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Activation of Seismicity in Central and South Asia after the Makran Earthquakes: Possible Acceleration of Preparation of Large Seismic Events in the Tien Shan Region

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Abstract—Two zones of seismicity (ten events with M_w = 7.0–7.7) stretching from Makran and the Eastern Himalaya to the Central and Eastern Tien Shan, respectively, formed over 11 years after the great Makran earthquake of 1945 (M_w = 8.1). Two large earthquakes (M_w = 7.7) hit the Makran area in 2013. In addition, two zones of seismicity ($M \geq 5.0$) occurred 1–2 years after the Makran earthquake in September 24, 2013, stretching in the north-northeastern and north-northwestern directions. Two large Nepal earthquakes struck the southern extremity of the "eastern" zone (April 25, 2015, M_w = 7.8 and May 12, 2015, M_w = 7.3), and the Pamir earthquake (December 7, 2015, M_w = 7.2) occurred near Sarez Lake eastw of the "western" zone. The available data indicate an increase in subhorizontal stresses in the region under study, which should accelerate the possible preparation of a series of large earthquakes, primarily in the area of the Central Tien Shan, between 70° and 79° E, where no large earthquakes ($M_w \geq 7.0$) have occurred since 1992.

Keywords: seismicity, Central and South Asia, 2013 Makran earthquakes, 2015 Pamir earthquake
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INTRODUCTION

The relation between the characteristics of seismicity in areas located at considerable distances from each other is presented in different works. For example, it is shown in (Triep and Sykes, 1997) that the number of events with $M \geq 7.0$ sharply decreased in the whole Asian region after the Great Assam Earthquake of August 15, 1950 (M_w = 8.6). It was established that after the great deep-focus Hindu Kush earthquakes (the Hindu Kush area is hit by 10–40 earthquakes every year), large crustal events with $M \geq 7.0$ often happen in Central and South Asia for 4.5 months (Kopnichev et al., 2002). In addition, after two seismic events, such as the large deep-focus Hindu Kush earthquake and the largest earthquake in the Altai area, a moderate intensity earthquake ($M \geq 6.0$) is usually recorded for 1.5 years in the North Tien Shan (Kopnichev and Sokolova, 2006). The increase in the number of relatively weak events in different areas of the Earth was noted after the catastrophic Tohoku–Oki earthquake in Japan on March 11, 2011 (M_w = 9.0) (Gonzales-Huizar et al., 2012).

Below we consider seismicity variations in Central and South Asia after quite large earthquakes with M_w = 8.1 and 7.7 that occurred in the Makran region (southern Iran and southern Pakistan) in 1945 and 2013, respectively. Special attention is paid to analysis of the data on rupture zone of the Pamir earthquake of December 7, 2015 (M_w = 7.2) that occurred near Sarez Lake, which began to be filled in after the large earthquake of February 18, 1911 (M_w = 7.2).

BRIEF GEOLOGICAL AND GEOPHYSICAL CHARACTERISTICS OF THE STUDIED AREA

We considered the seismicity characteristics in the large region of Central and South Asia confined to the coordinates of 20°–50° N, 60°–96° E. The tectonics and seismicity of the region under study are determined mainly by the northward movement of the Indian Plate, as well as by subduction of the Arabian Sea beneath South Asia (Molnar and Tapponnier, 1975). The western boundary of the Indian Plate is the largest Chaman left-lateral strike-slip fault (Fig. 1). The collision between the Indian and Eurasian plates caused the formation of the hugest mountainous systems in Central and South Asia: Pamir–Hindu Kush, Tien Shan, Kunlun, Karakorum, Himalaya, the Indo-Burman ranges, as well as the planet's largest Tibetan Plateau.

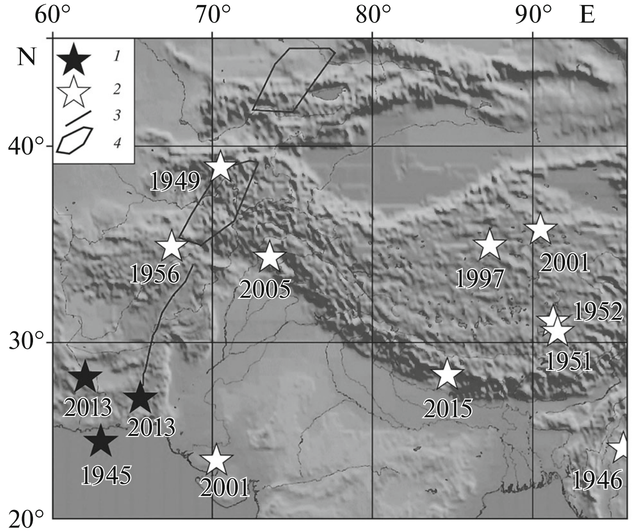

Fig. 1. Map of region under study. Epicenters of great earthquakes starting from 1940 ($h = 0–90$ km). (*1*) Makran earthquakes (M_w = 7.7–8.1); (*2*) earthquake with M_w = 7.5–7.8 (years of these events are indicated); (*3*) Chaman strike-slip fault; (*4*) zones of large attenuation.

