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Ring-Shaped Seismicity Structures in the Areas of Sarez and Nurek Water Reservoirs (Tajikistan): Lithosphere Adaptation to Additional Loading

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Abstract—Seismicity characteristics in the areas of Sarez Lake and the Nurek water reservoir are studied. Ring-shaped seismicity structures in two depth ranges (0–33 and 34–70 km) formed prior to the Pamir earthquake of December 7, 2015 ($M_w = 7.2$). Seismicity rings cross each other near the Usoi Dam, which formed after the strong earthquake in 1911 and led to the formation of Sarez Lake, and near the epicenter of the Pamir earthquake. In addition, three out of the four strongest events ($M \geq 6.0$) recorded in the Pamir region at depths of more than 70 km since 1950 have occurred near Sarez Lake. An aggregate of the data allows us to conclude that the Pamir earthquake, despite its very large energy, refers to events related to induced seismicity. Ring-shaped seismicity structures in two depth ranges also formed in the Nurek water reservoir area. It is supposed that the formation of ring-shaped structures is related to the self-organization processes of a geological system, which result in the ascent of deep-seated fluids. In this respect, the lithosphere is gradually adapting to the additional load related to the filling of the water reservoir. The difference between Nurek Dam (and many other hydroelectric power stations as well) and Usoi Dam is the permanent vibration in the former case due to water falling from a height of more than 200 m. Such an effect can lead to gradual stress dissipation, resulting in the occurrence of much weaker events when compared to the Pamir earthquake of December 7, 2015, in the areas of artificial water reservoirs.

Keywords: Sarez Lake, Nurek water reservoir, induced seismicity, ring-shaped structures, deep-seated fluids

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INTRODUCTION

Artificial and relatively recently filled natural water reservoirs accumulate quite large water volumes, sometimes exceeding 100 km^3 (Kissin, 1982). For example, the full water volume in Kariba Lake (Zimbabwe and Zambia) is 180 km^3, and that in the Bratsk water reservoir (Russia) is 169.3 km^3. This leads to a considerable additional load on the Earth's crust and to certain geodynamic processes that allow the crust to transit to a new equilibrium state. In particular, the effect of induced seismicity is well known: it manifests in an increased number of earthquakes and their energy even in areas which were not active before the reservoir was filled (Simpson and Negmatullaev, 1981; Kissin, 1982). The strongest earthquake of this type occurred in India, in a weakly seismoactive region near Koyna Dam in 1967 ($M = 6.6$). On the contrary, magnitudes of similar seismic events did not exceed 6.3 (earthquake in 1966 near Kremasta Dam, Greece).

One of the main reasons for induced seismicity is believed to be the penetration of water from reservoirs along cracks deep into the crust (Simpson and Negmatullaev, 1981; Kissin, 1982). However, water penetrates to a relatively small depth (about several kilometers). The study of the problem regarding what happens with the fluid field in areas of large water reservoirs and their vicinities at relatively large depths in the Earth's crust and upper mantle is of certain interest. In this respect, let us note that a long-term intensive technogenic effect leads, in particular, to the ascent of the fluids from the upper mantle in areas of large nuclear test sites (Kopnichev and Sokolova, 2001, 2008; Kopnichev et al., 2013). It has been found in recent years that the migration of deep fluids leads to the formation of ring-shaped seismicity structures, including cases of the preparation of strong crustal earthquakes (Kopnichev and Sokolova, 2009, 2010, 2011a, 2011b, 2013a, 2013b). In the present work, the method related to analyzing ring-shaped seismicity structures is used to study the geodynamical processes in the areas of two large water objects in Tajikistan:

