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Ring Structures of Seismicity in Central Tien Shan and Dzungaria: Possible Precursory Processes of Large Earthquakes

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Abstract—It is shown that episodes of comparative seismic quiescence that lasted about 20–25 years in the areas of study alternated with intervals of sharply increased seismicity as series of large ($M \geq 6.9$) earthquakes occurred during two to three decades. Since no $M \geq 6.6$ earthquake has occurred in the area for as long as 21 years after the 1992 Susamyr event, middle-term prediction would require identification of zones of imminent large earthquakes. More reliable identification of such zones rests on data relating to inhomogeneities in the field of S-wave attenuation in the lithosphere, as well as on the characteristics of ring structures of seismicity. Such structures are formed as zones of seismic quiescence that are bounded by $M \geq$ Mth earthquake epicenters, where Mth is the threshold magnitude value. Correlative relationships were previously derived, lgL(Mw) and Mth(Mw), for events with different focal mechanisms (L is the length of the longer axis of a seismicity ring and Mw is the magnitude of the associated large earthquake). These relationships were used to estimate the Mw of large events that can occur in these ring structures. The greatest earthquake with Mw $\gtrsim 7.5$ is probably about to occur in southern Tien Shan, east of the 1949 Khait earthquake rupture. A smaller event (Mw ~ 7.0) can occur in the Kyrgyz Range area. Still smaller earthquakes probably have their precursory areas north and east of Lake Issyk-Kul, as well as in Dzungaria.

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INTRODUCTION

It has been shown [Lu et al., 1984; Sobolev, 1993; Kopnichev and Mikhailova, 2000; Kopnichev and Sokolova, 2010d, 2013] that seismic ring structures were formed in intracontinental regions during several decades before many large earthquakes. Such structures are composed of epicenters of $M \geq$ Mth events, where Mth are threshold magnitudes. It was found that the lengths of the longer axes of these seismicity rings (L), as well as Mth, persistently increase with increasing energy of the associated mainshock earthquakes [Kopnichev and Mikhailova, 2000; Kopnichev and Sokolova, 2010, 2013]. In addition, there is some evidence to show that the quantities L and Mth significantly depend on the focal mechanism of the associated large seismic event [Kopnichev and Sokolova, 2013]. This makes it possible to try to predict the locations and energies of future large earthquakes based on characteristics of the ring structures [Kopnichev and Sokolova, 2011a]. With this goal in view, we now consider seismicity characteristics in central Tien Shan and in Dzungaria (west of 81° E).

HISTORICAL SEISMICITY

The area of study (39°–45° N, 70°–81° E) has generated 13 $M \geq 6.9$ earthquakes since 1885 (Table 1, Fig. 1), with the greatest being those in 1889 ($M = 8.3$), 1902 ($M = 8.1$), and 1911 ($M = 8.2$). It follows from Table 1 and Fig. 1 that clusters of large earthquakes occurred in the late 19th and 20th centuries (1885–1911, 1938–1955, and 1974–1992). These clustering episodes lasted for 17 to 26 years and were separated by intervals of relative quiescence that lasted for about 27 and 19 years. There have been no $M > 6.6$ events in Tien Shan for 21 years following the 1992 magnitude 7.3 Susamyr earthquake. In view of that fact, it may be hypothesized that the area is one of active precursory processes before several large earthquakes.

METHOD OF RESEARCH

Kopnichev and Sokolova [2010a, 2010b] and Kopnichev et al. [2012] found that the rupture zones of large earthquakes usually exhibit strong attenuation of short-period shear waves in the lithosphere. This effect is caused by concentration of deep-seated fluids in the lower crust

Table 1. Large ($M \geq 6.9$) earthquakes in central Tien Shan from the late 19th century until the present

Name	Date	Latitude, φ, N	Longitude, λ, E	M
Belovodskoe	Aug. 2, 1885	42.7	74.1	6.9
Vernyy	June 8, 1887	43.10	76.80	7.3
Chilik	July 11, 1889	43.20	78.70	8.3
Kashgar	Aug. 22, 1902	39.80	76.20	8.1
Kemin	Jan. 3, 1911	42.90	76.90	8.2
Kemin–Chu	June 20, 1938	42.70	75.80	6.9
Chatkal	Nov. 2, 1946	41.90	72.00	7.5
Khait	July 10, 1949	39.20	70.80	7.4
Ulugchat	Apr. 15, 1955	39.90	74.60	7.1
Markansu	Aug. 11, 1974	39.39	73.86	7.3
Zhalanash–Tyup	Mar. 24, 1978	42.88	78.58	7.0
Kashgar	Aug. 23, 1985	39.37	75.44	7.0
Susamyr	Aug. 19, 1992	42.07	73.63	7.3

and upper mantle in such regions. In this connection we sought to identify prediction-related ring structures with higher reliability by considering seismicity characteristics primarily in those zones where S-wave attenuation anomalies were observed. This is certain to eliminate "false" ring structures from the analysis, i.e., ones that are unrelated to the precursory processes of large earthquakes [Rong et al., 2003].