The region is characterized by very high seismicity. Since 1946, it has been hit by 12 large shallow earthquakes with $M_w \geq 7.5$ and one relatively deep earthquake (the Makran earthquake of April 16, 2013, $M_w = 7.7$, $h =$ 82 km, Table 1, Fig. 1). The Makran earthquake of November 27, 1945 ($M_w = 8.1$) was the largest of them (Rajendran et al., 2008). This event had an thrust type mechanism typical of subduction zones. The majority of the great earthquakes, including the 1948 Khait earthquake ($M_w = 7.6$), the 2001 Bhuj earthquake ($M_w = 7.6$), the 2005 Kashmir earthquake (M_w = 7.6), and the 2015 Nepal earthquake ($M_w = 7.8$), had the of reverse fault, oblique reverse fault, or oblique thrust mechanisms. The Makran earthquakes of April 16, 2013 ($M_w = 7.7$, $h =$ 82 km) and September 24, 2013 ($M_w = 7.7$) stand out against this background. The first of the earthquakes had a normal fault mechanism, and the second one, a left-lateral strike-slip mechanism. It is important that the event of September 24, 2013, occurred at the southern extremity of the Chaman strike-slip fault (Fig. 1).

Table 1. Great earthquakes in Central Tien Shan and South Asia starting from 1940

Date	Coordinates, deg		h, km	M_w
	N	E		
Nov. 27, 1945	24.5	63.0	15	8.1
Sep. 12, 1946	24.1	95.7		7.7
Jul. 10, 1949	39.0	70.5	16	7.6
Nov. 18, 1951	31.1	91.3	30	7.7
Aug. 17, 1952	30.6	91.6	25	7.7
Jun. 9, 1956	35.03	67.48	35	7.6
Nov. 8, 1997	35.11	87.37	24	7.5
Jan. 26, 2001	23.40	70.28	16	7.6
Nov. 14, 2001	35.95	90.54		7.8
Oct. 8, 2005	34.46	73.58	19	7.6
Apr. 16, 2013	28.11	62.05	82	7.7
Sep. 24, 2013	26.95	65.50	15	7.7
Apr. 25, 2015	28.23	84.73	8	7.8

Areas with high attenuation of shear waves in the Hindu Kush, Pamirs, and Central Tien Shan were identified in (Kopnichev and Sokolova, 2010). The analysis showed that these areas are associated with the presence of a noticeable share of fluids in the lithosphere. It follows from the data in Fig. 1 that the indicated areas were formed by the northeast-striking zones located on the continuation of the Chaman strike-slip fault.

MATERIALS OF STUDIES

We analyzed seismicity data from the catalogs (*Novyi katalog* ..., 1977; Engdahl and Villasenor, 2002) and catalogs of National Earthquake Information Center (NEIC) of the U.S. Geological Survey starting from 1940. We considered the characteristics of large ($M_w \geq 7.0$) earthquakes with focal depths primarily less than 90 km in the Central and South Asia region confined to the coordinates of 20°–45° N, 60°–96° E. We also analyzed NEIC data on weaker events ($M = 4.0–6.9$, $h = 0–33$ km) that occurred in the same region in 1973–2015.

DATA ANALYSIS

Large Earthquakes

Figure 2 shows the position of the epicenters of the large events ($M_w \geq 7.0$) that occurred after the 1945 Makran earthquake until 1956 inclusive (Table 2). It is seen that two zones of epicenters elongated in the north-northeast and north-northwest directions formed over 12 years. The western zone that appeared in 1945–1956 spreads from the margin of the Arabian Sea through the Hindu Kush and Pamirs to the Central Tien Shan. In the northern portion of this zone, there is a big "gap" related mostly to the Chaman strike-slip fault. The eastern zone that formed in 1946–1952 spreads from the Indo-Burman ranges through Himalaya to southern Tibet and then to the

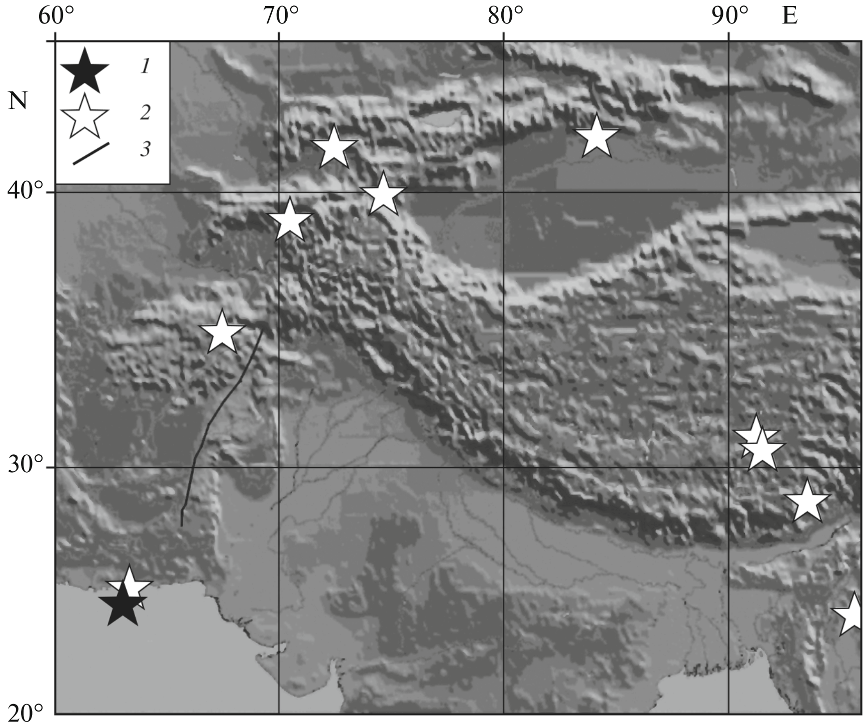

Fig. 2. Epicenters of large earthquakes that occurred in Central and South Asia in 1945–1956 (h = 0–33 km). (*1*) Makran earthquake (M_w = 8.1); (*2*) earthquakes with M_w = 7.0–7.7; (*3*) Chaman strike-slip fault.