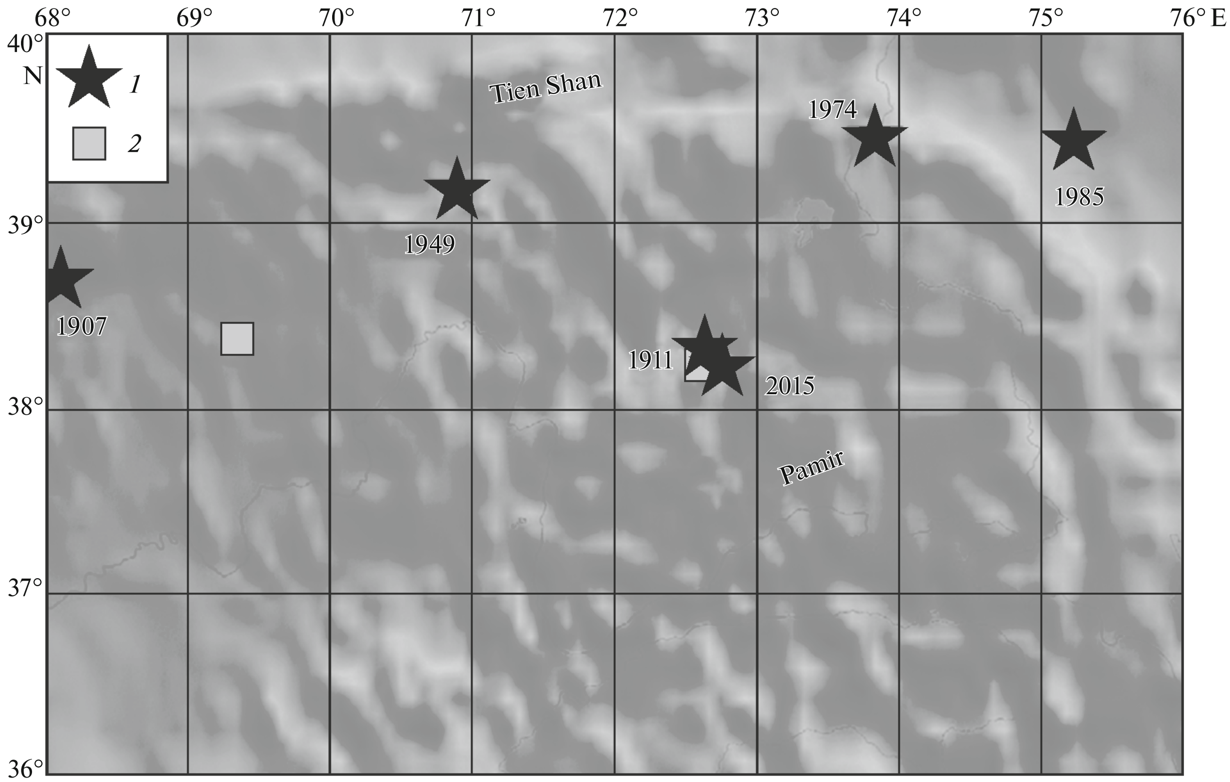

Fig. 1. Map of the study area. Arbitrary notes: (*1*) epicenters of shallow earthquakes with $M \geq 7.0$ since 1900; (*2*) Nurek HPS Dam (left) and Usoi Dam (right).

natural (Sarez Lake) and artificial (Nurek water reservoir). This problem is of particular interest because a quite strong crustal earthquake with $M_w = 7.2$ has occurred recently, on December 7, 2015, in the vicinity of Sarez Lake.

BRIEF GEOLOGICAL–GEOPHYSICAL CHARACTERISTICS OF THE STUDY AREAS

Sarez Lake is located in Central Pamir (Fig. 1). It began to be filled after the strong ($M_w = 7.2$) earthquake of February 18, 1911, when the Murgab River was dammed as a result of a large landslide that formed a 567-m-high dam. The volume of the landslide body was about 2 km^3 (Agakhanyants, 1989). In 1914, the first springs appeared downstream the dam, indicating that water was pouring from the lake. The water level in the lake rose approximately until 2000. The present-day length of the lake is 56 km, its largest depth is 505 m, the surface area is 80 km^2, and the water volume is 17 km^3. The altitude of the water level reaches 3265 m.

It is supposed that the natural dam that formed after the 1911 Sarez earthquake—known as the Usoi Dam—is unstable, and lands along the Bartang, Panj, and Amu-Darya rivers are endangered by catastrophic flooding if the dam was to destruct due to a possible strong earthquake. The main hazard is the unstable large rock volume when comparable to the dam (1.25 km^3) as revealed in 1967 on one of the slopes above the lake—the so-called Pravoberezhnyi (Right-bank) landslide (Agakhanyants, 1989). If the dam destructs or the landslide collapses, areas in several countries with a population of more than 6 million people may be flooded.

It should be noted that, after the 1911 Sarez earthquake and until 2015, no crustal earthquakes with $M \geq 6.0$ have occurred in the nearest vicinity of the lake (*Novyi katalog*..., 1977). However, on December 7, 2015, a strong earthquake with $M_w = 7.2$ and hypocentral depth of 33 km occurred near Sarez Lake (Fig. 2a). Interestingly, the intensity of surface oscillations during this earthquake appeared to be much smaller than is usually observed for earthquakes of this magnitude (*Novyi katalog*..., 1977). Judging by reports of Tajik seismologists, the shaking intensity in the area of Sarez Lake was as small as I = V–VI. Most likely, this was why the Usoi Dam remained and large landslides were not triggered by this earthquake. It is important to address the question as to whether the earthquake of December 7, 2015, was related to Sarez Lake, because, as was noted above, the strongest reported earthquake of this type was 6.6 in magnitude.

The Nurek water reservoir is located in the northern Tajik depression, at ~1000 m above sea level (Fig. 1). It

