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Ring-Shaped Seismicity Structures in the Northern Balkan Region: Possible Preparation of Large Earthquakes

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Abstract—Certain seismicity characteristics in the northern Balkan region are studied. A method is used based on identification of ring-shaped seismicity structures that often form prior to large earthquakes in continental regions. Relatively large, shallow (h = 0–33 km), ring-shaped structures are identified within two areas where no relatively large earthquakes ($M \geq 6.5$) have occurred since 1900. The meridional structure with a threshold magnitude $M_{\text{th}} = 4.2$ and major axis length $L \sim 150$ km formed within the western area bounded by coordinates of 42.0–44.5° N and 15.5–17.5° E. A larger structure ($M_{\text{th}} = 4.1$, $L \sim 180$ km) has been revealed within the eastern area (41.0–43.5° N and 21.5–23.5° E). Apart from shallow rings, deep seismicity bands (h = 34–70 km) formed within both areas. Magnitudes of possible large events are estimated based on previously obtained correlation dependences of the seismicity ring parameters on the energy of large earthquakes with different focal mechanisms: $M_w = 7.2 \pm 0.2$ and $M_w = 6.7 \pm 0.1$ for the western and eastern areas, respectively. By analogy with some continental regions (primarily, Greece), we suggest that the epicenters of possible large earthquakes can be located near the intersections of shallow rings and deep seismicity bands. The conclusion is made that a large event is the most probable within the eastern area in the near years.

Keywords: Northern Balkans, large earthquakes, ring-shaped seismicity structures
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INTRODUCTION

In the last decade, it has been found that many large intraplate earthquakes are preceded by the long-term formation (several decades) of ring-shaped seismicity structures (or seismicity rings) outlining zones of relative seismic quiescence (Kopnichev and Sokolova, 2009a, 2009b, 2010, 2011a, 2011b, 2012, 2013, 2015, 2016, 2017a, 2017b, 2017c, 2017d). It has been shown that these structures are formed by epicenters of earthquakes with $M \geq M_{\text{th}}$, where M_{th} is the threshold magnitude that increases with the increase in magnitude of the mainshock. The correlation dependences $L(M_w)$ and $M_{\text{th}}(M_w)$ have been obtained for a number of subduction zones; here, L is the length of the major axis of the large seismic ring and M_w is the magnitude of the respective large earthquake (Kopnichev and Sokolova, 2009b, 2011a, 2015). Analogous dependences have been obtained for large intracontinental earthquakes with various focal mechanisms (Kopnichev and Sokolova, 2013). The use of these dependences makes it possible to predict the locations and magnitudes of large earthquakes during preparation based on the characteristics of ring-shaped structures. Successful predictions of three large and very large earthquakes in different regions of the world from these parameters were published in (Kopnichev and Sokolova, 2011a, 2015, 2017a). In the present paper, an analogous study is carried out for the region including the northern Balkan Peninsula.

HISTORICAL SEISMICITY

The seismicity level on the northern Balkan Peninsula is much lower than in the regions of Greece and Aegean Sea (Makropoulos and Burton, 1984; Ambraseys, 2001; Abolmasov et al., 2011). In the considered region, confined by coordinates of 41°–47° N and 13°–26° E, only nine earthquakes with $M \geq 6.5$ have occurred since 1900, and only three of them had $M \geq 7.0$ (Fig. 1, Table 1). Only one event was reliably determined to have $M_w > 7.0$: The Kresna earthquake of April 4, 1904, in western Bulgaria (Ambraseys, 2001). In addition, three historical earthquakes with this energy are known: they occurred in the 16th–19th centuries, including the catastrophic Dubrovnik earthquake on April 6, 1667 (M = 7.2). The hypocenters of large earthquakes are typically located at small depths, usually down to 20 km.

It should be noted that no earthquakes with $M \geq 6.5$ have been reported in the studied region after 1979.