Inhomogeneities of the S-wave attenuation field in the lithosphere of central Tien Shan. Figure 3 shows a map of the attenuation field in the lithosphere of central Tien Shan based on an analysis of records of local earthquakes that were made at the MKAR station in 2003–2009 [Kopnichev and Sokolova, 2010a]. We used a method based on the analysis of the amplitude ratio between Sn and Pn waves that propagate in the upper mantle (the Sn/Pn parameter). It is apparent from this map that an extensive region of high attenuation can be identified between 73° and 76° E in the area of the Kyrgyz mountain range and adjacent parts of the Chu and Ili basins. We note that most of this area is the intervening space between the rupture zones of the Kemin quake (1911, $M = 8.2$) and the Susamyr event (1992, $M = 7.3$). Smaller anomalies were found at the boundary between Dzungaria and the Ili basin (between 77° and 78° E), in the Kokshaal mountain range area (between 80° and 81°), as well as at the boundary between Tien Shan and the Pamirs (between 71.5° and 73° E). In addition, some smaller areas of low Sn/Pn values are identical with the rupture zones of two large earthquakes (the magnitude 7.0 1978 Zhalanash-Tyup and the Susamyr earthquake). Based on these facts, we considered seismicity characteristics in zones of high attenuation and around them.

A Method for Identifying Ring Structures

(1) The period for which seismicity characteristics were studied is approximately 40 years, which is in agreement with the longest time of generation of the ring structures [Kopnichev and Sokolova, 2010c, 2010d, 2011a, 2013].

(2) We studied the seismicity parameters in two depth ranges, viz., 0–33 and 34–70 km, where ring structures are formed [Kopnichev and Sokolova, 2009b, 2010c, 2011a, 2013].

(3) Values of the threshold magnitude Mth were explored (in both of the depth ranges) to determine the optimal values that provide for the best identification of ring structures. The criterion was to decide between lesser values of Mth, with the associated seismicity rings becoming "hazy"; greater ones with the structures were delineated considerably more poorly [Kopnichev and Sokolova, 2010d, 2013].

(4) It is necessary (at intervals of about 1 year) to monitor seismicity parameters, since there have been cases of ring structures that appeared for the last 1–2 years with much greater Mth values, as was the case prior to the great Tohoku earthquake of March 11, 2011 [Kopnichev and Sokolova, 2011a].

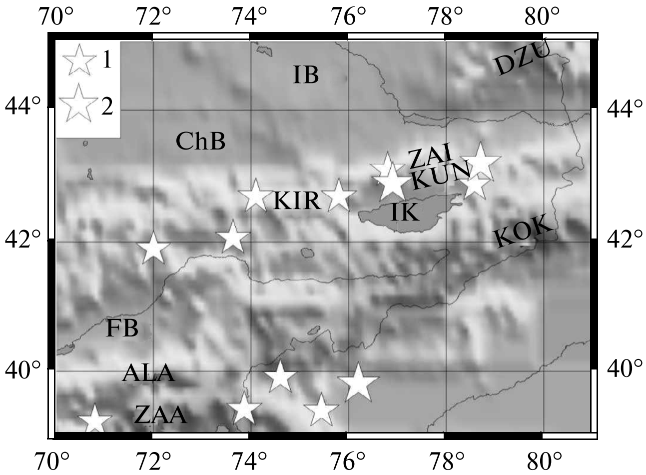

Fig. 1. The epicenters of large earthquakes in central Tien Shan.
(1) M = 6.9–7.5, (2) M > 8.0. The following basins are marked: ChB Chu, IB Ili, FB Fergana, IK Lake Issyk-Kul. Mountain ranges: DZU Dzungarian Alatau, KIR Kyrgyz, ZAI Zaili, KUN Kungei Alatau, KOK Kokshaal, ALA Alai, ZAA Zaalai.