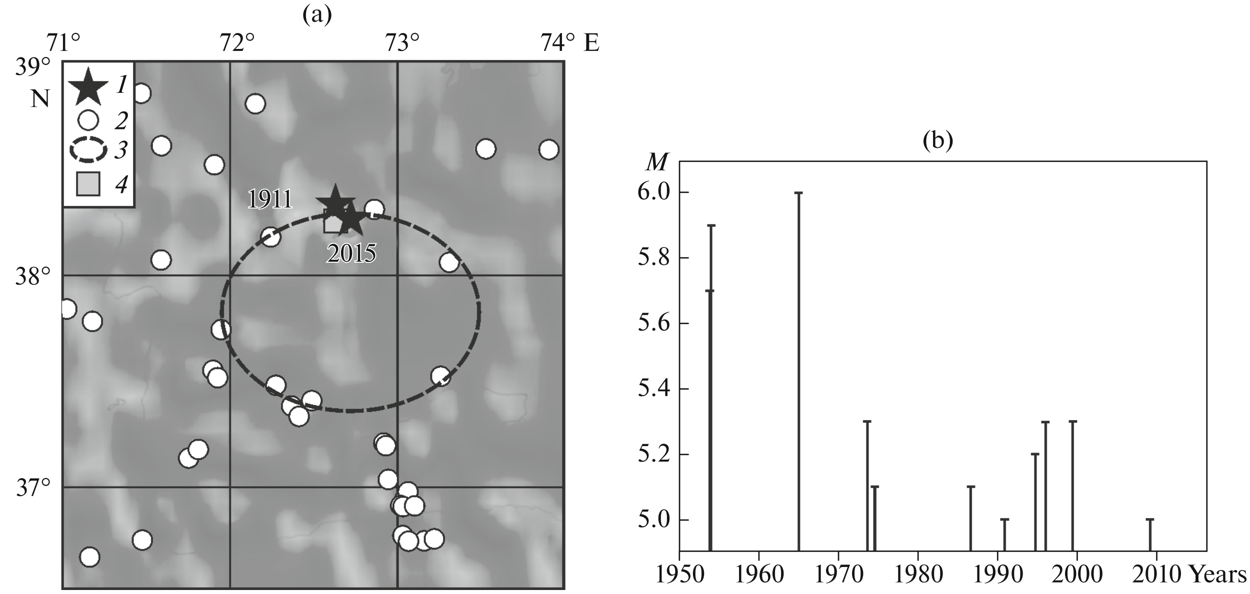

Fig. 2. Shallow-focus seismicity (a) and dependence of $M(T)$ in the zone of ring-shaped structure (b) in the vicinity of the Sarez Lake. Arbitrary notes: (*1*) epicenters of shallow-focus earthquakes with $M \geq 7.0$, (*2*) epicenters of earthquakes with $M \geq 5.0$, (*3*) shallower seismicity ring, and (*4*) Usoi Dam.

began to be filled after the construction of the Nurek HPS Dam in 1972 and reached the design level in 1978 (Simpson and Negmatullaev, 1981). The height of the Nurek Dam is 300 m; the calculated water head is 223 m. The length of the water reservoir is up to 70 km, the width is 1 km, and the average depth is 107 m. Maximal water volume is ~10.5 km^3, and the amplitude of water level oscillations is up to 53 m.

These data suggest that the potential energy of water hosted in Sarez Lake is much higher than that in the Nurek water reservoir. Importantly, in contrast to Usoi Dam, there is a permanent intensive vibration source at the Nurek HPS caused by water collapsing from a height of over 200 m.

DATA AND METHODS

In our work we used mainly the catalogs from the National Earthquake Information Center (NEIC, United States) for the areas of Sarez Lake and the Nurek water reservoir beginning from 1950 and 1973, respectively.

The method of distinguishing the ring-shaped structures has the following peculiarities.

(1) The characteristics of seismicity are studied for the longest possible period (usually at least 40 years).

(2) The parameters of seismicity are analyzed in two depth intervals: 0–33 and 34–70 km, within which the ring-shaped structures form. For each interval, we select the events with magnitudes no less than the threshold value (M_{th1} and M_{th2}, respectively).

(3) Threshold magnitude values M_{th} are adjusted for both depth intervals in order to determine the optimal values at which ring-shaped structures are seen the most clearly.

(4) Ring-shaped structures are usually approximated by ellipses. Seismicity rings are thus constructed in a way that an approximately equal number of relatively weak earthquakes is observed on both sides of the contours of the ellipses. We assume a seismicity ring to be formed if the maximal width of the band of epicenters comprising it (the sum of the largest deviations of epicenters, located within and beyond the ellipse, from its contour) does not exceed 1/4 the length of the minor ellipse axis (quality criterion for ring-shaped structure).

(5) We select ring-shaped structures with the highest possible threshold values M_{th1} and M_{th2}. All other things being equal, we select a seismicity ring with the maximal length of the major axis of ellipse (L and l, respectively, for the shallower and deeper rings).

(6) The parameters of seismicity need to be regularly (at least once in a half-year) controlled, because there were instances when new ring-shaped structures with much larger M_{th} formed in the last 1–2 years (for example, this took place before the March 11, 2011, Tohoku earthquake off the coast of northeast Japan (Kopnichev and Sokolova, 2011a)).

DATA ANALYSIS

Area of Sarez Lake

Figure 2a shows the epicenters of shallow-focus earthquakes (h = 0–33 km) that occurred in the area confined between 36.5°–39.0° N and 71°–74° E, incorporating the largest part of the Pamir, from January 1, 1950, to December 6, 2015 (M_{th1} = 5.0). Since the early 1950s, coordinates of earthquakes in this area began to be determined much more accurately because the Comprehensive Seismological Party of the Institute of Physics of the Earth (IPE), Academy of Sciences of the USSR, was organized here (*Garmskii*..., 1990). Figure 2a clearly demonstrates a ring-shaped structure with the major axis length L ~ 140 km, elongated in sublatitudinal direction. The epicenters of both the Sarez (February 18, 1911; M_w = 7.2) and Pamir (December 7, 2015; M_w = 7.2) earthquakes fall at the boundary of this ring-shaped structure, and the Usoi dam is also located in its vicinity. It follows from Fig. 2b that the ring-shaped structure formed after 1954, and the strongest (M = 6.0) seismic event occurred at its boundary in 1965. Interestingly, the first earthquake epicenters in the ring zone of seismicity were located relatively far from Sarez Lake, while in 1995–2009 they shifted into its nearest vicinity. It should be noted that the formation time of a ring-shaped structure (T_{th} ~ 61 year) in this case is much longer than the respective periods before other strong intracontinental earthquakes, which were usually no longer than 40 years (Kopnichev and Sokolova, 2013a).

