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Characteristics of Seismicity in the Areas of Large Water Reservoirs and Waterfalls: The Role of Effects from Additional Load and Permanent Vibration

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Abstract—The characteristics of seismicity in the near vicinity of five large water reservoirs and three large waterfalls from different regions of the Earth are considered. It is found that in some cases induced seismicity manifests itself during the filling of reservoirs at quite large depths: in the lower crust and even in the upper mantle. There is negative correlation between the maximum magnitudes $M_{\max}$ of the earthquakes recorded near water reservoirs and waterfalls and the water discharge in these objects (V_p). The largest values of $M_{\max}$ are characteristic of earthquakes that occurred near Sarez Lake (Tajikistan) and the Koyna Reservoir (India), which have the lowest V_p; in contrast, the smallest magnitudes are reported for earthquakes in the areas of the Khone Falls (Laos) and Niagara Falls (United States, Canada), where there are no large artificial water reservoirs, but huge water discharge takes place. The available data indicate that permanent vibration caused by falling water reduces the level of seismicity.

Keywords: seismicity, water reservoirs, waterfalls, vibrations, deep-seated fluids

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INTRODUCTION

Filling of many large artificial water reservoirs triggers the effect of so-called induced seismicity (Simpson and Negmatullaev, 1981; Kissin, 1982; Mirzoev et al., 2009). This effect is reflected in recording of relatively strong earthquakes in the near vicinity of water reservoirs, even in the areas which were weakly seismoactive before the filling. It is believed that induced seismicity is related to additional load on the Earth's crust, to infiltration of fluids through cracks and faults, and also to permanent vibrations of the Earth's surface due to falling water (Simpson and Negmatullaev, 1981; Kissin, 1982; Mirzoev et al., 2009). However, particular contributions of these factors are quite difficult to specify. In the present work, in order to estimate the contributions of additional load and vibration, we consider the characteristics of seismicity in the areas of four water reservoirs—Kariba (Zambia, Zimbabwe), Koyna (India), Nurek (Tajikistan), and Dworshak (United States); one natural lake (Sarez, Tajikistan); and three of the largest waterfalls—Victoria Falls (Zambia, Zimbabwe), Khone Falls (Laos), and Niagara Falls (United States, Canada).

MAIN CHARACTERISTICS OF STUDIED OBJECTS

The Kariba Dam was built in 1959 on the Zambezi River, at the border between Zambia and Zimbabwe; its height and length are 128 and 579 m, respectively, with average water discharge through it (V_p) of ~8000 m^3/s (Table 1). The Kariba Reservoir is ~5400 km^2 in area, 280 km in length, and $V \sim 180$ km^3 in capacity (the largest artificial lake in the world).

The Koyna Dam is located in western India, on the river of the same name; it was constructed in 1956–1964. The height and length of this dam are 103.2 and 807 m, respectively, and water discharge is 170 m^3/s. The reservoir area is ~892 km^2 and its capacity is $V \sim$ 2.8 km^3.

The Nurek Reservoir is located in the northern part of the Tajik Depression, at the elevation of ~1000 m above sea level. The reservoir began to be filled after construction of the dam in 1972 and reached the projected level in 1978 (Simpson and Negmatullaev, 1981). The height and length of the Nurek Dam are 300 and 700 m, respectively; the designed water level is 223 m, and the average water flow rate is 1350 m^3/s. The length of reservoir is up to 70 km, the width is 1 km, and its average depth is 107 m. The maximum

Table 1. Characteristics of studied objects (water reservoirs and waterfalls) with magnitudes of the largest seismic events in the respective regions

Object	V, km^3	V_p, m^3/s	M_{max}
Kariba Reservoir	180	8000	5.7
Koyna Reservoir	2.8	170	6.6
Nurek Reservoir	10.5	1350	5.3
Sarez Lake	17	45	7.2
Dworshak Reservoir	4.3	4200	3.8
Victoria Falls		1090	5.0
Khone Falls		11000	<3.0
Niagara Falls		2400	3.7

capacity is ~10.5 km^3; the water level varies by as much as 53 m.

Sarez Lake, located in the Central Pamir, Tajikistan, is the largest natural water reservoir, which began to be filled after the large (M_w = 7.2) earthquake of February 18, 1911, which caused the Murghab River to be dammed by a huge landslide block (known as the Usoi Dam, 567 m high). The volume of rock in the dam was estimated at about 2 km^3 (Agakhanyants, 1989). In 1914, the first springs appeared downstream of the dam to indicate water pouring through it. The water level in the lake rose until ca. 2000. At present, the lake is 56 km long, its maximum depth is 505 m, the surface area is 80 km^2, and the capacity is 17 km^3; the average water discharge through the Usoi Dam is ~45 m^3/s. The water level in the lake is at 3265 m above sea level.

It is thought that the dam formed by the 1911 Sarez earthquake is instable, and the lands along the Bartang, Panj, and Amu-Darya rivers will be in danger of being flooded if the dam is destroyed after some strong earthquake. The main danger is the instable rock massif on one of the slopes, having a volume of 1.25 km^3, which is comparable to the dam, and hanging above the lake, which was revealed in 1967 and is called the Right-Bank (Pravoberezhnyi) landslide (Agakhanyants, 1989). If the dam is destroyed or the landslide moves, the flood will affect the areas of several countries with more than 6 million people living there.

