3, and 6.2 ± 0.2, respectively.

DISCUSSION

Our findings suggest that in Altai, like in many other continental regions, shallow ringlike seismogenic structures are formed before large earthquakes (Kopnichev and Sokolova, 2012b, 2013, 2014a). There are no deep ringlike structures such as those formed in subduction zones before most of the large and largest earthquakes (Kopnichev and Sokolova, 2009, 2010c, 2012a). This is due to the fact that there are very few events at depths of 34 to 70 km. It was shown above that the ring structures in Altai, as well as in other regions (Kopnichev and Sokolova, 2012b, 2014a), are correlated with high-attenuation anomalies in short-period S-wave attenuation in the lithosphere. High attenuation of shear waves may be associated with the occurrence of partially melted rocks or fluids. However, the absence of young igneous rocks in Altai suggests that the high S-wave attenuation zones in the lithosphere are associated with deep-seated fluids. It is

Table 2. M_w estimates based on the parameters of ringlike seismogenic structures

Zone	L, km	$Mn1$	Tn, years	$M_w(L)$	$M_w(Mn1)$	M_w
47.0°–50.5° N, 84.5°–89.5° E	390	4.3	27	7.6	7.0	7.3 ± 0.3
48.5°–50.0° N, 89.0°–92.5° E	220	4.2	41*	7.1	6.8	7.0 ± 0.2
50.0°–50.5° N, 89.5°–91.0° E	120	4.3	41*	6.5	7.0	6.8 ± 0.3
50.5°–51.5° N, 92.0°–93.5° E	100	3.7	30*	6.4	6.0	6.2 ± 0.2

* Current values of Tn are specified for these zones.

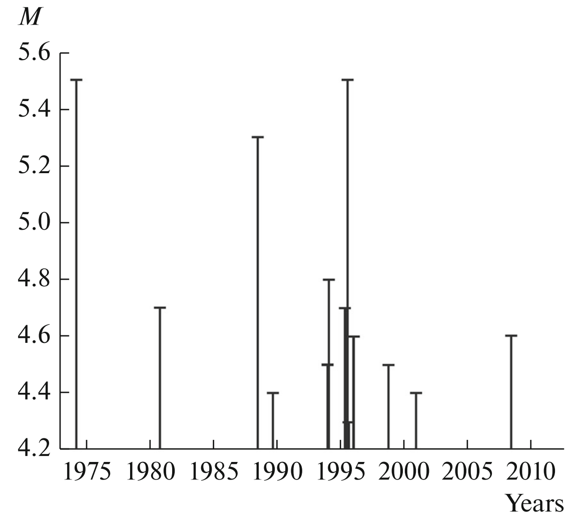

Fig. 10. *M*(*T*) for ringlike structure in the vicinity of the border between Mongolia and Russia from 1973 to 2010.

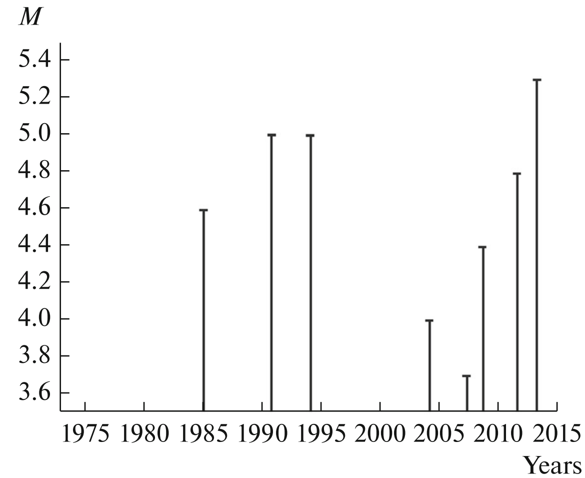

Fig. 12. *M*(*T*) for ringlike seismogenic structure in the vicinity of Ubsu Nur Lake and to the north of it (Southern Siberia) from 1973 to 2015.

known that only 1% of fluid phase may result in a 10% reduction of *S*-wave velocities and sharp increase in *S*-wave attenuation (Hammond and Humpreys, 2000).

It may be assumed that ringlike seismogenic structures reflect the processes of self-organizing of geological systems (Letnikov, 1992), which eventually leads to a decrease in the potential energy of the Earth as a result of the ascent of light fluid phase. Like most continental regions, the absence of deep ringlike seismogenic structures in Altai is most likely due to significantly lower content of free fluids in the continental lithosphere, when compared to subduction zones, which is demonstrated by various geophysical data (Molnar and Oliver, 1969; Deep ..., 1987; Yamasaki and Seno, 2003). Note that the ring seismogenic structure formed before the 2003 Chuya earthquake was probably fed with mantle fluids as a result of the 1990 deep Zaysan earthquake and its aftershocks on the edge of the structure.