Figure 3 shows the aftershock zone of the 2015 Pamir earthquake. We can see that this zone is ~75 km long and NE-elongated. It should be noted that the Pamir earthquake had a shear slip in its source, and one of the nodal planes coincided with the orientation of the aftershock cloud.

Figure 4a presents the characteristics of relatively deep-focus seismicity (h = 34–70 km) observed in the studied are since 1973. In this case, a narrow sublatitudinal ring-shaped structure manifested in 1989–2014 mainly north of the shallow ring (M_{th2} = 4.4, l ~ 140 km). The strongest earthquake in the zone of this ring was recorded in 2010 (M = 5.6; Fig. 4b). It should be noted that shallower and deeper ring-shaped structures cross at latitudes of ~72.2° and 72.8° E, with the epicenter of the Pamir earthquake of December 7, 2015, and Usoi Dam being located at distances of ~10 and 15 km, respectively, from the eastern intercept between two rings.

Figure 4c presents the epicenters of the strongest deep earthquakes ($M \geq 6.0$, h = 71–200 km) recorded in the Pamir region since 1950. It is seen that four earthquakes fitting this magnitude-and-depth range occurred, and all were within the depth range of 110–125 km. Importantly, the epicenters of three out of four fall within a small zone of ~35 × 35 km^2 in size, with Sarez Lake being located in its center. The area of this zone is ~1.6% from the area of the considered region. The probability that three epicenters occurred within this area randomly is determined by the formula

$$P_{3,4} = C_4^3(0.016)^3(0.984) \sim 2.5 \times 10^{-5}. \quad (1)$$

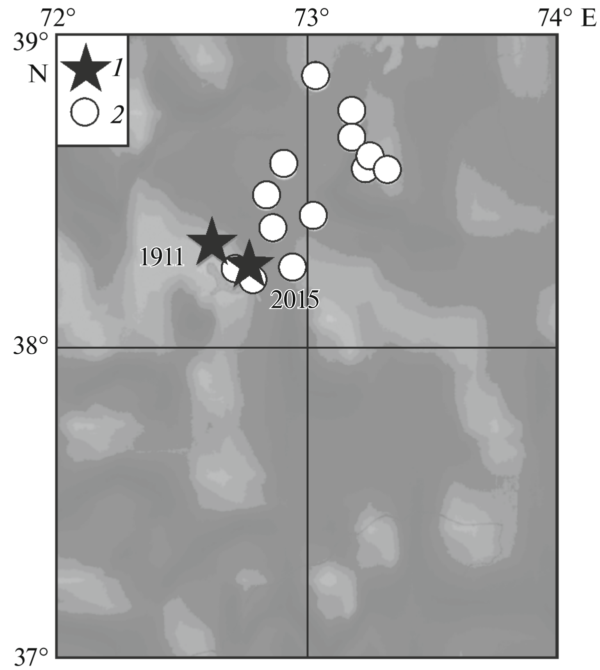

Fig. 3. Aftershock zone of the Pamir earthquake of December 7, 2015. Arbitrary notes: (*1*) epicenters of shallow-focus earthquakes with $M \geq 7.0$; (*2*) epicenters of earthquakes with $M \geq 4.0$ in the period of December 7–17, 2015.

Hence, the probability of the random occurrence of three strong deep-focus earthquakes with no relationship to Sarez Lake is very small.

Area of the Nurek Water Reservoir

Figure 5a provides the epicenters of shallow earthquakes in the region of the Tajik depression and South Tien Shan, confined by 37.5°–39.5° N and 68.5°–71.0° E, since 1973 (M_{th1} = 4.5). The ring-shaped structure with major axis (L ~ 100 km) being submeridionally oriented is clearly distinguished. This structure formed in 1979–2015 (Fig. 5b), and the strongest earthquakes (M = 5.0) occurred here in 1993 and 1998.

Figure 6a illustrates the characteristic of relatively deep earthquakes. In this case, the sublatitudinally elongated ring-shaped structure with M_{th2} = 4.4 and l ~ 110 km, formed in 1976–2011, is distinguished (Fig. 6b). The strongest earthquakes (M = 5.0 and 5.1) were recorded in it in 2005. It is important that the intercept between the shallower and deeper rings is located as close as ~10 km from the Nurek HPS dam.