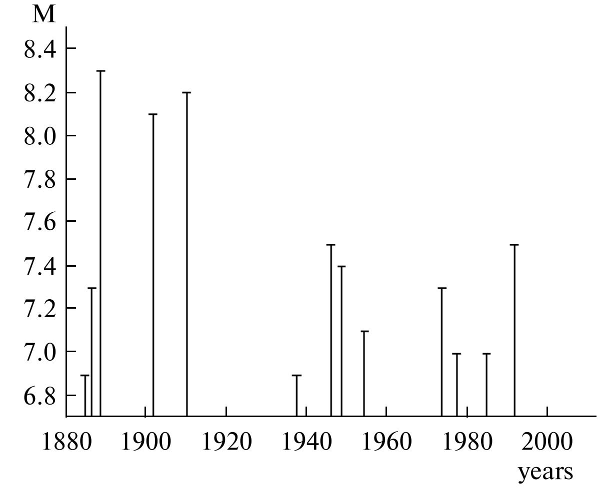

Fig. 2. The magnitudes of large earthquakes over time.

(5) The dimensions of the longer axes of the seismicity rings, L, and the quantities, Mth, were used to estimate the magnitude of a possible large earthquake, taking the dominant focal mechanism into account [Kopnichev and Sokolova, 2013]. With the above arguments taken into consideration, we examined seismicity data for the from period January 1, 1973 to January 1, 2012. We selected the earthquakes with M ≥ Mth in the depth ranges 0–33 and 34–70 km, mostly from the NEIC catalogs of the U.S. Geological Survey (http://earthquake.usgs.gov/earthquakes/search), as well as from the catalogs that were lent to us by the SOME MON RK (the Russian abbreviation for the Seismological Technique Testing Expedition of the Ministry of Education and Science of the Republic of Kazakhstan) (http://www.some.kz).

DATA ANALYSIS

The Kyrgyz Mountain Range area

Figure 4 shows seismicity data for the eastern Kyrgyz Range and around it. From this figure it follows that a large ring structure with the threshold magnitude Mth = 4.5 had formed in the area at depths of 0–33 km by January 1, 2012. In this particular case the seismicity ring, whose longer axis is L ~ 85 km, extends northwest. One notes that the last large earthquake (M ~ 6.5) occurred in the area as far back as the 15th century; the rupture zone of that event contains numerous paleo-dislocation [Krestnikov et al., 1979]. Figure 5 shows the magnitude of the events in the ring structure as a function of time. The plot is U-shaped; it can be inferred from this plot that the rate of seismotectonic deformation (STD) was the highest in 1973–1978 and in 2004–2010. The maximum earthquake magnitude in the seismicity ring is Mmax = 5.1.

The Zaili mountain range area

It follows from Figs. 6 and 7 that a ring structure with a comparatively low Mth (3.7) has been visible in the area at depths of 0–33 km since 1983. The structure is elongate north–northwest (L ~ 90 km). The seismicity ring covers the eastern Zaili Range, a small area of the Kungei Alatau Range, as well as an adjacent part of the Ili basin. Several large earthquakes have occurred in the area since the end of the 19th century. The seismicity ring contains the rupture zone of the 1887 Vernyy earthquake (M = 7.3) to the west and the zone of the 1978 Zhalanash–Tyup earthquake to the southeast (M = 7.0, see Fig. 1). The southern part of the ring structure falls into the rupture zone of the great M 8.2 Kemin earthquake. It can be seen in Fig. 7 that the M(T) relationship is U-shaped, just as in the preceding case. The highest rate of STD was observed in 1983–1988 and in 2007–2011, Mmax = 5.3. It should be noted that the areas considered here contain "shallow" seismicity rings only; "deeper" ones (h = 34–70 km), which are nearly always formed before large and great earthquakes with hypocenters at depths shallower than 40–45 km at subduction zones [Kopnichev and Sokolova, 2009a, 2009b, 2011a, 2011b] did not occur, even in cases of sufficiently low Mth.

Southern Tien Shan

Figure 8 shows seismicity parameters for the area of southern Tien Shan enclosed within 39.0°–40.5° N and 70.0°–72.5° E. A large shallow ring structure with a high threshold magnitude (Mth = 5.2) extending east–west (L ~ 150 km) formed in the area since 1976. The seismicity ring covers the Alai Range and the western margin of