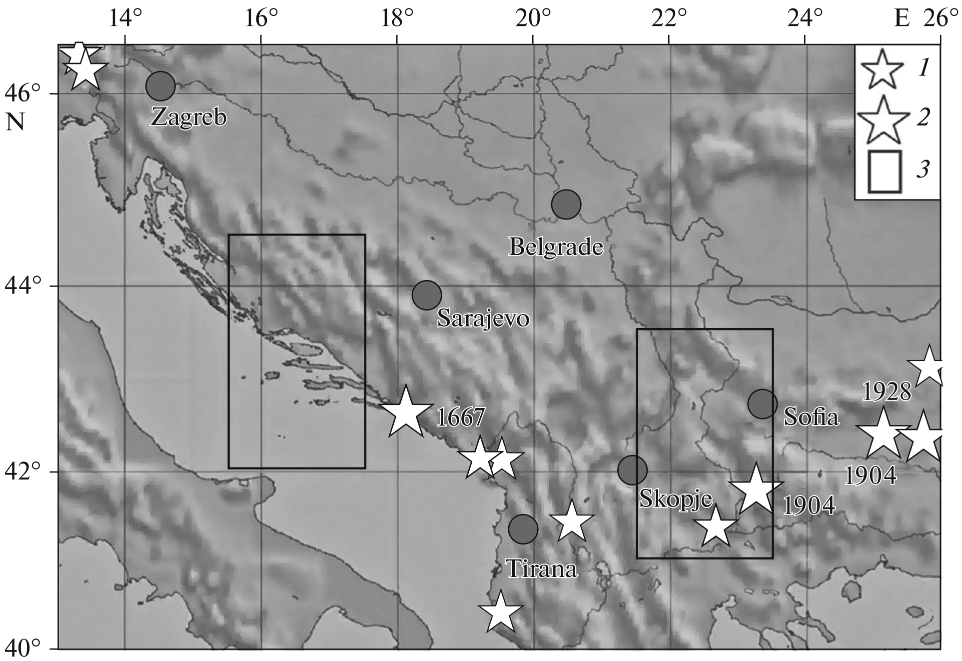

Fig. 1. Most notable seismic events in studied region (years are indicated near epicentral locations): (*1*) $7.0 > M \geq 6.5$; (*2*) $M \geq 7.0$; (*3*) zones where seismicity characteristics were studied.

The mean recurrence interval of these earthquakes (T_r) for 1904–1979 is ~9.5 ± 11.1 years. The time elapsed after the earthquake of April 15, 1979, is more than 38 years, i.e., four times the calculated T_r values, and considerably exceeds the 2σ interval, suggesting a high large earthquake occurrence probability in the region in the nearest future.

The Centroid Moment Tensor (CMT) catalog (Dziewonski et al., 1981; Ekström et al., 2012) provides the focal mechanisms of many relatively large earthquakes that occurred in the northern Balkan region beginning from 1976. We considered focal mechanisms for earthquakes with intermediate magnitudes (M = 5.5–6.0) that occurred in two zones corresponding to the ring-shaped seismicity structures we distinguished (see below). It follows from the data of the CMT catalog that in the western part of the studied region (the territories of Croatia and Bosnia and Herzegovina), the dominant mechanisms are reverse faulting and oblique-reverse faulting; in the eastern part (southern Serbia and western Bulgaria), normal faulting and oblique-normal faulting. Notably, according to the geological data, the largest 1904 Kresna earthquake also had a normal fault mechanism (Ambraseys, 2001).

Table 1. Large ($M \geq 6.5$) earthquakes on northern Balkan Peninsula

Date	Lat.,° N	Lon.,° E	M	M_w
March 26, 1511	46.2	13.4	6.9	
April 6, 1667	42.6	18.1	7.2	
January 2, 1866	40.4	19.5	6.5	
April 4, 1904	41.75	23.25	7.2	7.1
April 18, 1904	42.36	25.11	7.1	
June 1, 1905	42.1	19.5	6.6	
June 14, 1913	43.1	25.8	6.8	
April 14, 1928	42.33	25.72	7.1	
March 8, 1931	41.34	22.66	6.6	
November 30, 1967	41.39	20.53	6.7	
May 06, 1976	46.36	13.28	6.5	6.5
April 15, 1979	42.10	19.21	6.9	6.9

DATA AND METHODS

We used earthquake catalogs of the National Earthquake Information Center (NEIC), United States Geological Survey (USGS), for the period from 1973 to January 1, 2018. We considered the characteristics of all seismic events recorded in the studied region north of 41° N.