Figure 6c shows the epicenters of the deepest ($h \geq$ 71 km) earthquakes. In this case, five earthquakes have been recorded here since 1973 with M = 4.6–4.7 (depths are 78–119 km), and all of them are located quite far from the water reservoir (≥100 km). Thus, in contrast to the area of Sarez Lake, even relatively weak

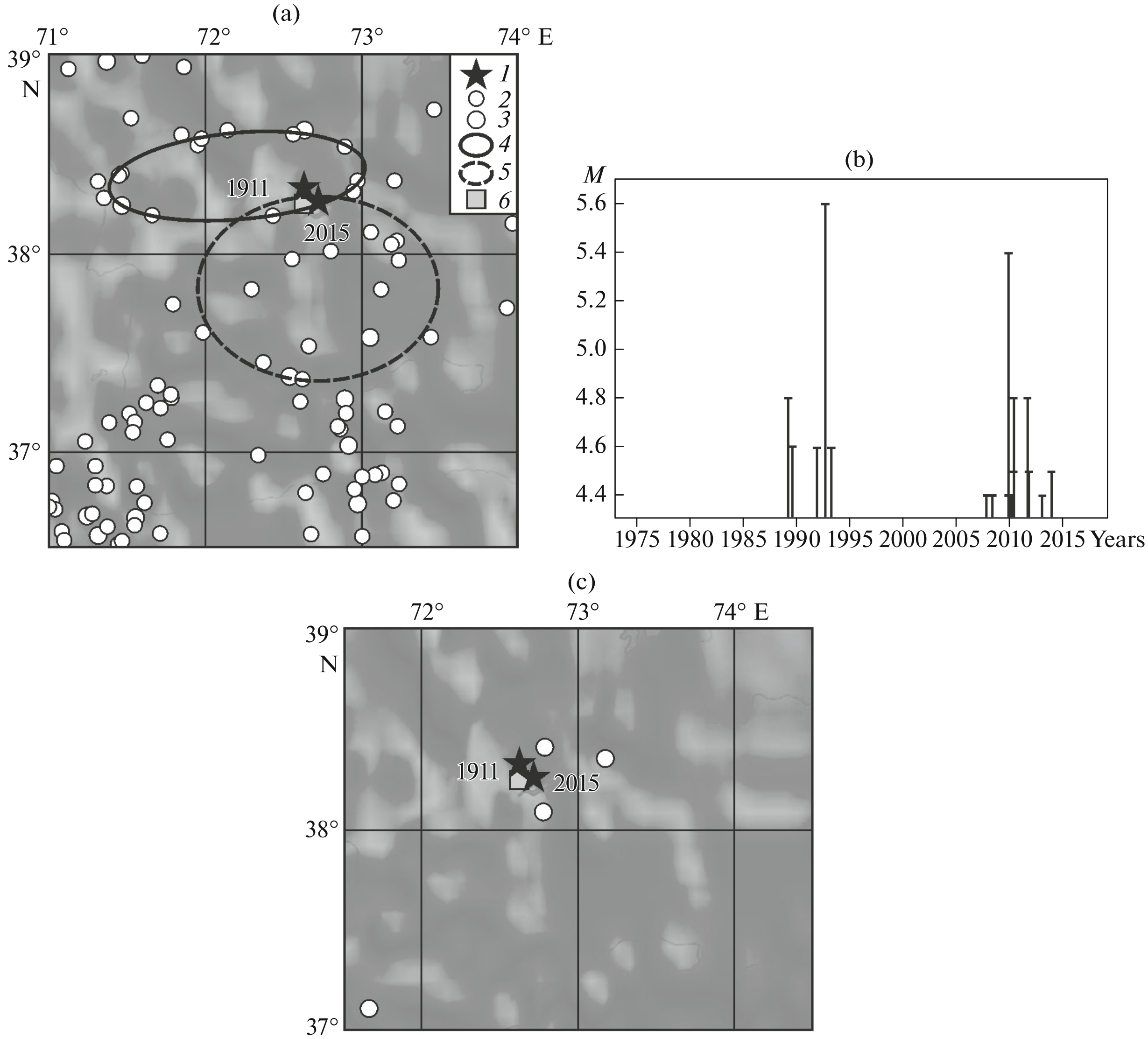

Fig. 4. Deep-focus seismicity (a), dependence of $M(T)$ in the zone of ring-shaped structure (b), and elements of seismicity ($M \geq 6.0$) at depths of 71–200 km since 1950 (c) in the vicinity of Sarez Lake. Arbitrary notes: (*1*) epicenters of shallow-focus earthquakes with $M \geq 7.0$, (*2*) epicenters of earthquakes with $M = 4.4$–4.9, (*3*) epicenters of earthquakes with $M \geq 5.0$, (*4*) deeper seismicity ring, (*5*) shallower seismicity ring, and (*6*) Usoi Dam.

earthquakes have not been recorded in the vicinity of the Nurek water reservoir at more than a 70 km depth.