The Dworshak Dam is located on the Clearwater River, Idaho, western United States (constructed in 1966–1973). The height and length of the dam are 219 and 1002 m, respectively, and the average water discharge is 4200 m^3/s. The dam formed the Dworshak Reservoir with a volume of 4.3 km^3 and surface area of 69 km^2.

Victoria Falls (local name is translated as "The Smoke that Thunders") on the Zambezi River in South Africa is located at the border between Zambia and Zimbabwe. Its height is ~120 m and width is ~1800 m. Victoria Falls is the only waterfall in the world more than 100 m high and more than one kilometer wide at the same time. The average water discharge is ~1090 m^3/s, and the peak one is ~9100 m^3/s.

Victoria Falls is remarkable for the fact that it is located upstream (at the distance of about 360 km) from the Kariba Dam. The southwestern margin of the Kariba Reservoir is located at the distance of 130 km from Victoria Falls.

Khone Falls is located on the Mekong River, in Southern Laos, near the Cambodian border. This is the succession of waterfalls forming multiple islands and branches, so its local name is "4000 Islands" ("Si Phan Don" in Lao). The tallest waterfall is 21 m and the whole succession stretches 9.7 km. The average water discharge is ~11000 m^3/s, and the peak one is more than 49000 m^3/s.

Niagara Falls is a collective name for the three waterfalls on the Niagara River flowing from Lake Erie to Lake Ontario, at the border between Canada and the United States. From largest to smallest in energy, the waterfalls are Horseshoe Falls, the American Falls, and the Bridal Veil Falls. The height of the waterfalls is 57 m and their total length is ~1100 m. The average water discharge is ~2400 m^3/s, and the peak one is ~5700 m^3/s.

ANALYSIS OF SEISMICITY CHARACTERISTICS

In our work, we analyzed the seismic data for the mentioned areas according to the catalogs of the NEIC USGS obtained in 1950–2015.

South Africa

Figure 1 shows the epicenters of earthquakes ($M \geq 4.0$, h = 0–33 km) that occurred in the region between 14° and 20° S, 20° and 30° E beginning from 1960. The majority of earthquakes form an inverse L-shaped structure whose longer (eastern) part of about 350 km in size passes across the dam and the Kariba Reservoir, whereas the shorter (western)

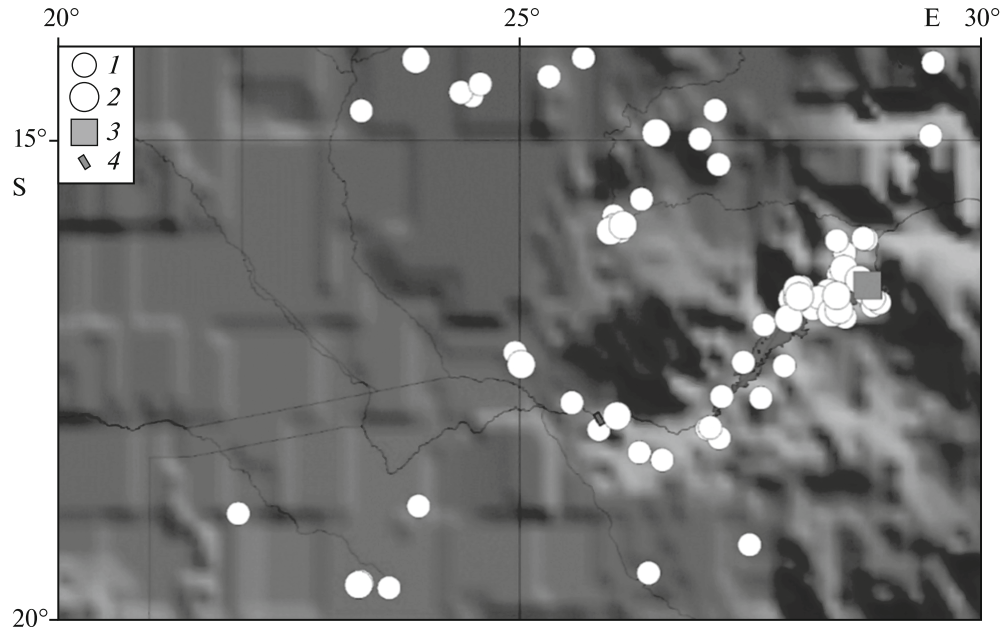


Fig. 1. Seismicity in the studied region of South Africa (0–33 km depth). (*1*, *2*) Earthquake epicenters: (*1*) M = 4.0–4.9; (*2*) $M \geq 5.0$; (*3*) Kariba Dam; (*4*) Victoria Falls (symbols *3* and *4* are also in the other figures).

one of about 200 km runs across Victoria Falls. The densest cluster of epicenters is located around the dam. Note that earthquakes deeper than 33 km are not recorded in this area.