The method of analyzing seismicity in continental regions to reveal ring-shaped structures was described in (Kopnichev and Sokolova, 2012, 2013, 2016, 2017a). The analyzed seismic characteristics are for depths of 0–33 km, where ring-shaped structures can form. The selected earthquakes had magnitudes of no less than the threshold value M_{th} (these values are usually less than the magnitudes of mainshocks by two to three units of magnitude). In some continental regions, the seismicity parameters for depths of 34–70 km are also considered (Kopnichev and Sokolova, 2017a). Apart from threshold magnitudes, ring-shaped structures have such characteristics as the length of the major axis (L).

DATA ANALYSIS

Let us consider certain seismicity characteristics in two regions where no relatively large earthquakes have occurred for a long time and where the largest ring-shaped structures have been identified. Figure 2a shows the locations of epicenters of shallow (h = 0–33 km) earthquakes in the western Balkan region (42.0°–44.5° N, 15.5°–17.5° E) that occurred in the period from January 1, 1973, to January 1, 2018. We can clearly see a large submeridionally elongated ring-shaped structure (M_{th} = 4.2, L ~ 150 km). The majority of this structure is located in the Adriatic Sea, but also includes part of Croatia. The structure that formed in 1974–2016 is located east of the epicenter of the 1667 Dubrovnik earthquake with M = 7.2. The largest magnitude within the limits of the ring-shaped structure (M_{max} = 5.4) corresponds to the 1988 earthquake (Fig. 2b).

Figure 2c shows elements of deep-focus seismicity. There are two seismicity bands formed by epicenters with h = 34–47 km: one band (M = 4.3–4.7) crosses the northern part of the seismicity ring in the northeastern direction and the other (M = 3.1–4.4) nearly touches the northern boundary of the ring.

Another, larger ring-shaped structure is clearly manifested in the central Balkans, within an area with coordinates of 41.0°–43.5° N and 21.5°–23.5° E (Fig. 3a). This seismicity ring (M_{th} = 4.1, L ~ 180 km), which formed in 1981–2016, also has a submeridional orientation. The inner parts of the ring incorporate certain areas of Serbia, Bulgaria, and Macedonia. Interestingly, the epicenter of the 1904 Kresna earthquake (M_w = 7.1) is located near the southeastern boundary of this ring-shaped structure. The largest magnitude within the limits of this structure corresponds to the 2012 earthquake, whose epicenter is located in the southeast (M_{max} = 5.6, Fig. 3b). Note that the total magnitude per unit time can be a rough estimate of the seismotectonic deformation rate. This rate abruptly increases in the zone of the ring-shaped structure in 2009–2016, when eight earthquakes with M = 4.2–5.6 occurred.

Figure 3c shows deep-focus seismicity. We can see that only one seismicity band formed in the studied region (M = 3.1–4.2, h = 37–48 km): it is a NNW-trending band crossing the shallow ring-shaped structure in its southeast.

ESTIMATED MAGNITUDES OF EARTHQUAKES CORRESPONDING TO RING-SHAPED STRUCTURES IN THE STUDIED REGION

In (Kopnichev and Sokolova, 2013), the correlation dependences $L(M_w)$ and $M_{th}(M_w)$ were obtained for large intracontinental earthquakes with different focal mechanisms. The following dependences were obtained for reverse faulting and oblique-reverse faulting:

$$\log L(\text{km}) = -1.11 + 0.45M_w,\ r = 0.85; \quad (1)$$

$$M_{\text{th}} = -0.92 + 0.73M_{\text{w}}, r = 0.77; \quad (2)$$

for normal faulting and oblique-normal faulting, they were

$$\log L(\text{km}) = 0.40 + 0.28M_w,\ r = 0.73; \quad (3)$$

$$M_{\text{th}} = -0.19 + 0.64M_{\text{w}},\ r = 0.55. \quad (4)$$

Here, r is the correlation factor.