Eastern Tien Shan (with a gap of ~1500 km in the comparatively low seismicity areas of Tibet and Tarim).

We analyzed the data on the large events that occurred in two regions bounded by 35°–45 N, 65°–75° E and 24°–34° N, 86°–96° E, respectively. The first region included the earthquakes that occurred in Pamirs, and Hindu Kush, and Central Tien Shan; the second one contained the events in the Indo-Burman ranges, Himalaya, and southern Tibet. These regions were hit by the greatest number of large earthquakes over 11 years after the 1945 Makran earthquake.

Figures 3 and 4 show the positions of the epicenters of the earthquakes that occurred before December 10, 2015, and the time dependences of their magnitudes in the two regions under consideration. The epicenters of seven large earthquakes fell within the first region (Fig. 3, Table 2). It is important to note that four of them, including two with M_w = 7.6 are close to the 1945 Makran earthquake in time (they were recorded in 1946–1956) and only three occurred much later, in 1974 (Makransu), 1992 (Susamyr), and 2015 (Pamir). Interestingly, four foci tend to the zones of high *S*-wave attenuation in the lithosphere of the Hindu Kush, Pamirs, and the Central Tien Shan.

We estimate the probability of four out of six large events randomly falling into the 11-year time interval after the 1945 Makran earthquake. (We do not take the 2015 Pamir event into account here, since it occurred after the 2013 Makran earthquakes.) This probability is expressed by the formula

$$P_{4,\,6} = C_6^4(11/70)^4(59/70)^2 \sim 6 \times 10^{-3}. \quad (1)$$

Five events with $M_w \geq 7.0$ occurred in the second region (Fig. 4, Table 3). Here, four of them fell within a 7-year interval after the 1945 Makran earthquake. The probability of them randomly falling into this interval is

$$P_{4,\,5} = C_5^4(7/70)^4(63/70) \sim 5 \times 10^{-4}. \quad (2)$$

Table 2. Large earthquakes in first region

Date	Coordinates, deg		h, km	M_w
	N	E		
Nov. 2, 1946	41.50	72.50	30	7.3
Jul.10, 1949	39.00	70.50	16	7.6
Apr 15, 1955	39.90	74.70	20	7.0
Jun. 9, 1956	35.03	67.48	35	7.6
Aug. 11, 1974	39.38	73.80	3	7.1
Aug. 19, 1992	42.11	73.61	13	7.2

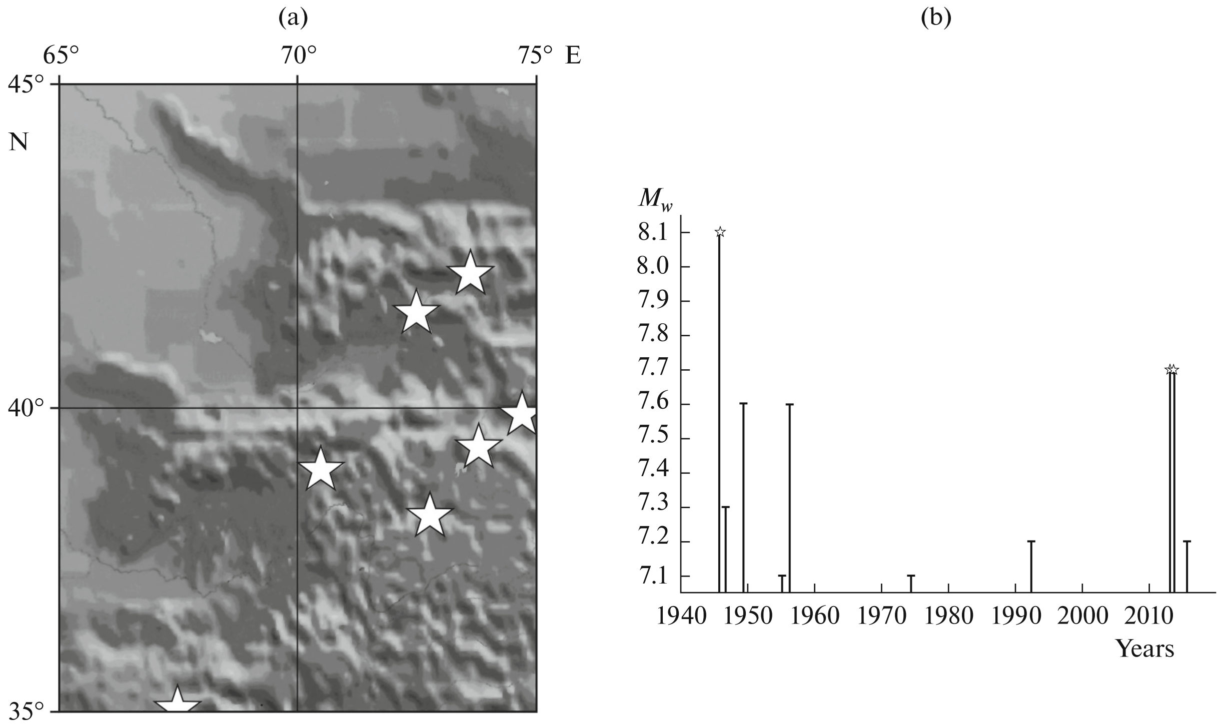

Fig. 3. (a) Epicenters of large earthquakes and (b) time dependence of magnitudes of large events in region of Pamir—Hindu Kush and Central Tien Shan (first region) since 1945. Asterisks represent Makran earthquakes.