The reservoir began to be filled in December 1958, and weak earthquakes began to be recorded in the region in May 1959. The reservoir reached its designed level in August 1963, and from August 14 until November 8, 1963, a series of moderate earthquake occurred here (two of them were 5.7 and 5.5 in magnitude). Another moderate earthquake with M = 5.6 was recorded in 1972. Thus, the Kariba Reservoir is a clear example of a region with induced seismicity (Kissin, 1982).

Western India

Figure 2 shows the epicenters of shallow (h = 0–33 km) earthquakes with $M \geq 3.5$ occurring since 1964 in Western India (16°–18° N, 73°–75° E). The largest earthquake occurred here near the Koyna Dam in 1967 (M = 6.6). It should be noted that this earthquake was the largest induced one until 2015. Beginning from 1980, a NW-elongated (major axis length L is ~45 km) ring-shaped seismicity structure with the threshold magnitude M_{th} = 3.9 has been forming in this area. Interestingly, the seismicity ring runs across the Koyna Dam. The strongest earthquake in the seismicity ring occurred in 1980 (M = 5.5). Note that few relatively deep-focus earthquakes are recorded in this area.

Nurek Reservoir Area

Figure 3 shows the epicenters of shallow earthquakes with $M \geq 4.5$ recorded in the region of Tajik Depression and South Tien Shan (37.5°–39.5° N, 68.5°–71.0° E) beginning from 1973. There we can clearly distinguish the seismicity ring with a submeridional major axis (L ~ 100 km). The structure was formed in 1979–2015, and its largest earthquakes (M = 5.0) occurred in 1993 and 1998. Note that the Nurek Dam is also located at the margin of the seismicity ring. The strongest earthquake within a 60-km radius from the dam was 5.3 in magnitude.

It was shown in (Kopnichev and Sokolova, 2016) that the deep-seated (h = 34–70 km) ring-shaped structure was formed in the studied area. Interestingly, the shallow and deep seismicity rings cross in the vicinity of the dam.

Sarez Lake Area

Figure 4a shows the epicenters of shallow (h = 0–33 km) earthquakes with $M_{\text{th}} \geq 5.0$ recorded from January 1, 1950, to December 6, 2012, in the most part of the Pamirs (36.5°–39.0° N, 71°–74° E). We can clearly distinguish the seismicity ring with a sublatitudinal major axis (L ~ 140 km). The epicenters of both the Sarez earthquake of February 18, 1911 (M_w = 7.2) and the Pamir earthquake of December 7, 2015 (M_w = 7.2, h = 22 km) fall at the boundary of this ring-shaped structure; the Usoi Dam is also located near it. It follows from the data shown in Fig. 4b that the seismicity ring began to form in 1954, and the strongest (M = 6.0)

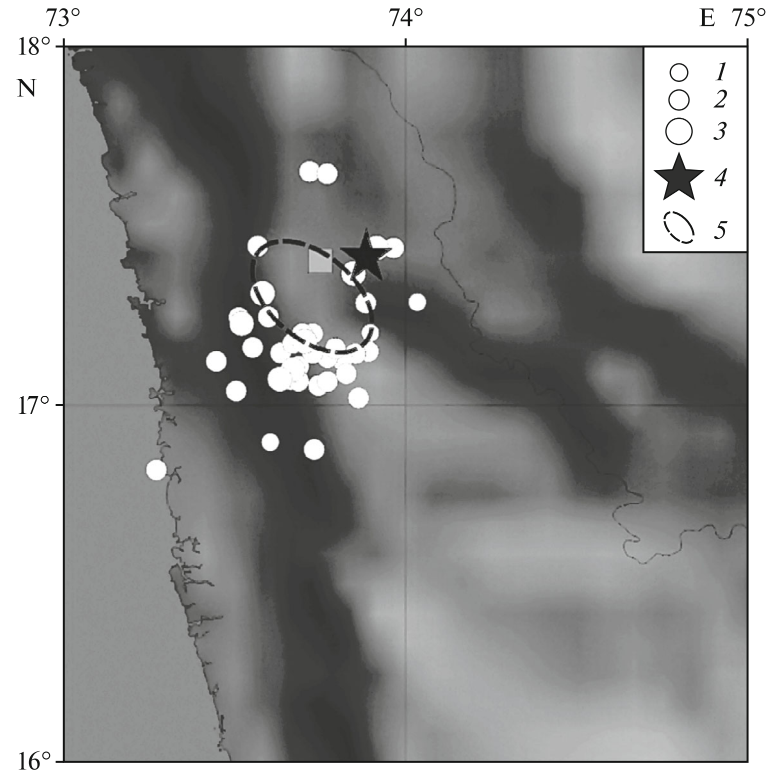


Fig. 2. Seismicity in the studied region of Western India (0–33 km depth). (*1–4*) Earthquake epicenters: (*1*) $M = 3.5$–3.9; (*2*) $M = 4.0$–4.9; (*3*) $M = 5.0$–5.9; (*4*) $M = 6.6$; (*5*) shallow ring-shaped structure.