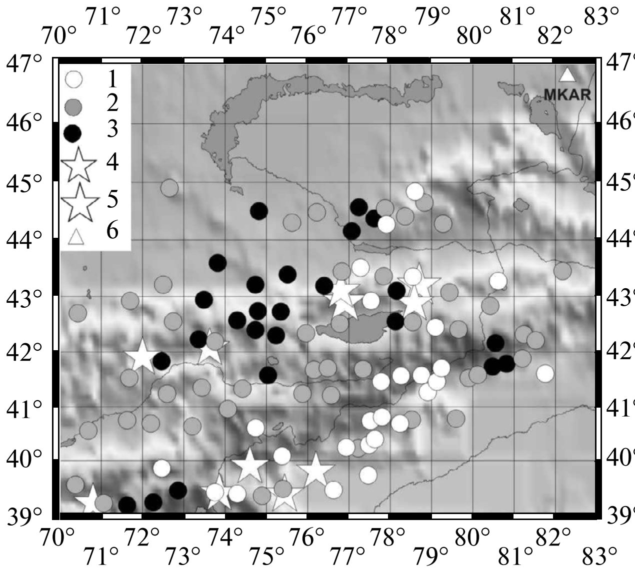

Fig. 3. Inhomogeneities in the S-wave attenuation field in the lithosphere of central Tien Shan.
(1–3) attenuation: (1) low, (2) intermediate, (3) high; (4, 5) epicenters of large earthquakes: (4) $7.0 \leq M < 8.0$, (5) $M > 8.0$; (6) seismic station.

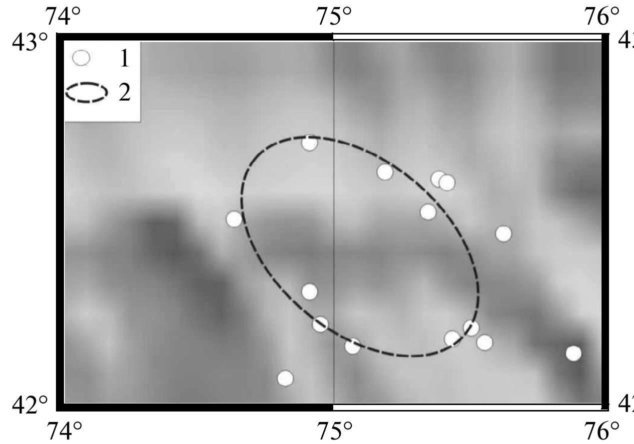

Fig. 4. The ring structure of the seismicity in northern Tien Shan (depth range is 0–33 km). Mth = 4.5.
(1) earthquake epicenters, (2) seismicity ring.

the Zaalai Range. From Fig. 9 it follows that a small deep ring structure (Mth = 4.0) with a longer axis of $L \sim 40$ km was also formed southeast of the minor ring. The ring structures intersect in the area between 71.7° and 72.0° E. We wish to point out that the southern boundary of the shallow ring gave rise to two rather large earthquakes a few decades before it began to form: the 1941 Garm quake (M = 6.4) and the 1949 Khait earthquake (M = 7.5). It is also of interest to note that the areas where the shallow and the deep seismicity ring intersect contain a zone of high-density paleo-dislocation that survived after a large earthquake that took place during Holocene time [Krestnikov et al., 1979].

Figure 10 shows the M(T) relationship for the shallow ring. The plot is also seen to have a U shape. The highest rates of STD were observed in 1976–1984 and in 2002–2011, when four M = 6.0–6.2 events occurred.

Figure 11 shows a map of earthquake epicenters in southern Tien Shan within the coordinates 41.5°–42.5° N and 80.0°–81.5° E. A ring structure had formed in the area since 1995, one that is less well defined compared with the preceding cases. A seismicity ring with the threshold magnitude Mth = 3.6 and a longer axis of about 70 km is elongate nearly east–west in the Kokshaal Range area. From Fig. 12 it can be seen that the STD rate in the ring structure area rose sharply during 2002–2008, Mmax = 4.9.

Dzungaria

Figure 13 shows seismicity characteristics in the region enclosed within 43.5°–45.0° N and 77.0°–78.5° E. Here we used earthquake catalogs compiled by the SOME MON (the Russian abbreviation for the Ministry of Education and Science) RK. A ring structure formed in the area since 1974 with threshold energy class Kth = 9.8, which is equivalent to mb = 3.8. The seismicity ring ($L \sim$ 110 km) is elongate north–northwest. Most of this ring structure is in the southeastern margin of the Kazakh Platform. From Fig. 14 it follows that the highest STD rates occurred in 1973–1986 and in 2000—2011; the value of Kmax was 12.7. We note that the two last cases did not involve deep ring structures, similarly to the northern Tien Shan area.