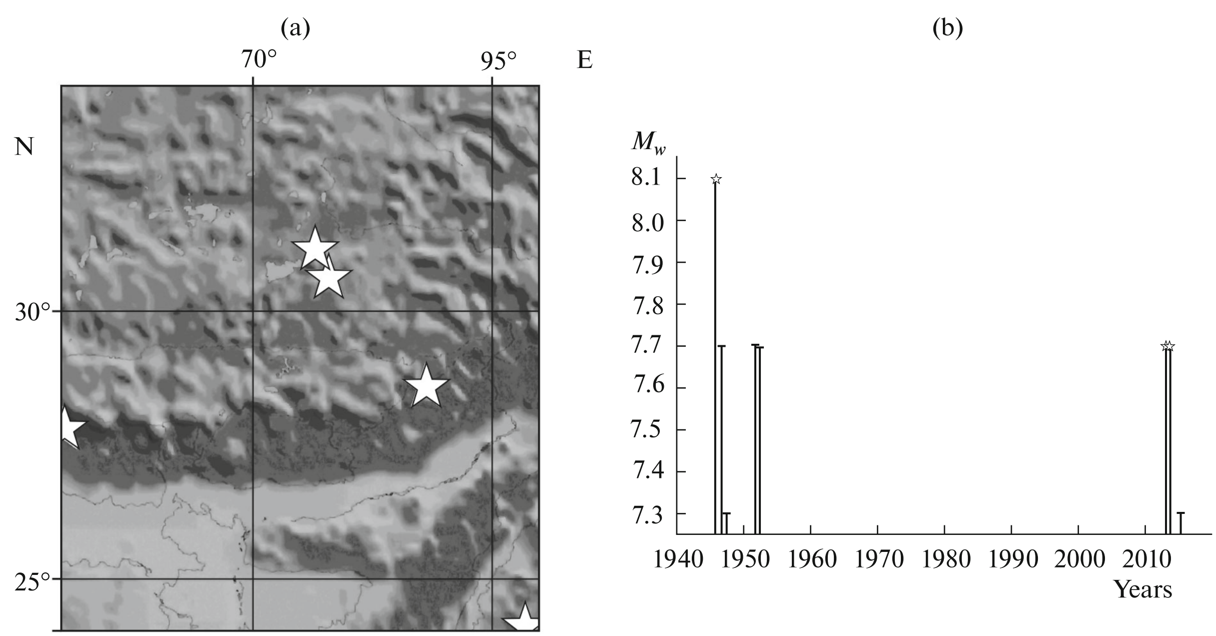

Fig. 4. (a) Epicenters of large earthquakes and (b) time dependence of magnitudes of large events in region of Indo-Burman ranges, Himalaya, and Southern Tibet (second region) since 1945. Asterisks represent Makran earthquakes.

From this it follows that the total probability of random occurrence of large earthquakes in the two indicated regions 11 and 7 years, respectively, after the 1945 Makran earthquake is negligibly small.

Seismicity after the Makran Earthquake of September 24, 2013

First, we consider the data on the shallow (h = 0–33 km) events with $M \geq 4.8$ that occurred in the region confined to 20°–50° N, 60°–96° E from September 24, 2013, until September 1, 2014. They are presented in detail in (Kopnichev and Sokolova, 2014). Figure 5 shows the aftershock region of the Makran earthquake of September 24, 2013 (16 events were recorded here). In addition, it clearly demarcates the two seismicity zones with big gaps in low seismicity regions. The first zone strikes north-northeast, spreading from the coast of the Arabian Sea through the Makran earthquake focus and the West Tien Shan towards central Kazakhstan. It is important that it is located quite close to the west zone shown in Fig. 2. The second zone oriented in the north-northwest direction intersects the Eastern Himalaya, Tibet, Kunlun, the west of Tarim and the northern Tien Shan. This zone includes the focal zone of a rather large earthquake of February 12, 2014 (M_w = 6.9) in the Kunlun area. This structure is located west of the eastern zone (Fig. 2) and runs parallel to it. We can consider that the both zones that comprise more than 80% of the epicenters of the total quantity of earthquakes in Fig. 5 intersect each other in a low seismicity area of central Kazakhstan. We suggested in (Kop-

Table 3. Large earthquakes in second region

Date	Coordinates, deg		h, km	M_w
	N	E		
Sep. 12, 1946	24.1	95.7	15	7.7
Jul. 29, 1947	28.6	93.6	20	7.3
Nov. 18,1951	31.1	91.3	30	7.7
Aug. 17, 1952	30.6	91.6	25	7.7
May 12, 2015	27.81	86.07	15	7.3