Estimation of Magnitudes of Maximum Possible Earthquakes

It was shown earlier (Kopnichev and Sokolova, 2009, 2011a, 2013a, 2014) that magnitudes of future strong earthquakes can be estimated from characteristics of shallow ring-shaped structures. In (Kopnichev and Sokolova, 2013a), correlation dependences of $\log L$ (km) and M_{th1} values on magnitude M_w were obtained for strong intracontinental earthquakes with different focal mechanisms whose preparation formed the mentioned ring-shaped structures. These dependences for earthquakes with shear-type mechanisms, which were implemented during the earthquake of December 7, 2015, are of the following form:

$$\log L\ (\text{km}) = -1.12 + 0.49M_w,\ r = 0.94, \quad (2)$$

$$M_{\text{th1}} = -0.17 + 0.64M_w,\ r = 0.67, \quad (3)$$

where r is the correlation factor.

For the seismic events with reverse-faulting and oblique reverse-faulting mechanisms, which are predominant in the region of the Tajik depression (Abers et al., 1988), the following formulas were obtained:

$$\log L\ (\text{km}) = -1.11 + 0.45M_w,\ r = 0.85, \quad (4)$$

$$M_{\text{th1}} = -0.92 + 0.73M_w,\ r = 0.77. \quad (5)$$

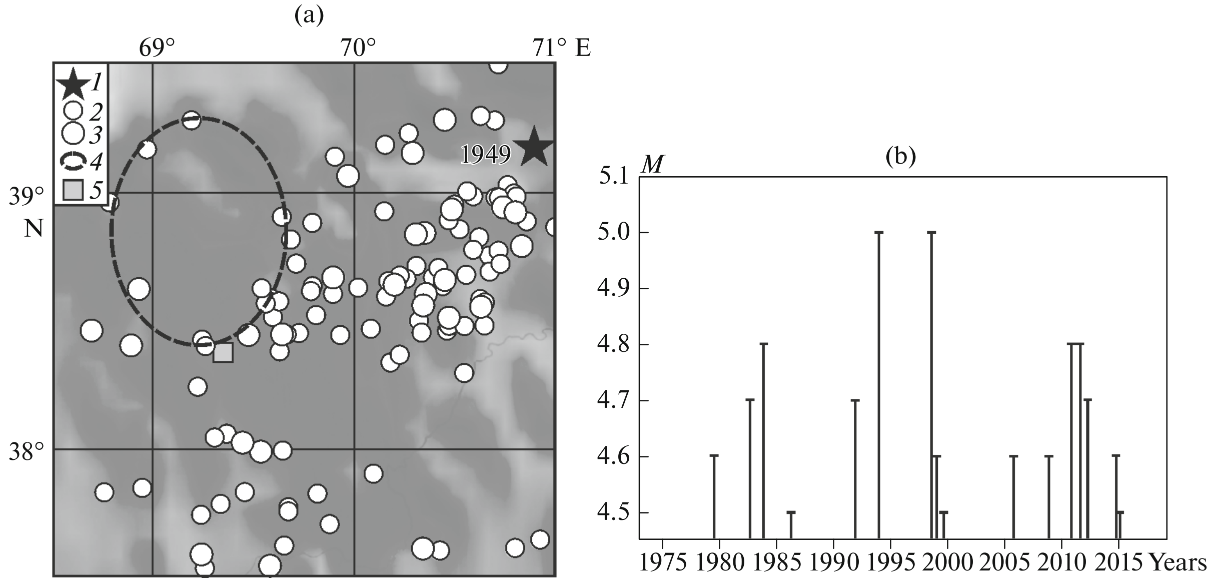

Fig. 5. Shallow-focus seismicity (a) and dependence of $M(T)$ in the zone of ring-shaped structure (b) in the vicinity of the Nurek water reservoir. Arbitrary notes: (*1–3*) same as Fig. 4, (*4*) deeper seismicity ring, and (*5*) Nurek HPS Dam.

Table 1 provides the estimated magnitudes M_w, which can correspond to the parameters of ring-shaped structures in the areas of Sarez Lake and the Nurek water reservoir.

DISCUSSION AND CONCLUSIONS

An analysis of the data has shown that ring-shaped seismicity structures formed in the areas of Sarez Lake and the Nurek water reservoir in two depth ranges. Similar structures form before the majority of the strong and strongest earthquakes in subduction zones (Kopnichev and Sokolova, 2009, 2011a, 2011b, 2013b). In the mentioned works, it was supposed that this effect had been related to self-organization processes in geological systems (Letnikov, 1992); these processes result in the ascent of fluids from the upper mantle into the Earth's crust, eventually leading to a decrease in the potential energy of the Earth. An analysis of inhomogeneities of the shear wave absorption field shows that fluids usually ascend along the boundaries of ring-shape structures (Kopnichev and Sokolova, 2010). On the one hand, under the formation of layers of two-phase material with interconnecting pores and cracks, deep fluids lead to the concentration of stresses at tops of these layers (Karakin and Lobkovskii, 1982; Gold and Soter, 1984/1985), which may trigger strong seismic events; on the other hand, the earthquakes proper and their aftershock sequences promote the ascent of fluids owing to vibrations that increase in permeability of rocks (Barabanov et al., 1987; Rojstacher and Wolf, 1992; Blekhman, 1994; Ogawa and Heki, 2007; Miyazawa and Brodsky, 2008). It is essential that epicenters of strong earthquakes with which the formation of ring-shaped structures is associated are usually located near zones where shallower and deeper seismicity rings cross or touch—the two-phase layers are thickest there, and the value of additional stresses is proportionate to this thickness (Karakin and Lobkovskii, 1982; Gold and Soter, 1984/1985). Note that one of the main sources of fluids is dehydration of the crustal and upper mantle rocks, and this process causes rock to become more brittle (Raleigh and Paterson, 1965; Yamazaki and Seno, 2003; Jung et al., 2004). It is this effect that can cause the formation of seismicity rings at relatively large depths.