We used these dependences to estimate the magnitudes of large earthquakes possibly being prepared in the areas of ring-shaped structures shown in Figs. 2a and 3a. For the western part of reverse faults and oblique (with a reverse-fault component) strike-slip faults, the obtained value was M_w = 7.2 ± 0.2. For the western part of the studied region, where normal faults and oblique (with a normal-fault component) strike-slip faults are typical, the possible maximum magnitude is slightly less: M_w = 6.9 ± 0.3. Of course, both obtained values should be considered only as first approximations.

DISCUSSION

The previously obtained data (Kopnichev and Sokolova, 2017c) indicate that shallow ring-shaped seismicity structures form before large earthquakes in the region of northern Greece and the northern Aegean Sea, similarly to many intracontinental regions (Kopnichev and Sokolova, 2012, 2013, 2016, 2017a, 2017b, 2017c) and subduction zones (Kopnichev and Sokolova, 2009a, 2009b, 2011a, 2011b, 2015, 2017d). It was noted in the mentioned works that the formation of ring-shaped structures is related to self-organization processes in geological systems (Letnikov, 1992): these processes manifest themselves in deep-seated fluids migration in the crust and upper mantle. Due to the low density of fluids, these processes ultimately lead to a decrease in the Earth's potential energy.

The data presented above show that two quite large ring-shaped structures formed in the northern Balkans region by January 1, 2018. Interestingly, two large earthquakes—in the 17th century and in the beginning of the 20th century—occurred in the vicinities of both structures. This suggests that the detected seismicity