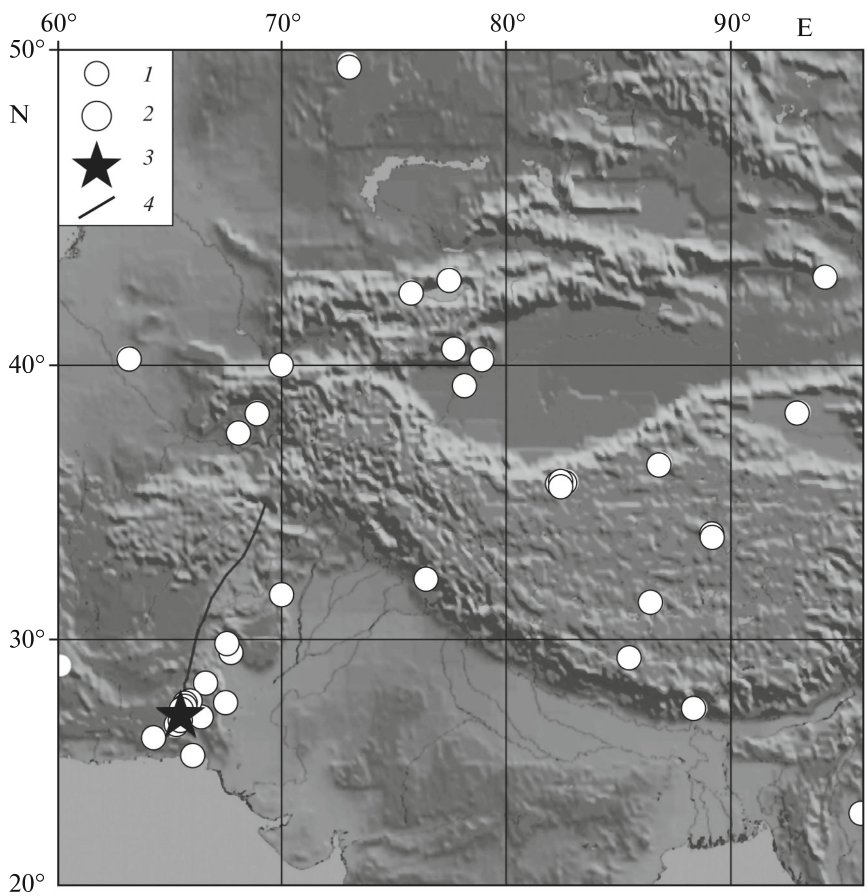

Fig. 5. Seismicity after Makran earthquake of September 24, 2013 (until September 1, 2014) (h = 0–33 km). (*1*) Earthquakes with M = 4.8–6.0; (*2*) earthquakes with $M_w \geq 6.5$; (*3*) epicenter of Makran earthquake of September 24, 2013; (*4*) Chaman strike-slip fault.

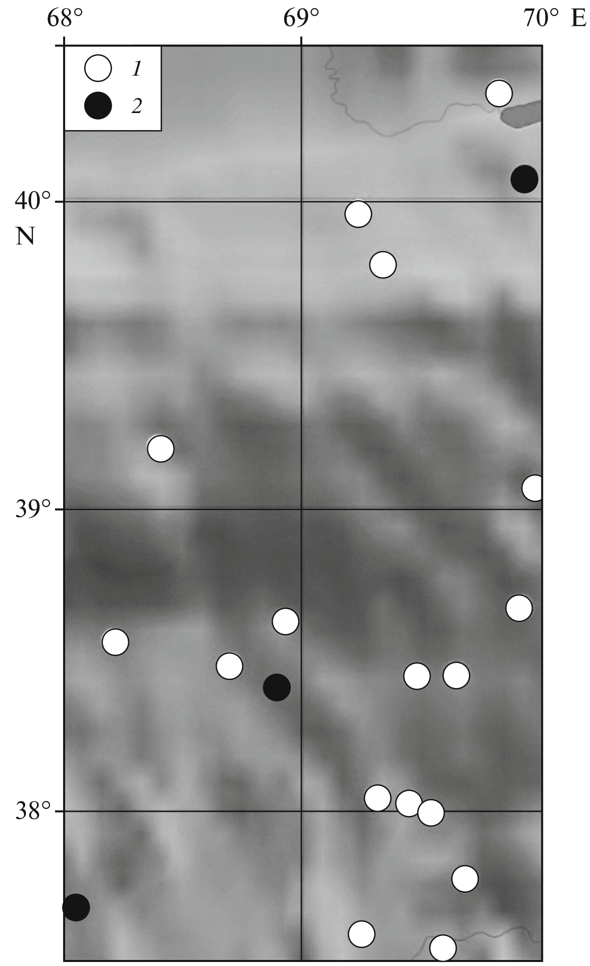

Fig. 6. Seismicity ($M \geq 4.9$) in region of Western Tien Shan and Tajik Basin since January 1, 1973 (*1*) before and (*2*) after Makran earthquake of September 24, 2013.