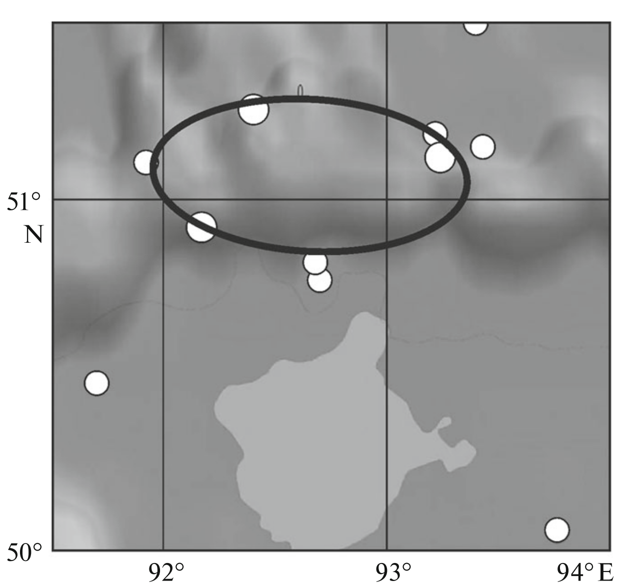

Fig. 11. Ringlike seismicity to the north of Ubsu Nur Lake ($Mn1 = 3.7$). For legend see Fig. 4.

When compared with the Central Tien Shan, *S*-wave attenuation in the lithosphere beneath the West Altai is much weaker, which suggests that there are smaller amounts of fluids there. This is correlated with a significantly lower level of seismic activity in Western Altai (New Catalogue ..., 1977). In (Kopnichev et al., 2009; Kopnichev and Sokolova, 2013), the release of deep-seated fluids is considered one of the most important effects of large crustal earthquakes. It may be assumed that the lower percentage of fluids in the lithosphere beneath Western Altai does not "require" as many large earthquakes as in the Central Tien Shan.

The new data confirm earlier conclusions about the relatively high content of fluids in the upper mantle below the focal zones before large inland earthquakes (Kopnichev and Sokolova, 2003, 2007, 2010a, b, 2011; Kopnichev et al., 2009). The results of (Karakin and Lobkovskii, 1982; Gold, Soter, 1984/1985; Kopnichev and Sokolova, 2005; Hier-Majumder and Kohlstedt, 2006) suggest that the amounts of fluids in the lithosphere increase as a result of the gradual ascent of fluids from the upper mantle.

In (Kopnichev and Sokolova, 2003; Kopnichev et al., 2009), an analysis of temporal variations in the *S*-wave attenuation field showed that large shallow earthquakes cause fluids to ascend to the Earth's crust from the upper mantle over several decades. Geochemical data, viz., higher $^3He/^4He$ isotopic ratios in hydrothermal vents located in earthquake focal areas and in their vicinities, also indicate that fluids migrate upward from the mantle (Kopnichev and Sokolova, 2005). This explains the low attenuation of *S*-waves in the upper mantle beneath the rupture zone of large earthquakes that occurred before 1990 and rather high attenuation in the Earth's crust beneath the rupture zone of the Mongolian-Altai and Ureg-Nur earthquakes; this was confirmed earlier by an analysis of variations in *Lg* and *Pg* amplitudes ratios, based on MKAR data (Kopnichev and Sokolova, 2010b). The ascent of fluids in the area of the 1970 earthquake was likely to take no more than 30–35 years, which is consistent with the estimates based on global data (Kopnichev and Sokolova, 2003; Kopnichev et al., 2009). The ascent of fluids in the focal zone of the Chuya earthquake is also demonstrated by data on deep-focus seismicity after this event (see Fig. 6b).

Importantly, the magnitude of the Chuya earthquake estimated from the parameters of the ringlike seismogenic structure, with the focal mechanism taken into account, is roughly coincident with the real magnitude of this event. The epicenter of the earthquake was near the edge of the ringlike structure, which is characteristic of almost all large seismic events (Kopnichev and Sokolova, 2009, 2010c, 2012a, 2013). Also, the time this ringlike structure took to form is consistent with the average values for inland earthquakes with strike-slip focal mechanisms: $Tn \sim 25 \pm 5$ years (Kopnichev and Sokolova, 2013). This leads to the conclusion that the timely use of information about the ringlike seismogenic structure could have been useful for a medium-term forecast of this large seismic event. This is particularly important in the light of very large return periods of earthquakes with $M \sim 7$ in the Altai region: on average, ~1500–2000, years with an accuracy of several hundred years (Rogozhin and Platonova, 2002).