The magnitudes of the large earthquakes that can occur within the ring structures will be estimated from the data

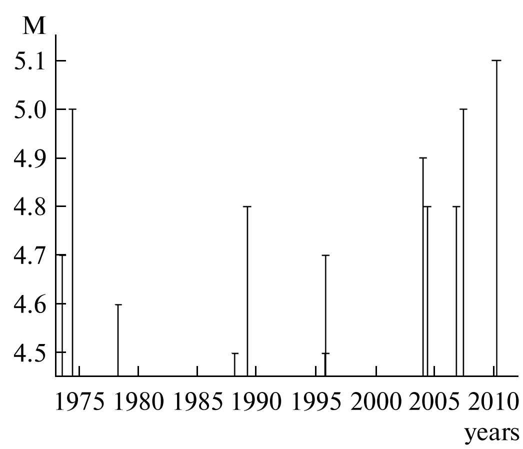

Fig. 5. The magnitude of events as a function of time in the ring structure area.

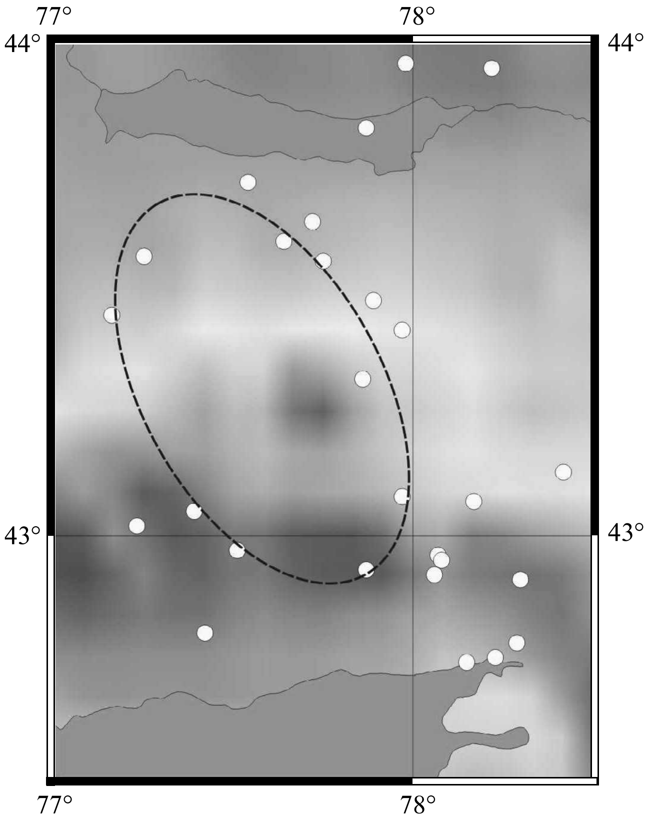

Fig. 6. The ring structure of seismicity in northern Tien Shan, Mth = 3.7. For the legend, consult Fig. 4.

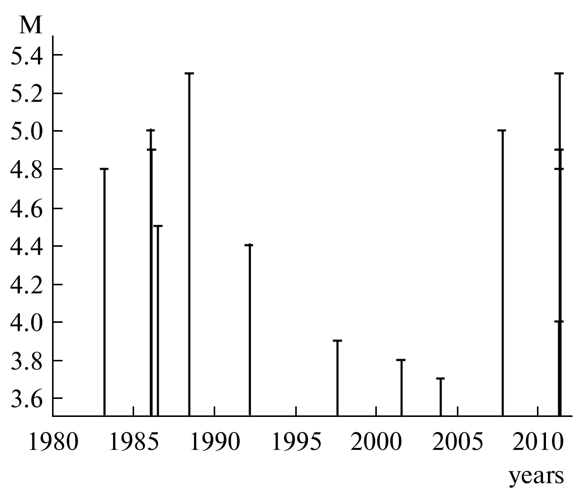

Fig. 7. The magnitude of events as a function of time in the ring structure area.

that were obtained by Kopnichev and Sokolova [2013], who quote correlative relationships of ring-structure size and threshold magnitudes Mth versus main event magnitudes for intracontinental earthquakes with different focal mechanisms. It has been shown [Tapponnier and Molnar, 1979; Poleshko, 2009] that large Tien Shan earthquakes have a reverse and reverse–oblique type of displacement, while those in Dzungaria show strike-slip with a small reverse component. Such types of mechanism were examined by Kopnichev and Sokolova [2013] to derive the following relationships:

for reverse and reverse-oblique mechanisms:

$$\log L(\mathrm{km}) \sim 0.45\mathrm{Mw} - 1.11,\ r = 0.85, \tag{1}$$

$$\mathrm{Mth} \sim 0.73\mathrm{Mw} - 0.92,\ r = 0.77, \tag{2}$$

for strike-slip mechanisms:

$$\log L(\mathrm{km}) \sim 0.49\mathrm{Mw} - 1.12,\ r = 0.94, \tag{3}$$

$$\mathrm{Mth} \sim 0.64\mathrm{Mw} - 0.17,\ r = 0.67 \tag{4}$$

(r is the correlation coefficient).