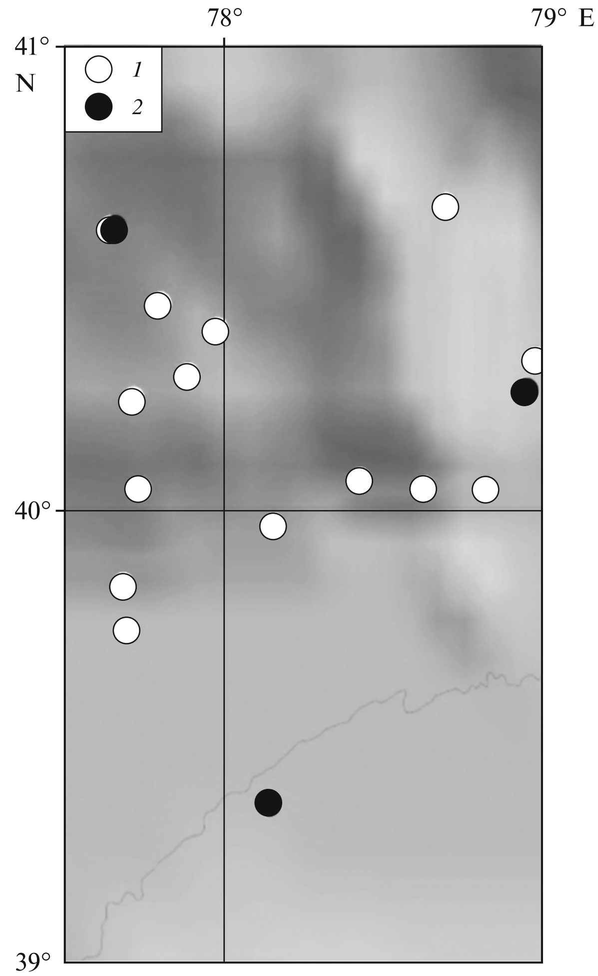

Fig. 7. Seismicity ($M \geq 5.0$) in region of Southern Tien Shan and Tarim from January 1, 1973 (*1*) before and (*2*) after Makran earthquake of September 24, 2013.

nichev and Sokolova, 2014) that by analogy with the series of events in 1946–1956 after the 2013 Makran earthquakes, the sudden activation of seismicity could be expected in the region bounded by these zones.

We consider some elements of these zones in more detail. Figure 6 shows the seismicity characteristics (for events with $M \geq 4.9$) in the central portion of the first zone (~120 km wide) from January 1, 1973, to September 1, 2014. It is seen that there were only ten such events here ($M_{max} = 5.6$), three of which ($M =$ 4.9–5.2) occurred from September 24, 2013, to December 6, 2013. We estimate the probability of random occurrence of three out of ten events over 2.5 months after the Makran earthquake of September 24, 2013:

$$P_{3,\,10} \sim C_{10}^{3}(2.5/500)^3(497.5/500)^7 \sim 1.5 \times 10^{-5}. \quad (3)$$

Figure 7 illustrates the data on seismicity in the region of the Southern Tien Shan and northwestern Tarim. Starting from January 1, 1973, 17 earthquakes have occurred here with $M \geq 5.0$ ($M_{max} = 5.9$), three of which ($M =$ 5.0–5.4) happened from September 24, 2013, until July 9, 2014. The probability of their random occurrence over 10 months is

$$P_{3,\,17} \sim C_{17}^{3}(10/500)^3(490/500)^{14} \sim 4 \times 10^{-3}. \quad (4)$$

And finally, according to the instrumental and historical data, there was only one event with $M > 4.0$ (June 21, 2014, $M = 4.8$) in the low seismicity region of central Kazakhstan with coordinates of 49°–52° N, 70°–75° E for at least 200 years (*Novyi katalog*..., 1977). The probability of its random occurrence is

$$P_{1,\,1} < \sim 0.75/200 \sim 4 \times 10^{-3}. \quad (5)$$

It follows from estimates (3)–(5) that the full probability of random occurrence of seven events in three stated regions over 10 months after the Makran earthquake of September 24, 2013, was negligibly small.

Figure 8 shows the seismicity characteristics ($M \geq$ 5.0, $h = 0$–33 km) in the region under study from Sep-