New data shows that the high-attenuation anomalies between 89° E and 94° E tend to be related to several large ringlike seismogenic structures, with which no large seismic event has been associated so far. By analogy with other regions (Kopnichev and Sokolova, 2010a, b, 2012b, 2014a, b), it may be assumed that large earthquakes will probably occur in the areas of these anomalies. Based on the parameters of the ringlike structures, a seismic event with the largest magnitude may occur in Western Mongolia, where the largest seismogenic ringlike structure ($M_w = 7.0 \pm 0.2$) was formed. Weaker earthquakes may happen to the north and east of this structure. Current duration *Tn* of the formation of the two western structures is close to the maximum values known at the moment: ~40 years (Kopnichev and Sokolova, 2013). *Tn* for the eastern structure is about 30 years, which corresponds to the average values for earthquakes with strike-slip focal mechanisms. Despite the relatively low population density there, large seismic events may cause extensive economic damage. It should be noted that the ring structures shown in Figs. 7 and 9 are located near the planned Western Siberia-to-China gas pipeline route. Consequently, geodynamic processes in these areas should be continuously monitored using geophysical and geochemical techniques with a view to the medium-term forecast of large earthquakes.

The identified ringlike seismogenic structures are large enough, especially in Western Mongolia. Additional study, specifically by methods of paleoseismology (Rogozhin and Platonova, 2002), should be carried out to locate probable large earthquake rupture zone.

REFERENCES

Engdahl, E. and Villaseñor, A., Global seismicity: 1900–1999, in *International Handbook of Earthquake and Engineering Seismology*, Lee, W.H.K., Kanamori, H., Jennings, P.C., and Kisslinger, C., Eds., Academic, 2002, part 1, pp. 665–690.

Glubinnoe stroenie slaboseismichnykh regionov SSSR (Deep Structure of Weakly Seismic Regions of the USSR), Shchukin, Yu.K. and Ryaboi, V.Z., Eds., Moscow: Nauka, 1987.

Gold, T. and Soter, S., Fluid ascent through the solid lithosphere and its relation to earthquakes, *Pure Appl. Geophys.*, 1984/1985, vol. 122, pp. 492–530.

Hammond, W. and Humpreys, E., Upper mantle seismic wave velocity: Effect of realistic partial melt geometries, *J. Geophys. Res.*, 2000, vol. 105, pp. 10975–10986.

Hier-Majumder, S. and Kohlstedt, D., Role of dynamic grain boundary wetting in fluid circulation beneath volcanic arcs, *Geophys. Res. Lett.*, 2006, vol. 33, L08305.

Husen, S. and Kissling, E., Postseismic fluid flow after the large subduction earthquake of Antofagasta, Chile, *Geology*, 2001, vol. 29, no. 9, pp. 847–850.

Karakin, A.V. and Lobkovskii, L.I., Hydrodynamics and the structure of two-phase asthenosphere, *Dokl. Akad. Nauk SSSR*, 1982, vol. 268, no. 2, pp. 324–329.

Kopnichev, Yu.F., *Korotkoperiodnye seismicheskie volnovye polya* (Short-Period Seismic Wave Fields), Moscow: Nauka, 1985.

Kopnichev, Yu.F. and Arakelyan, A.R., On the nature of short-period seismic fields at distances up to 3000 km, *Vulkanol. Seismol.*, 1988, no. 4, pp. 77–92.

Kopnichev, Yu.F. and Sokolova, I.N., Spatiotemporal variations of the *S*-wave attenuation field in the source zones of large earthquakes in the Tien Shan, *Izv., Phys. Solid Earth*, 2003, vol. 39, no. 7, pp. 568–579.

Kopnichev, Yu.F. and Sokolova, I.N., Rise of mantle fluids in areas of sources of strong earthquakes and large fault zone: Geochemical evidence, *Vestn. NYaTs RK*, 2005, no. 2, pp. 147–155.

Kopnichev, Yu.F. and Sokolova, I.N., Heterogeneities in the field of short period seismic wave attenuation in the lithosphere of central Tien Shan, *J. Volcanol. Seismol.*, 2007, vol. 1, no. 5, pp. 333–348.

Kopnichev, Yu.F., Gordienko, D.D., and Sokolova, I.N., Space–time variations of the shear wave attenuation field in the upper mantle of seismic and low seismicity areas, *J. Volcanol. Seismol.*, 2009, vol. 3, no. 1, pp. 44–58.

Kopnichev, Yu.F. and Sokolova, I.N., Characteristics of ring seismicity in different depth ranges before large and great earthquakes in the Sumatra region, *Dokl. Earth Sci.*, 2009, vol. 429, no. 1, pp. 1385–1388.