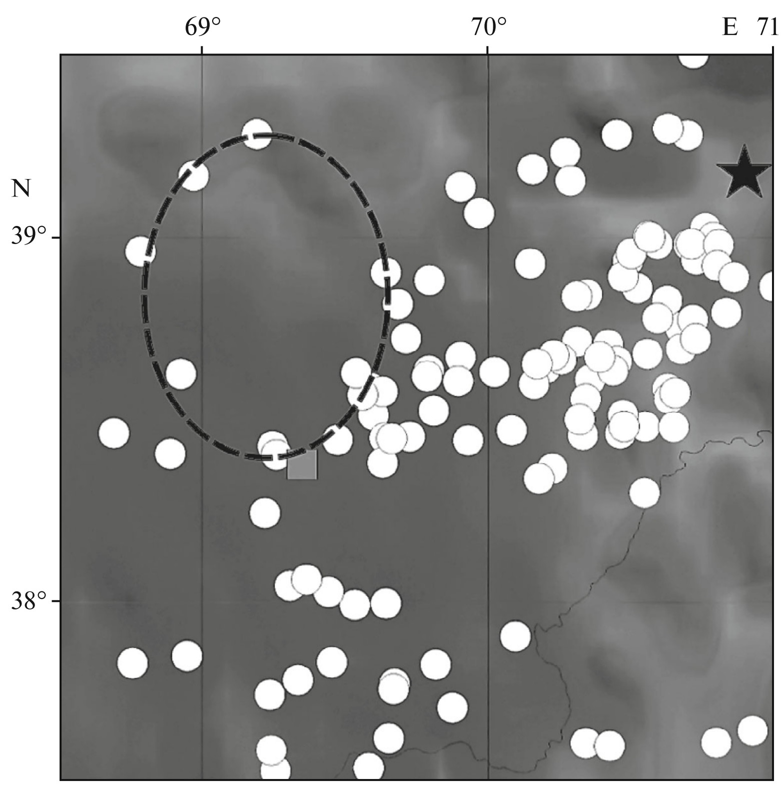


Fig. 3. Shallow seismicity in the studied region of Tajikistan ($M \geq 4.5$). Legend is the same as Figs. 1 and 2. Star denotes the epicenter of the 1949 Khait earthquake ($M_w = 7.6$).