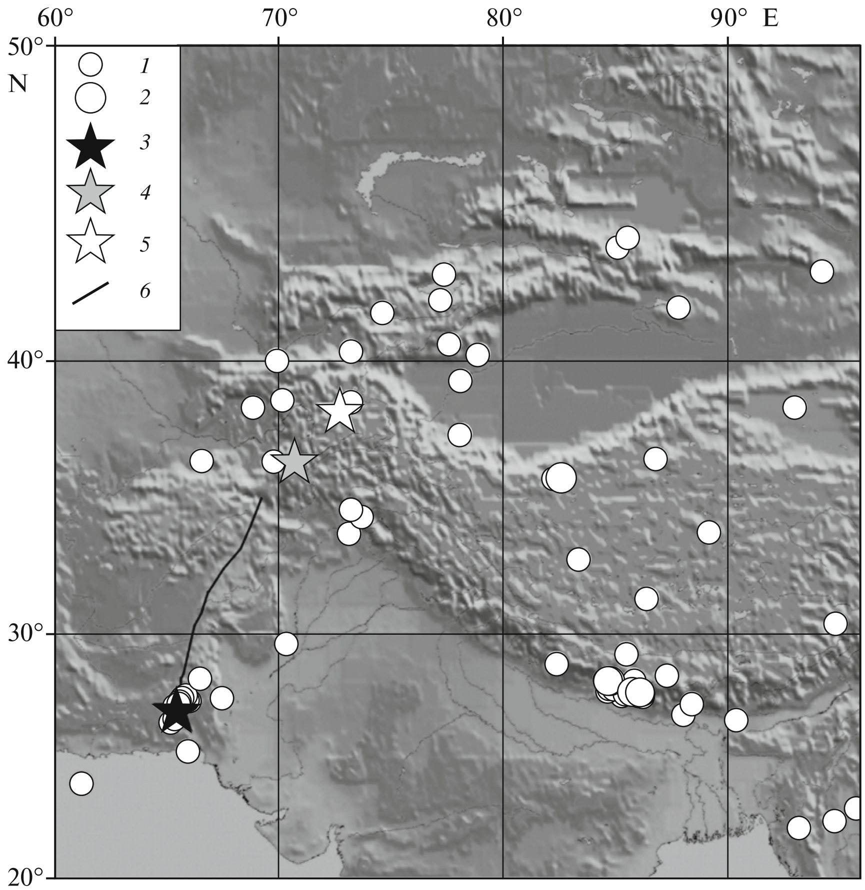

Fig. 8. Seismicity (h = 0–33 km) after Makran earthquake of September 24, 2013 (until December 10, 2015). (*1*) Earthquakes with M = 5.0–6.5; (*2*) earthquakes with $M_w \geq 6.5$; (*3*) epicenter of Makran earthquake of September 24, 2013; (*4*) epicenter of Hindu Kush earthquake of October 26, 2015, h = 231 km; (*5*) epicenter of Pamir earthquake of December 7, 2015; (*6*) Chaman strike-slip fault.

tember 24, 2013, to December 10, 2015. We mention that two powerful earthquakes accompanied by numerous aftershocks (M_w was 7.8 and 7.3, respectively) hit the southern flank of the eastern zone in the area of Nepal (Fig. 8) on April 25, 2015, and May 12, 2015. The earthquake of April 25, 2015, occurred in the area where events of such force had not been known from the instrumental and historical data (Rajendran et al., 2013). Comparison of the data presented in Figs. 5 and 8 shows that after September 1, 2014, the zones of seismicity started "spreading out" and a noticeable quantity of epicenters appeared in the region between them. Of special interest is the Pamir earthquake of December 7, 2015 (M_w = 7.2), which occurred less than 1.5 months after the great Hindu Kush earthquake of October 26, 2015 (M_w = 7.5, the hypocentral depth is 231 km, Fig. 8). Let us study the seismicity characteristics in the focal area of this event in more detail.

Figure 9 shows the epicenters of the Pamir earthquake of December 7, 2015, and its aftershocks ($M \geq 4.0$) recorded before December 15, 2015. It is seen that the cloud of aftershocks ~75 km long is elongated in a northeast direction. The earthquake focal mechanism is almost pure strike-slip, where one of the possible nodal planes coincides with the strike of the cloud of aftershocks. We note that this event occurred near the epicenter of the 1911 Sarez earthquake, after which Sarez Lake was formed as a result of the largest Usoi avalanche, which blocked the Murgab River.

DISCUSSION

The obtained data indicate that seismicity was suddenly stirred up in two zones extending from the Hindu Kush to the Central Tien Shan and from the Indo-Burman ranges to southern Tibet, respectively, over 11 years after the great 1945 Makran earthquake. Estimates (1) and (2) show that it was highly unlikely that four large earthquakes with M_w = 7.1–7.6 and four with M_w = 7.3–7.7 could occur occasionally in the western and eastern zone, respectively, in that period. Thus, there is a space-time relationship

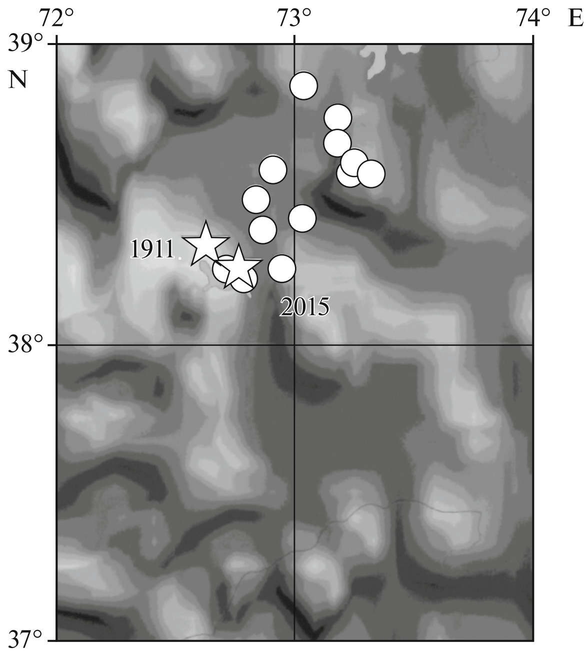

Fig. 9. Aftershock region of Pamir earthquake ($M \geq 4.0$) until December 17, 2015. Asterisks designate epicenters of events in 1911 and 2015.

between the 1945 Makran earthquake and the large events in the indicated regions.

Let us discuss the possible mechanism of this relationship. It follows from the data in Fig. 1 that the zone containing the foci of the large earthquakes that occurred in 1946–1956 is located at the continuation of the Chaman strike-slip fault. We can suggest that the movement during the subduction type Makran earthquake led to the acceleration of slow creep displacements along the Chaman strike-slip fault (Furuya and Satyabala, 2008), which resulted in the increase in shear stresses northeastward of the fault.