Table 1. Magnitudes M_w estimated from parameters of ring-shaped structures

Region	L, km	M_{th1}	T_{th}, yrs	$M_w(L)$	$M_w(M_{th1})$	M_w
38°–39° N 72°–74° E	140	5.0	61	6.7	8.1	7.4 ± 0.7
38°–39° N 69°–70° E	100	4.5	36*	6.9	7.4	7.2 ± 0.3

* For this region, the current value of T_{th} is indicated.

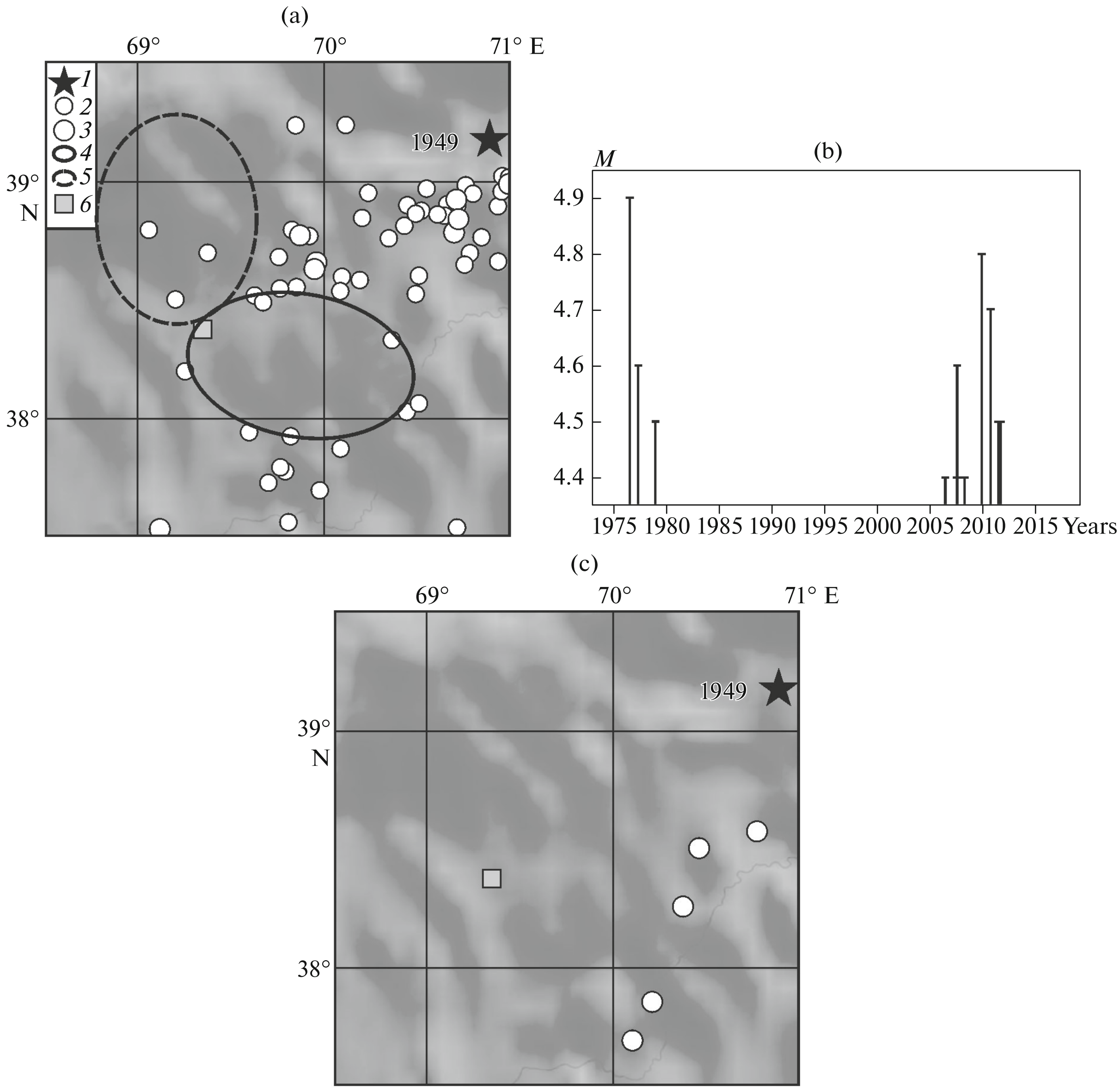

Fig. 6. Deep-focus seismicity (a), dependence of $M(T)$ in the zone of ring-shaped structure (b), and elements of seismicity ($M \geq 4.5$) at depths of 71–200 km (c) in the vicinity of the Nurek water reservoir. Arbitrary notes: (*1–5*) same as Fig. 4; (*6*) Nurek HPS Dam.