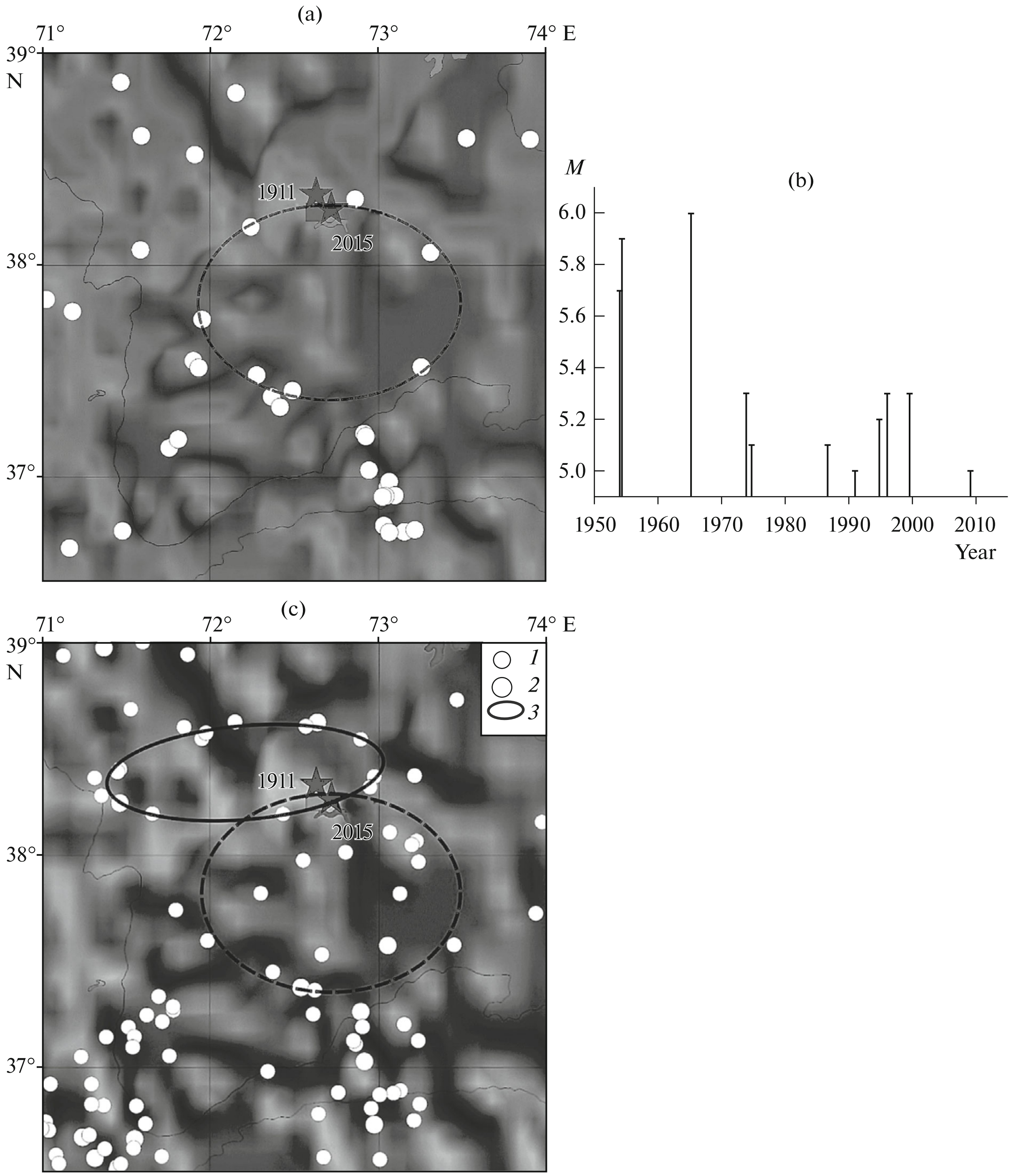


Fig. 4. Shallow seismicity ($M \geq 5.0$) in the studied region of Pamir (a), dependence of $M(T)$ in the area of ring-shaped structure (b), and elements of seismicity at 34–70 km depth (c). (*1*, *2*) Earthquake epicenters: (*1*) $4.4 \leq M \leq 4.9$; (*2*) $M \geq 5.0$; (*3*) deep ring-shaped structure. The remaining symbols are the same as in Figs. 1 and 2.

seismic event at its boundary (until 2015) occurred in 1965. Note that in this case the duration of the seismicity ring formation (T_{th} ~ 61 years) is much longer than the respective period for other large intracontinental earthquakes—no more than 40 years as a rule, according to (Kopnichev and Sokolova, 2010, 2013, 2016).

Figure 4c depicts relatively deep-focus (h = 34–70 km) seismicity recorded in this area since 1973. In this case, we can see the narrow seismicity ring with a sublatitudinal major axis (M_{th} = 4.4, L ~140 km), formed mainly north of the shallow-focus ring in 1989–2014. The largest earthquake within this seismicity ring (M = 5.6) was recorded in 2010. It should

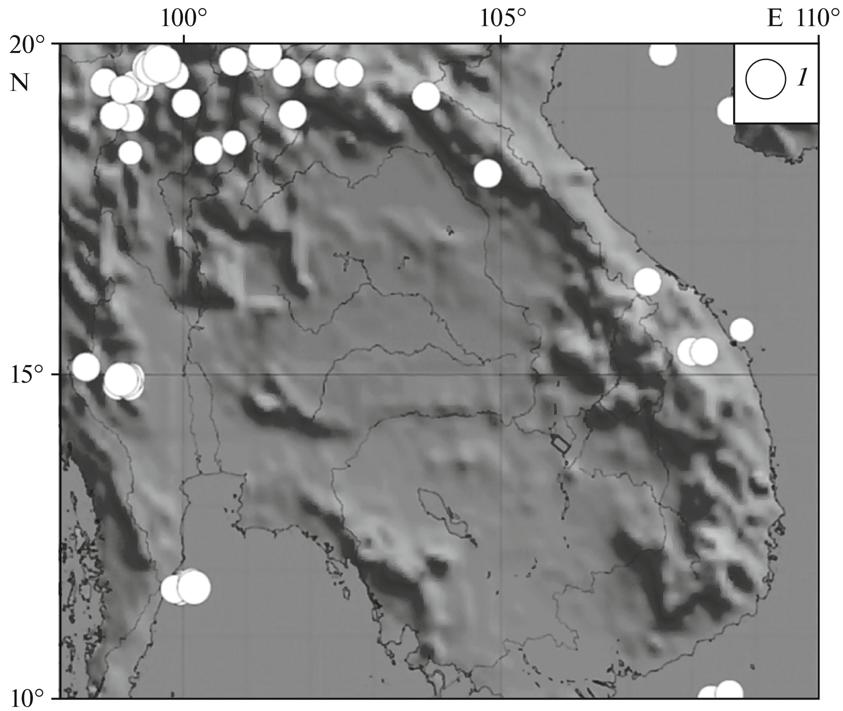


Fig. 5. Seismicity in the studied region of Southeast Asia (0–33 km depth). (*1*) Epicenters of earthquakes with $M > 6.0$. The remaining symbols are the same as in Fig. 2.

be noted that the shallow and deep rings cross at ~72.2° and 72.8° E, with the epicenter of the Pamir earthquake of December 7, 2015, and the Usoi Dam being located at the distances of ~10 and 15 km, respectively, from the eastern intercept of the rings.

It was shown earlier (Kopnichev and Sokolova, 2016) that the given area was remarkable for relatively deep-focus (110–125 km) seismicity, which was very likely related to the filling of Sarez Lake.