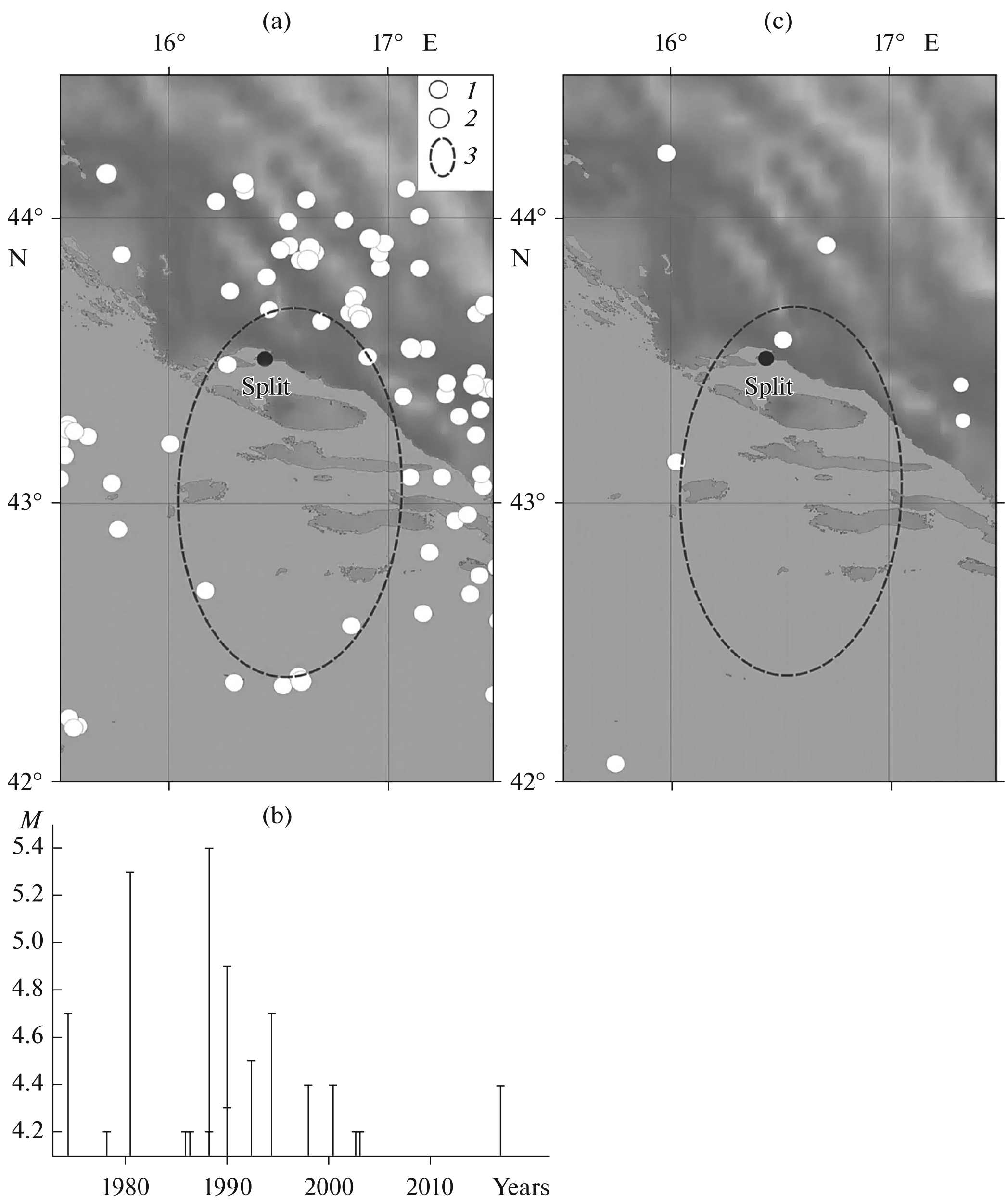

Fig. 2. Seismicity in western part of study area. (a) Shallow seismicity: (*1*) 4.9 > $M \geq 4.2$; (*2*) 6.0 > $M \geq 5.0$; (*3*) shallow ring-shaped structure. (b) Dependence of $M(T)$ for ring-shaped structure. (c) Deep seismicity. Circles denote epicenters of earthquakes with $M = 3.1–4.3$. Other notation same as in Fig. 2a.

rings may be related to preparation of new large earthquakes.

It was shown in (Kopnichev and Sokolova, 2017a, 2017c, 2017d) that the epicenters of large and great earthquakes in some continental regions and in the Cascadia subduction zone are located near the intersections or the maximum approach of shallow seismicity rings and deep (h = 34–70 km) seismicity bands. The available data indicate that shallow seismicity rings outline rigid lithosphere, while deep seismicity bands, analogous to deep ring-shaped seismicity structures, trace the zones of relatively low-viscosity material (Kopnichev and Sokolova, 2010, 2011b). Deep-seated fluids ascend at the boundaries of shallow rings and in the zones of deep seismicity bands. Note that the two-phase layer with a significant fraction of fluids is the thickest at the intersections or in the zones of maximum approach of shallow rings and deep bands. If fluids are connected closely enough to form a network, the stress builds up at the top of this layer, and the excess stress level is proportional to the layer thickness (Gold and Soter, 1984). It is stress