These formulas were used to estimate the magnitudes of possible large earthquakes in these areas (Table 2). This estimate was based on the assumption of a mean value for Dzungaria and equal probabilities of reverse–oblique and strike-slip displacements.

DISCUSSION

The above results provide evidence of several major ring structures of seismicity in Dzungaria and Tien Shan by early 2012. One important fact is that these structures were observed in regions of high shear-wave attenuation in the lower crust and upper mantle [Kopnichev and Sokolova, 2010a], so that the structures can with more likelihood be classified as zones of precursory processes before large earthquakes. Kopnichev and Sokolova [2009b, 2010c, 2011a, 2011b] pointed out that the appearance of seismicity rings reflected self-organization of geologic structures to provide for the rise of deep-seated fluids; it is these fluids that cause high shear-wave attenuation. The ultimate effect of these processes is to reduce the Earth's potential energy.

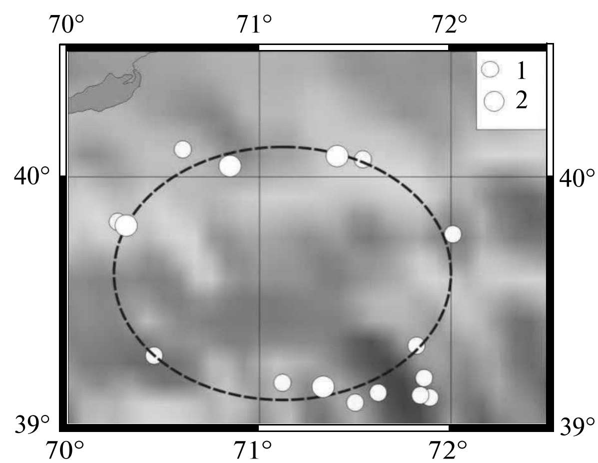

Fig. 8. The shallow (h = 0–33 km) ring structure of the seismicity in southern Tien Shan.
(1) 5.2 ≤ M < 6.0, (2) M ≥ 6.0. The dashed line delineates the seismicity ring.

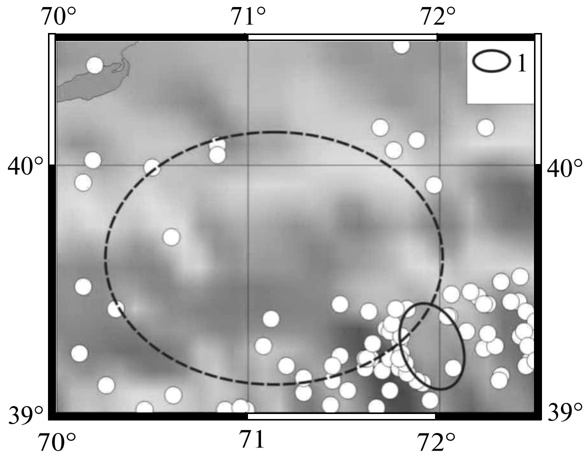

Fig. 9. The deep (h = 34–70 km) ring structure of seismicity (1), Mth = 4.0.
The dashed line delineates the shallow seismicity ring.

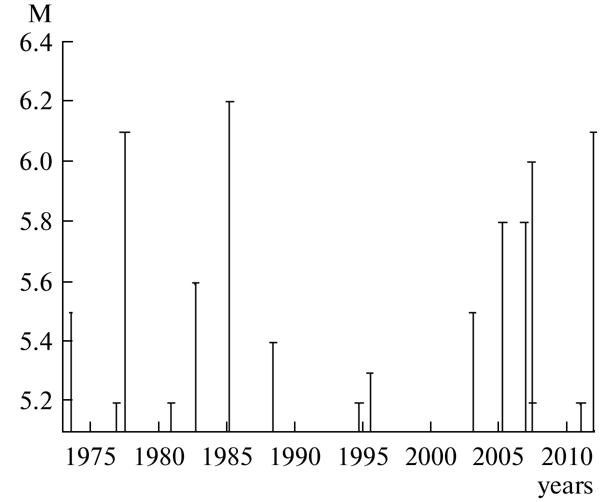

Fig. 10. The magnitude of an event as a function of time in the shallow ring area.