Southeast Asia

Figure 5 shows the distribution of shallow (h = 0–33 km) earthquakes with $M \geq 3.5$ recorded in Southeast Asia (10°–20° N, 98°–110° E) beginning from 1960. The absolute majority of epicenters form the ring-shaped structure with a NW-elongated major axis (L ~ 1300 km). The Khone Falls is located within the seismicity ring, and the nearest earthquake epicenters (east of it) are at the distance of ~200 km. Remarkably, earthquakes as small as $M \geq 3.0$ have not been recorded within the 200-km radius from the waterfall. The largest earthquake with M = 6.1 occurred in the northwestern margin of the seismicity ring in 2014. Note that all relatively large seismic events with $M \geq 5.0$ were recorded at significant distances—about or more than 500 km—from the Khone Falls. This area is characterized by a small number of recorded earthquakes at depths of 34–70 km, and all of them occurred at considerable distances from the waterfall.

Dworshak Reservoir Area

Figure 6 shows the earthquakes with $M \geq 3.0$ in the vicinity of the Dworshak Dam beginning from 1973. Despite the fact that the given area is located in a mountain region (branches of the Rocky Mountains), quite low seismicity is observed here. It follows from the data shown in this figure that there was the only earthquake with M = 3.8 at the distance of up to 50 km from the dam for the 43-year period (occurred in 1998).

Niagara Falls Area

Figure 7a shows the epicenters of shallow (h = 0–33 km) earthquakes with $M \geq 4.0$ that occurred in the vicinity of the waterfall (39°–49° N, 72°–82° W) beginning from 1973. This area is located on the ancient North American Craton; however, it demonstrates quite significant seismic activity. The absolute majority of epicenters form a ring-shaped structure with a submeridional major axis (L ~ 800 km). Interestingly, Niagara Falls is located within the seismicity ring, at the distance of about 150 km from its western boundary. The strongest of the mapped earthquakes were 5.0 to 5.2 in magnitude. It follows from the data shown in Fig. 7b that a small number of earthquakes

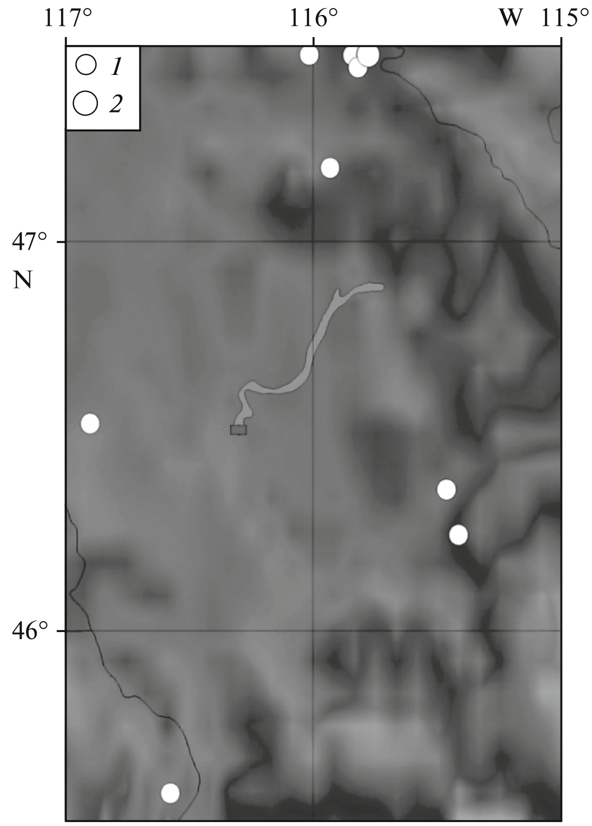


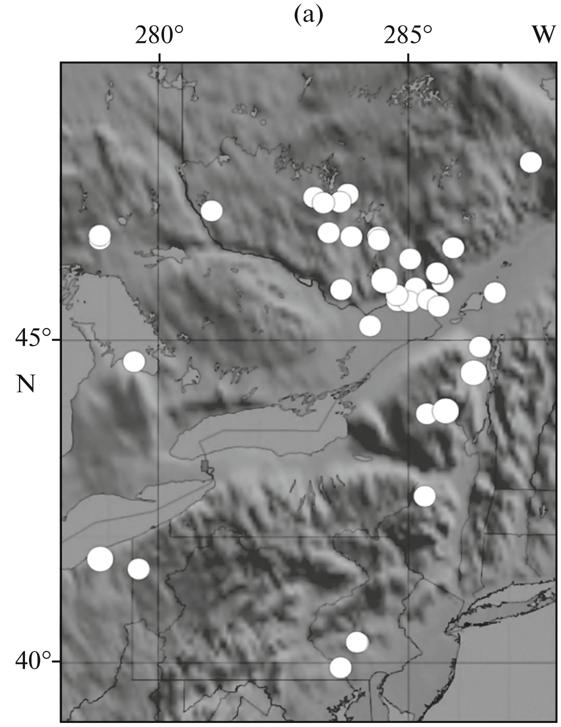
Fig. 6. Seismicity in the studied region of North America. Earthquake epicenters: (*1*) $3.0 \leq M \leq 3.9$; (*2*) $M \geq 4.0$.

with $M = 3.5$–3.9 are recorded within the ring-shaped structure, and the largest of them ($M = 3.7$) was recorded at the distance of 60 km from Niagara Falls in 1999. It can also be noted that no relatively deep-focus earthquakes ($h = 34$–70 km) have been recorded here since 1960.