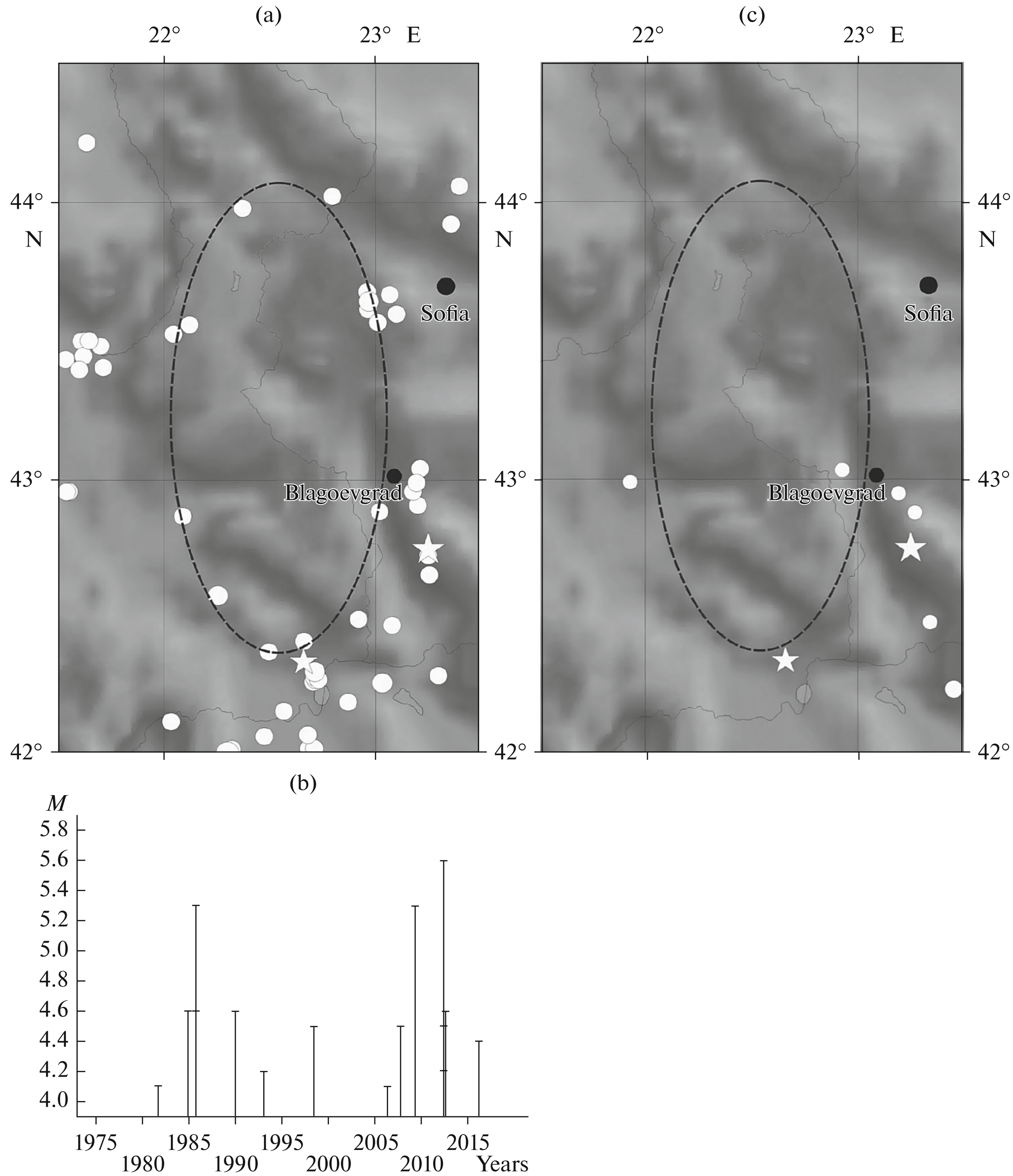

Fig. 3. Seismicity in eastern part of study area. (a) Shallow seismicity. Small circles denote epicenters of earthquakes with $M = 4.1–4.9$. Other notation same as in Figs. 1 and 2a. (b) Dependence of $M(T)$ for ring-shaped structure. (c) Deep seismicity. Notation same as in Figs. 2c and 3a.

buildup of that can trigger the displacement during a large earthquake.

Above we have considered ring-shaped structures in areas where large earthquakes had not occurred for quite long time. It follows from our estimates that earthquakes with $M_w \sim 7.0$ might be preparing there. In the western part of the studied region, such an earthquake may result in human casualties and considerable destruction, primarily in resort areas where the population density is quite high. For example, Split, Croatia's second largest city is located here, with a population of about 180000. Judging from the available data, the epicenter of the forecasted earthquake may be located near one of the zones where deep seismicity bands cross ring-shaped structures or approach closest to them (Fig. 2c). The most likely location of the epicenter of the upcoming large event is in the northernmost part of the ring-shaped structure, since the largest magnitudes here are also observed for the deep seismicity band.

In the eastern part of the studied region, the epicenter of a large earthquake may also be located near the intercept between the shallow ring and deep band (Fig. 3c). The population density in this area is less than in the west; however, there are several towns with populations of up to about 80000 (Blagoevgrad, Bulgaria). In addition, Sofia, the capital of Bulgaria, with a population of about 1.5 million, is located about 80 km from this area. Note that in many cases, an abrupt increase in seismotectonic deformation rate is observed in the areas of ring-shaped structures during time periods normally no longer than ten years before large and great earthquakes, with which formation of these structures has been related (Kopnichev and Sokolova, 2010, 2011a, 2011b, 2017a, 2017b, 2017c). In this respect, it is highly probably that a large earthquake will occur in the nearest future in the area of the eastern ring-shaped structure (Fig. 3a), since a similar effect is observed here. In our opinion, intensive geophysical and geochemical studies should commence in the mentioned area for mid-term forecast of a possible large earthquake.

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