Kopnichev, Yu.F. and Sokolova, I.N., Heterogeneities in the absorption field of short-period *S*-waves in the lithosphere of Tien Shan and Dzungaria with their relation to seismicity, *Dokl. Earth Sci.*, 2010a, vol. 433, no. 2, pp. 1119–1123.

Kopnichev, Yu.F. and Sokolova, I.N., Mapping of the *S*-wave absorption field in the Earth's crust and upper mantle of Altai, *Vestn. NYaTs RK*, 2010b, no. 1, pp. 93–99.

Kopnichev, Yu.F. and Sokolova, I.N., On the correlation between seismicity characteristics and *S*-wave attenuation in the ring structures that appear before large earthquakes, *J. Volkanol. Seismol.*, 2010c, vol. 4, no. 6, pp. 396–411.

Kopnichev, Yu.F. and Sokolova, I.N., Heterogeneities of the field of short-period shear wave attenuation in the lithosphere of Central Asia and their relationship with seismicity, *Dokl. Earth Sci.*, 2011, vol. 437, no. 1, pp. 363–367.

Kopnichev, Yu.F., Kunakova, O.K., and Sokolova, I.N., Heterogeneities of the field of short-period shear wave absorption in the lithosphere of Central and South Asia and their relation to seismicity, *Vestn. NYaTs RK*, 2012, no. 1, pp. 147–152.

Kopnichev, Yu.F. and Sokolova, I.N., Ring structures of seismicity in northeastern Japan and the catastrophic earthquake of March 11, 2011 in Tohoku (M_w = 9.0), *Vestn. NYaTs RK*, 2012a, no. 1, pp. 121–130.

Kopnichev, Yu.F. and Sokolova, I.N., Heterogeneities of the field of shear wave absorption and ring structures of seismicity in the area of the Baikal rift zone, *Vestn. NYaTs RK*, 2012b, no. 4, pp. 33–41.

Kopnichev, Yu.F. and Sokolova, I.N., Ring structures of seismicity generated in the continental areas before strong earthquakes with different source mechanisms, *Geofiz. Issled.*, 2013, vol. 14, no. 1, pp. 5–15.

Kopnichev, Yu.F. and Sokolova, I.N., Ring structures of seismicity in central Tien Shan and Dzungaria: Possible precursory processes of large earthquakes, *J. Volcanol. Seismol.*, 2014a, vol. 8, no. 3, pp. 194–201.

Kopnichev, Yu.F. and Sokolova, I.N., Variations in short-period shear-wave attenuation in the Baikal Rift Zone and their relationship to seismicity, *J. Volcanol. Seismol.*, 2014b, vol. 8, no. 5, pp. 307–313.

Letnikov, F.A., *Sinergetika geologicheskikh sistem* (Synergy of Geological Systems), Novosibirsk: Nauka, 1992.

Molnar, P. and Oliver, J., Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere, *J. Geophys. Res.*, 1969, vol. 74, pp. 2648–2682.

Novyi katalog sil'nykh zemletryasenii na territorii SSSR s drevneishikh vremen do 1975 g (New Catalog of Strong Earthquakes in the USSR from ancient times to 1975) Kondorskaya, N.V. and Shebalin, N.V., Eds., Moscow: Nauka, 1977.

Nurmagambetov, A., Sadykov, A., Timush, A.V., Khaidarov, M.S., Vlasova, A.A., et al., The Zaisan earthquake of June 14, 1990, in *Zemletryaseniya v SSSR v 1990 g.* (USSR Earthquakes in 1990), Moscow: Nauka, 1996, pp. 54–60.

Ogawa, R. and Heki, K., Slow postseismic recovery of geoid depression formed by the 2004 Sumatra–Andaman earthquake by mantle water diffusion, *Geophys. Res. Lett.*, 2007, vol. 34, L06313. doi 10.1029/2007GL029340

Rogozhin, E.A. and Platonova, S.G., *Ochagovye zony sil'nykh zemletryasenii Altaya v golotsene* (Source Zones of Strong Earthquakes of Altai in the Holocene), Moscow: OIFZ RAN, 2002.

Sil'noe zemletryasenie na Altae 27 sentyabrya 2003 g (The Strong Earthquake of September 27, 2003 in Altai), Gliko, A.O., Ed., Moscow: IFZ RAN, 2004.

Wang, Z., Fukao, Y., Kodairo, S., and Huang, R., Role of fluids in the initiation of the 2008 Iwate earthquake (M = 7.2) in northeast Japan, *Geophys. Res. Lett.*, 2008, vol. 35, L24303. doi 10.1029/2008GL035869

Yamazaki, T. and Seno, T., Double seismic zone and dehydration embrittlement of the subducting slab, *J. Geophys. Res.*, 2003, vol. 108, no. B4. doi 10.1029/ 2002JB001918

Translated by B. Shubik