In intracontinental regions, ring-shaped seismicity structures most often form only in the upper depth range, which can be explained by less fluid content in this part of the lithosphere when compared to the active continental margins (Kopnichev and Sokolova, 2013a).

By analogy with the preparation of strong earthquakes, we can think that the formation of ring-shaped structures and the proximity of the zone where they cross and touch Sarez Lake and the Nurek water reservoir also prove their genetic relationship. We can consider the formation of seismicity rings in the studied cases related to the release of potential energy of deep fluids, and, owing to the ascent of fluids, the medium gradually attains a new equilibrium state. Note that the data obtained in (Kopnichev and Sokolova, 2013a, 2013b) can indicate that the seismic energy of strong shallow earthquakes is proportionate to the value of the potential energy of fluids released during seismic events there. In this respect, it is important that the magnitude of the Pamir earthquake of December 7, 2015, estimated from formulas (2) and (3), is close to the real value (however, the small accuracy of this estimate must be taken into consideration).

Nevertheless, the sharp difference between the levels of seismic activity in the studied areas needs to be explained. As was already noted, the Pamir earthquake of December 7, 2015, appeared to be much stronger than all reported events associated with induced seismicity. Additionally, its hypocentral depth was much shallower when compared to other similar earthquakes. In our opinion the reasons for this are as follows: first, the depth of Sarez Lake (and, therefore, additional pressure on its bottom) is much greater than that of any artificial water reservoir; second, one of the main features of Sarez Lake that makes it different from the majority of artificial lakes is that it has no permanently operating vibration source (water falling from a big height). As is known, vibration causes an increase in permeability of rocks, even in model experiments (Barabanov et al., 1987; Blekhman, 1994). It is more than obvious to expect the same at relatively small depths in the Earth's crust and uppermost mantle, where the Archimedes force tends to push fluids towards the surface (Ogawa and Heki, 2007; Miyazawa and Brodsky, 2008). We can suppose that permanent vibrations in the upper crust, despite their relatively small amplitudes, do not allow the relatively thick two-phase layer with associated pores and cracks to exist long enough to enable the preparation of a strong earthquake.

The relationship between the Pamir earthquake of December 7, 2015, and Sarez Lake is also indicated by the locations of the strongest deep-focus earthquakes in the study area (Fig. 4c). We can think that quite strong earthquakes with $M = 6.0–6.3$ at depths 110–125 km also occurred here, resulting from the dehydration of mantle rocks that became brittle (Raleigh and Paterson, 1965; Yamazaki and Seno, 2003; Jung et al., 2004). At the same time, dehydration could be triggered by additional loading to the lithosphere during the filling of Sarez Lake, which is also related to the self-organization processes in geological systems (Letnikov, 1992), in turn leading to a decrease in potential energy of the Earth.

Thus, there is strong evidence for the fact that the Pamir earthquake of December 7, 2015, despite its very big energy and great depth, is also in the class of induced seismic events. It should also be noted that, except for the role played by Sarez Lake, there are certain additional effects that might accelerate the preparation of this seismic event. It was shown in (Kopnichev and Sokolova, 2014) that the Makran earthquake of September 24, 2013 ($M_w = 7.7$), in Southern Pakistan had been followed by abruptly intensified shallow-focus seismicity in the vast region of Central and South Asia—this phenomenon was attributed to the increased motion rate of the Indian Plate relative to Eurasia. Additionally, the very strong deep-focus ($M_w = 7.5$, $h = 231$ km) Hindu Kush earthquake occurred on October 26, 2015. As was noticed in (Kopnichev et al., 2002), for 4.5 months after these earthquakes, strong ($M \geq 7.0$) crustal earthquakes were frequently reported in the region of Central and South Asia, which was also attributed to the induction of the fluid field in the lithosphere (in the case of the earthquake of October 26, 2015, less than 1.5 month passed).

More indirect evidence for the relationship between the Pamir earthquake of December 7, 2015, and the filling of Sarez Lake is the general level of seismicity in Central and South Pamir. According to the NEIC catalog and (*Novyi*..., 1977), at least since the beginning of the 19th century to 2015, only two strong crustal earthquakes with $M \geq 7.0$ have been reported here: one of them occurred in 1911 and formed Usoi Dam and the second occurred 2015 near the lake appearing upstream this dam. In this respect, the recurrence interval for earthquakes with $M \geq 7.0$ in the largest part of the Pamir is a priori more than 200 years; therefore, it is highly improbable that two earthquakes of this energy would occur in such a small area during ~100-year-long interval only resulting from the accumulation of deformation.

In the area of the Nurek water reservoir, ring-shaped structures also touch each other in the vicinity of the reservoir proper. In this respect, we can suppose that formation of these structures in both studied cases was related first and foremost to the loading of water. However, in the area of the Nurek water reservoir, like the areas of many other artificial HPS-related lakes where water falls from a great height, earthquakes with $M \gtrsim 7.0$, corresponding to the estimates by formulas (4) and (5), should not be expected. The data on seismicity in the areas of the Nurek water reservoir and other large ones may indicate that permanent vibration provides a slow ascent of deep fluids and stress dissipation, in turn providing a gradual decrease in the potential energy of fluids and preventing quite strong earthquakes.

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