Figure 8 presents the dependence of the maximum magnitudes ($M_{\max}$) for earthquakes occurring at distances of up to 60 km from dams and waterfalls on the average water flow rate. The data shown in this figure suggest that a smaller water flow rate corresponds to a higher $M_{\max}$.

DISCUSSION

One of the significant factors affecting the level of seismicity in the studied areas is the capacity of artificial and natural reservoirs. The data in Table 1 show that the lowest values of $M_{\max}$ were observed in the vicinities of two waterfalls with no large artificial reservoirs nearby. The additional load of water mass in reservoirs, which is in many cases as large as many billions of tons, leads to the disturbance of the equilibrium state of the crust. The medium tends to pass to a new equilibrium state, partially by slow viscous flow and partially by the increase in level of seismicity. The contribution of viscous flow is indicated by, in particular, ongoing subsidence of the bed of the Nurek Reservoir in Tajikistan, which has lasted for several



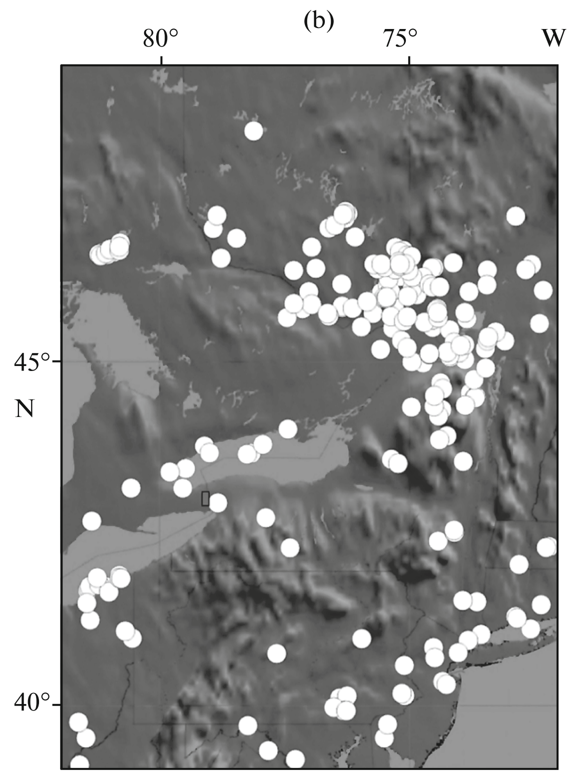


Fig. 7. Relatively large earthquakes (a) and weak ones ($M = 3.5$–3.9) (b) in the studied region of North America (0–33 km depth). Legend for panel (a) is the same as in Fig. 1.

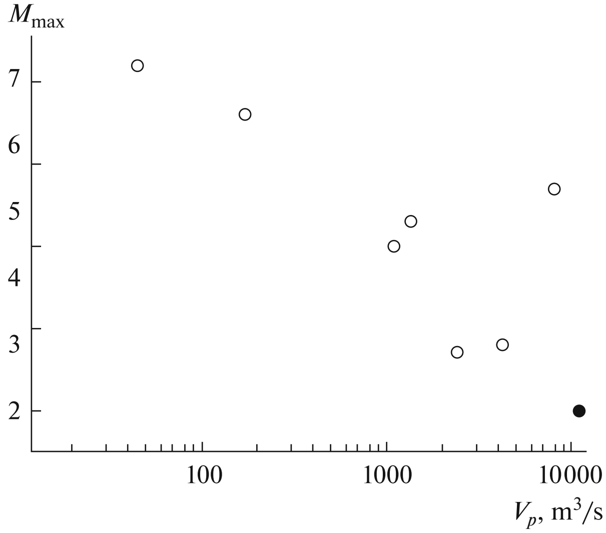


Fig. 8. Dependence of M_{max} on average water flow in the considered waterfalls and reservoirs. Filled circle means the upper estimate of M_{max} for the near vicinity of the Khone Falls.

decades (Mirzoev et al., 2009). One of the mechanisms stimulating viscous deformation can be dehydration of crustal and mantle rocks (Raleigh and Paterson, 1965; Yamazaki and Seno, 2003; Jung et al., 2004). Water release during dehydration leads to the decrease in viscosity of the medium (Kalinin et al., 1989). In addition, the important consequence of dehydration is that rocks get brittle and the seismicity level temporarily grows (Raleigh and Paterson, 1965; Yamazaki and Seno, 2003; Jung et al., 2004). Such effects most likely explain activation of deep-focus seismicity in Tajikistan: at depths down to 125 km in the area of Sarez Lake and down to 70 km in the area of the Nurek Reservoir (Kopnichev and Sokolova, 2016).

Note that the appearance of relatively large fluid volumes as a result of dehydration stimulates their vertical migration, which in turn causes, in particular, formation of ring-shaped seismicity structures (Kopnichev and Sokolova, 2009, 2010, 2013, 2016). Ascent of fluids is a reflection of self-organization processes in geological systems (Letnikov, 1992), which eventually lead to reduction of potential energy of the Earth. Interestingly, when seismicity rings form (Figs. 2–4), dams fall at their boundaries.