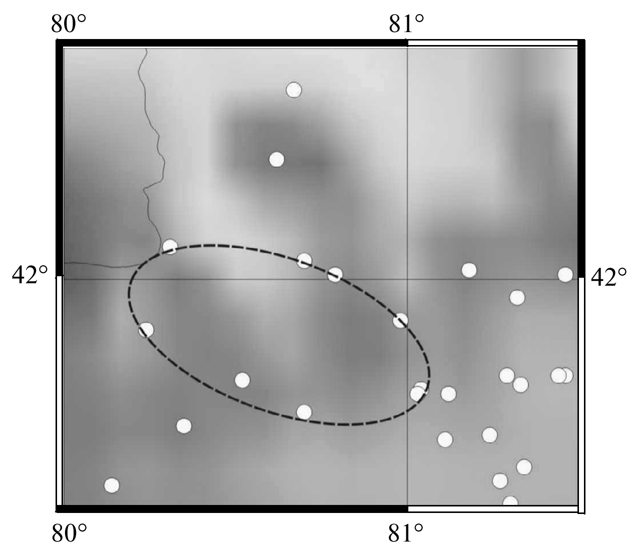

Fig. 11. The ring structure of seismicity in southern Tien Shan. Mth = 3.6. For legend, consult Fig. 4.

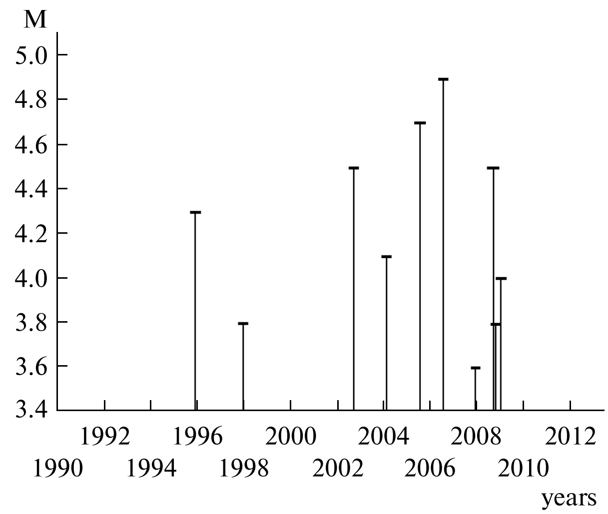

Fig. 12. The event magnitude in the ring structure area as a function of time.

The existence of several major ring structures in Tien Shan and Dzungaria is probably related to the precursory processes leading to the occurrence of series of large earthquakes. As has been remarked, three such series lasting 17–26 years occurred in the late 19th and 20th centuries. The relative quiescence following the Susamyr earthquake has lasted longer than 21 years now, which is similar to the durations for similar episodes during the 20th century. From Table 2 it follows that two earthquakes with Mw ~ 7.1 and 6.6 are likely to occur in northern Tien Shan. The event related to the ring structure that is situated in the Kyrgyz Range area is more likely to occur at the northern boundary of the structure. It is in that area that one observes a high density of seismic paleo-dislocation that is still extant after an M ~ 6.5 earthquake that occurred several hundred years ago [Krestnikov et al., 1979].

A large earthquake in the ring structure north of Lake Issyk-Kul can also occur in the zone of a high density of paleo-dislocation confined to Lake Issyk-Kul in the Zaili Range area [Krestnikov et al., 1979] (the age of this paleo-dislocation is still not known). Another possible area is the Kungei Alatau Range west of the 1990 Baisorun earthquake (M 6.4).

The epicenter of the largest event (Mw = 7.9 ± 0.6) to hit southern Tien Shan must most likely lie near the area where the shallow and the deep ring structures intersect, as is commonly observed in subduction zones [Kopnichev and Sokolova, 2009a, 2009b, 2010c, 2010b,