In addition to it, the foci of the described events tend to the zones of high attenuation of *S*-waves in the lower crust and the upper mantle (Kopnichev and Sokolova, 2010). These zones of the indicated region are related to the presence of a noticeable share of fluids that provide smaller viscosity to the lower lithosphere. In turn, the low viscosity determines the relatively high deformation rate and an additional increase in shear stresses. It is known that a connected fluid-filled net of pores and fractures is formed under the action of shear stresses (Hier-Majumder and Kohlstedt, 2006). This leads to the gradual formation of a two-phase layer having a considerable vertical length in the lower crust and the upper mantle, which concentrates the stresses on its roof (Gold and Soter, 1984/1985). For a sufficient thickness of this layer, the stresses exceed the strength limit of rocks, which causes movement during a large earthquake.

An increase in the deformation rate at the western boundary of the Indian Plate should lead to an increase in stresses in the lithosphere and at its eastern boundary. In our opinion, this might be the reason for seismic activation in the region between the Indo-Burman ranges and southern Tibet (Fig. 2).

There are grounds to believe that a similar mechanism could also have been implemented after the two great Makran earthquakes of 2013. This is proved by a series of three large events with $M_w = 6.9–7.8$ in the region of the eastern zone, as well as by moderate earthquakes in the low seismicity regions after September 24, 2013. It is noteworthy that in our previous work (Kopnichev and Sokolova, 2014), we concluded that there was a high probability that large shallow earthquakes could occur in seismicity zones and between them several years after the 2013 Makran earthquakes. Thus, we can state that this prediction was partially fulfilled as a result of the occurrence of two large events in 2015 in the Himalaya and one event in the Pamir area.

It is interesting that unlike the series of events in 1946–1952, a new eastern zone of seismicity has been significantly displaced to the west. We can assume that the redistribution of stresses in the upper segment of the lithosphere after the great surge in seismic activity at the eastern boundary of the Indian Plate in 1946–1952, which also included the great Assam earthquake of August 15, 1950, led to the fact that the formation of a new eastern zone of seismicity extending from the Himalaya to the Central Tien Shan became more beneficial energetically. By analogy with the series of earthquakes in 1946–1956, after the events of April 25, 2015, and May 12, 2015, in the southern flank of the eastern zone of seismicity and the Pamir earthquake of December 7, 2015, a boost in seismicity is expected in the near future in the region of the closest approach of two seismicity zones in the Central Tien Shan (approximately between 70° and 79° E), where no events with $M_w \geq 7.0$ occurred after the 1992 Susamyr earthquake. This episode of activation can last for ~10–12 years (until approximately 2024) like after the 1945 Makran earthquake.

Therefore, note that the great Hindu Kush earthquake that occurred on October 26, 2015, likely markedly accelerated the preparation of the large crustal event of December 7, 2015, in the Pamir area. This is evidenced by the results of (Kopnichev et al., 2002), where crustal earthquakes with $M \geq 7.0$ were shown to occur frequently in Central and South Asia 4.5 months after large deep-focus Hindu Kush events.

We should also mention that the great Makran earthquakes, as well as the deep-focus Hindu Kush events, serve only as a trigger that accelerates the preparation of large earthquakes in a large region of Central and South Asia. Fluids rise slowly in the lithosphere over a long time, and the tectonic structure should be ready to react to the change in the stress field. It is significant in this respect that way back in (Kopnichev and Sokolova, 2007), we identified fluid-rich zones of high attenuation of shear waves in the Central Tien Shan area and also ring structures of seismicity in recent years (Kopnichev and Sokolova, 2014), which are usually exhibited before large crustal earthquakes. The data indicate that constant monitoring of the different geophysical and geochemical fields is required here for medium-term prediction of large earthquakes.

We turn our special attention to the Pamir earthquake of December 7, 2015. It occurred near Sarez Lake, a unique natural basin that started to be filled in 1911; its water level rose until at least 2000. At the present time, the lake exceeds 500 m in depth and the total volume of water accumulated reaches 17 km^3. The duration of lake filling is greater by an order of magnitude compared to the respective values for the majority of existing artificial water reservoirs. We know that in man-made water reservoirs, there is the effect of induced seismicity, which consists in a sharp increase in the quantity of recorded earthquakes as a result of their filling (Kissin, 1982). The great such event was the 1967 earthquake in the Koyna Dam area ($M = 6.6$), which occurred in a low seismicity zone in India. The induced seismicity is assumed to manifest itself as a result of gravity load of a water volume and/or penetration of water into deeper crustal layers through faults and fractures (Kissin, 1982). If the 2015 Pamir earthquake is also associated with the filling of Sarez Lake, it will become the great seismic event of this type known today. It is not improbable that its energy is explained by the very long duration of filling of the water reservoir and its considerable depth, which results in facilitation of fluid rise from the lower crust and the upper mantle to the middle crust.

It is considered that the possible destruction of an Usoi avalanche or a new rock slide to the lake may cause a very large ecological catastrophe in regions located along the Bartang, the Panj, and the Amu-Darya rivers, which has a population of over 6 mln people. According to available reports, the intensity of the Pamir earthquake in the region of Sarez Lake remained anomalously low (5–6 points on the MSK scale); therefore, as a result of this event, the Usoi Dam fortunately suffered little. Unexpected effects of such low shaking intensity in the region of Sarez Lake requires a separate detailed analysis. Here, we only note that the high water content in the upper crust caused by its vertical and horizontal migration as a result of the large additional load from Sarez Lake may serve as one of the possible reasons for this effect. It is known that considerable water content leads to a sudden increase in attenuation of short-period *S*-waves, which yield the greatest amplitudes of large motions (Aptikaev, 2012).

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