Migration of water from new reservoirs along fault zones and fractures (including those stretching in the horizontal direction) leads to seismic activation at relatively shallow depths both beneath reservoirs and in their near vicinity; this is what is classically understood to be induced seismicity (Simpson and Negmatullaev, 1981; Kissin, 1982; Mirzoev et al., 2009).

It follows from the data from Table 1 and the data shown in Fig. 8 that the largest magnitudes of earthquakes recorded near dams and waterfalls correlate to water discharge in them: as V_p declines, M_{max} grows, and vice versa. The weakest seismic events occurred in the area of the Khone Falls (Southeast Asia), where the water discharge was maximal, whereas the largest one occurred near the Usoi Dam in the Pamirs, where water discharge was very low. For the areas in the vicinity of five large dams, the smallest magnitudes corresponded to three structures (Kariba, Nurek, and Dworshak dams), where water discharge are the greatest. The water discharge serves as a measure of vibration of the Earth's surface produced by falling water in the areas where dams and waterfalls are located. As is known, permanent vibration and microseisms lead to the increase in contribution of viscous deformation and the decrease in level of seismicity (Barabanov et al., 1987; Mirzoev et al., 1987, 2009; Deshcherevskii et al., 2015, Kolosova et al., 2015). Vibration caused by falling water is recorded at quite large distances; for example, amplitudes of these vibrations in the area of the Nurek Dam can exceed the regular level of microseismic noise at distances of up to 25 km (Mirzoev et al., 2009). Hence, the main factor determining the level of seismic activity in the areas under consideration is the synergetic effect of additional load from the water mass in reservoirs and permanent vibration from falling water.

The unusual earthquake with M_w = 7.2 that occurred in the Central Pamir on December 7, 2015, should be considered in particular. The peculiarities making this seismic event unusual are the location of its source near that of the 1911 Sarez earthquake, high magnitude, and considerable hypocentral depth. As was mentioned above, the earthquake that occurred in 1967 in the area of the Koyna Dam $M = 6.6$ was considered the strongest one related to induced seismicity until 2015. Therefore, energy of the 2015 Pamir earthquake exceeds that of the Koyna earthquake by almost an order of magnitude. As was stated above, the peculiarity of the 2015 Pamir earthquake is the location of its source near the lake, characterized by a quite large capacity but very weak vibration upon escape of water through the Usoi Dam. It was shown in (Kopnichev and Sokolova, 2016) that, despite the quite deep hypocenter of the 2015 Pamir earthquake, the probability that this seismic event is not related to Sarez Lake (and therefore to induced seismicity) is negligibly small. Thus, the 2015 Pamir earthquake is currently the largest seismic event that occurred as a result of reservoir filling.

The data considered above indicate that there is a clear deficit of relatively large ($M \geq 4$) earthquakes in the vicinity of the two largest waterfalls (Khone Falls and Niagara Falls). However, earthquakes with $M \geq 5$ are recorded in the vicinity of Victoria Falls. In our opinion, this difference in seismicity is related to the following. There is the Kariba Reservoir, the largest artificial water body in the world, relatively close to the

Victoria Falls. After filling of the Kariba Reservoir, a sequence of relatively large earthquakes occurred beneath it and in the near vicinity (Fig. 1). At the distance of ~320 km from the Kariba Dam, the band of earthquake epicenters related to the reservoir turns northwestward, to Victoria Falls. There are solid reasons to think that this effect is also related to the influence of permanent vibration of the Earth's surface due to falling water. It is known that relatively weak vibration increases the rock permeability. Since this effect has been revealed even in model experiments (Barabanov et al., 1987), it can logically be expected at small depths (of few kilometers) in the crust where the pressure of the water column eases its horizontal migration. It seems that the inverse L-shaped earthquake band stretching from the Kariba Dam to Victoria Falls is related to seepage of water along cracks and faults into the upper crust and to its further horizontal diffusion (Rojstacher and Wolf, 1992). It is characteristic that the last remarkable earthquake in the vicinity of the waterfall occurred as long ago as 1991. In this respect, we can suppose that the crust in the vicinity of the waterfall passed to a new equilibrium state by the early 1990s.

In contrast to Victoria Falls, the Khone Falls and Niagara Falls are located in the areas where there are no large artificial reservoirs from which water could slowly migrate toward the waterfalls. In such a case, the leading role is played by the effect of permanent vibration due to falling of large volumes of water. We can suppose that, as a result of vibration in the near vicinity of the Khone Falls and Niagara Falls, which has lasted for quite a long time (about 10 kyr for Niagara Falls (Calkin and Brett, 1978)), in the absence of additional supply of water to the upper crust (as in the case of Victoria Falls), the medium passed to the equilibrium state a long time ago; therefore, relatively strong earthquakes do not occur here.

The presented data allow us to make certain conclusions about the magnitudes of possible large earthquakes in the areas of existing and designed dams. It seems that the largest seismic events can occur in the areas of water reservoirs characterized by quite large capacity and relatively low water discharge.

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