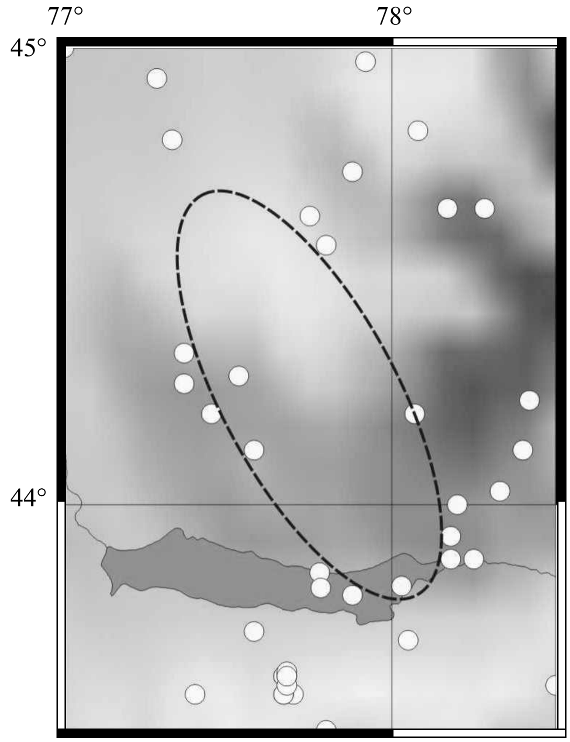

Fig. 13. The ring structure of seismicity in the Dzungaria area, Kth = 9.8.
For legend consult Fig. 4.

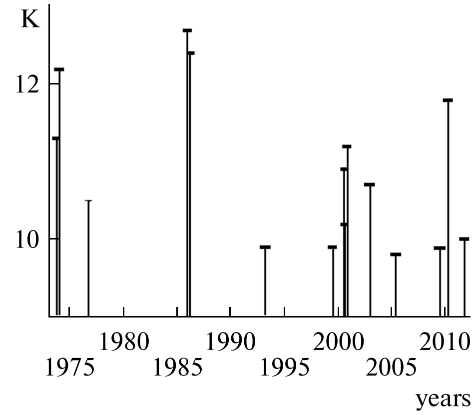

Fig. 14. The value of K as a function of time in the ring-structure area.

2011b]. The rupture zone of such an event fills the area between the Khait (M = 7.5) and the Daraut–Kurgan (1978, M = 6.8) rupture zones. A zone with a high density of paleo-dislocation with an unknown age was also identified [Krestnikov et al., 1979].

A considerably smaller event (M ~ 6.4) may emanate from the ring structure in the Kokshaal Range area. One notes the devastating M ~ 7.5 ± 0.7 Aksu earthquake, which occurred near this structure in 1716, as related in historical records [*Novyi* ..., 1982].

Judging by the dimensions of the ring structure, a comparatively small earthquake (M ~ 6.4) also seems to be about to occur in Dzungaria. We note that no M > 6.5 earthquakes are known to have occurred in the area [*Novyi* ..., 1982]. The rupture zone of such an event are most likely situated about the western boundary of the Dzungarian Alatau mountain range.

From Table 2 it follows that the current time (by early 2012) in the generation of the shallow ring structures considered here, ΔT, varies between 16 and 38 years. One important fact is that the values of ΔT, as estimated for the three seismicity rings in northern and southern Tien Shan

Table 2. The parameters of shallow ring structures and predicted magnitudes of possible large earthquakes in central Tien Shan and Dzungaria

Coordinates		L, km	Mth	Mmax	ΔT, years	Mw	Area
N	E						
42.0–43.0	74.0–76.0	85	4.5	5.1	38	7.1 ± 0.6	north Tien Shan
42.5–44.0	77.0–78.5	90	3.7	5.3	36	6.6 ± 0.3	north Tien Shan
39.0–40.5	70.0–72.5	150	5.2	6.2	35	7.9 ± 0.6	south Tien Shan
41.5–42.5	80.0–81.5	70	3.6	5.2	16	6.4 ± 0.2	south Tien Shan
43.5–44.5	76.5–78.5	100	3.4	4.7	38	6.4 ± 0.3	Dzungaria

ΔT is the current (until January 1, 2012) duration of the generation of a ring structure.

and in Dzungaria (35–38 years), are near the upper bound for the variation of that parameter (about 40 years, see [Kopnichev and Sokolova, 2010c, 2013]. From this it might follow that the events in these ring structures are the most likely in the near future. At the same time, a large earthquake in the Kokshaal Range area is least likely, because its ΔT is no more than 16 years.

To sum up, our analysis of the parameters for the seismicity rings identified in zones of high shear-wave attenuation in central Tien Shan and Dzungaria yields a forecast of several large earthquakes that may occur in the areas during a few next years. The greatest threat will be posed by the events that are to occur in northern Tien Shan, as inferred here, because their rupture zones may happen to be at comparatively short distances from large cities, viz., Bishkek (the capital of Kyrgyzstan) and Almaty (the southern capital of Kazakhstan). The method proposed here can also be used for middle-term prediction of large seismic events in other intracontinental areas.

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