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GEOPHYSICS

Characteristics of Ring Seismicity in Different Depth Ranges before Large and Great Earthquakes in the Sumatra Region

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Abstract—Characteristics of the seismicity in depth ranges 0–33 and 34–70 km before ten large and great ($M_w = 7.0–9.0$) earthquakes of 2000–2008 in the Sumatra region are studied, as are those in the seismic gap zones where no large earthquakes have occurred since at least 1935. Ring seismicity structures are revealed in both depth ranges. It is shown that the epicenters of the main seismic events lie, as a rule, close to regions of overlap or in close proximity to “shallow” and “deep” rings. Correlation dependences of ring sizes and threshold earthquakes magnitudes on energy of the main seismic event in the ring seismicity regions are obtained. Identification of ring structures in the seismic gap zones (in the regions of Central and South Sumatra) suggests active processes of large earthquake preparation proceed in the region. The probable magnitudes of imminent seismic events are estimated from the data on the seismicity ring sizes.

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Characteristics of seismicity in the Sumatra region in the depth ranges 0–33 and 34–70 km were analyzed before ten large earthquakes with $M_w = 7.0–9.0$ that occurred in 2000–2008, and in seismic gap zones as well. Structures of ring seismicity are revealed in both depth ranges. It is shown that epicenters of main seismic events lie, as a rule, close to regions of overlap or in close proximity to “shallow” and “deep” rings. The correlation dependences of ring sizes and threshold earthquake magnitudes on the energy of the main seismic event in the ring seismicity regions are obtained. Identification of ring structures in the seismic gap zones (in the regions of Central and South Sumatra) suggests that active processes of preparation for large earthquakes proceed in the region.

It is shown in [1, 2] that before large and great earthquakes, ring seismicity structures develop in the subduction zones within different depth ranges. Large fluctuations in the sizes of seismicity rings are observed for similar magnitudes of the main events, which is perhaps due largely to the dissimilarities in seismotectonic conditions in different subduction zones. To clarify the question, a more detailed analysis is carried out in the present work. Ring seismicity characteristics are studied in the Sumatra region where several great seismic events, including the $M_w = 9.0$ Great Sumatra earthquake of December 26, 2004, have occurred during the past nine years.

By analogy with [1, 2], we considered the characteristics of seismicity for different parts of the Benioff zone within depth ranges 0–33 and 34–70 km. Earthquake catalogues ISC (before 1973) and NEIC (from January 1, 1973) were used. Data were analyzed about the earthquakes that occurred in the vicinities of future focal zones, the magnitudes of earthquakes being $M \geq M_{t1}$ and $M \geq M_{t2}$, respectively, where M_{t1} varied from 4.5 to 5.5 for the shallower depth range, and M_{t2} from 4.0 to 5.5 for the deeper one (Table 1). Here, as a rule, the time interval was chosen from January 1, 1973, up to the day preceding the main event. An exception was the data for the source region of the December 26, 2004, Sumatra earthquake, for which the seismicity characteristics were considered starting from January 1, 1969. Data about seismic activity before ten large and great earthquakes with $M_w = 7.0–9.0$ in the Sumatra region are processed (Table 1). In addition, seismicity characteristics are studied in two zones of seismic gaps (in regions of Central and South Sumatra). For these zones, we considered seismic events that occurred before January 1, 2009.

Figure 1 displays the characteristics of seismicity before the February 13, 2001, earthquake ($M_w = 7.4$) in South Sumatra. Shallow seismic events ($M_{t1} = 4.8$) together with aftershocks of the June 4, 2000, earthquake ($M_w = 7.9$) formed, inter alia, a ring structure

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Table 1. Parameters of ring structures formed before large and great earthquakes in the Sumatra region

Data	Latitude	Longitude	H, km	M_w	M_{n1}	L, km	M_{n2}	l, km
04.06.2000 year	4.72° S	102.09° E	33	7.9	5.5	150	5.5	70
13.02.2001 year	4.68 S	102.56 E	36	7.4	4.8	80	4.5	60
02.11.2002 year	2.82 N	96.09 E	30	7.4	4.8	65	4.2	40
26.12.2004 year	3.30 N	95.98 E	30	9.0	5.5	700	5.5	200
28.03.2005 year	2.09 N	97.11 E	30	8.6	5.0	190	5.0	180
12.09.2007 year	4.44 S	101.37 E	34	8.5	5.0	290	5.0	100
12.09.2007 year	2.63 S	100.84 E	35	7.9	5.0	150	5.0	160
13.09.2007 year	2.13 S	99.63 E	22	7.0	4.5	85	4.0	40
20.02.2008 year	2.77 N	95.96 E	26	7.3	4.8	35	4.5	30
25.02.2008 year	2.49 S	99.97 E	25	7.2	4.5	60	4.5	60

Note: L and l are major axes of a “shallow” and a “deep” ring, respectively.

Table 2. Parameters of ring structures in the seismic gap zones

Zone	Latitude	Longitude	L, km	l, km	M_w	M_{n1}	M_{n2}	ΔM_{n1}	ΔM_{n2}
1	1° S–1° N	97°–99° E	170	95	8.1 ± 0.1	5.3	5.1	0.3	0.3
2	6.5–4.5 S	101.5–103.5 E	130	100	8.0 ± 0.2	5.5	5.5	0.5	0.7
3	7.5–5.5 S	102.5–105.0 E	160	110	8.2 ± 0.2	5.3	5.3	0.3	0.4

with its major ~80-km-long L axis elongated to the north-northwest. Earthquakes with intermediate depth of hypocenters ($M_{t2} = 4.5$) formed a smaller ring with its major ~60-km-long l axis parallel to the coastline. It should be mentioned that the epicenter of the main event lay at a distance of $\Delta r \sim 10$ km from the area of ring structure overlap. (According to [1, 2], for the sake of convenience the rings of the first type will hereinafter be called shallow, and those of the second type, deep.)

Analysis showed that ring seismicity structures had been formed before all earthquakes within both depth ranges (Fig. 2, Table 1). It is important that in nine cases the epicenters of the main events lay close to the areas of intersection or the nearest proximity of shallow and deep rings. The only exception was the September 12, 2007, earthquake ($M_w = 7.9$) with its epicenter located at a distance $\Delta r \sim 50$ km from the region of the rings overlap.

It is of interest that the ring structures are revealed also in the seismic gap zones in South and Central Sumatra where there have been no large earthquakes with $M \geq 7.8$ since at least 1935 [3] (Fig. 2, Table 2). From Table 2 it follows that the L and l values for the rings in these zones vary from 130 to 170 km and from 95 to 110 km, respectively, whereas M_{t1} and M_{t2} values lie within the ranges of 5.3–5.5 and 5.1–5.5.

It is apparent from Fig. 2 that the shallow and deep rings for different events are practically tangent or overlapping. Rings developed before the largest earthquakes with $M_w \geq 7.9$ and also those in seismic gap regions fill almost the whole latitudinal belt between7°N and 7°S. The only exception is the region between 1° S and 2° S where no pair of rings with M_{n1}, $M_{n2} \geq 5.0$ has been revealed so far.

The $\log L\,(M_w)$ dependency for the data obtained in the Sumatra region is plotted in Fig. 3. The sizes of shallow rings show a linear dependency on magnitude, with a regression equation in the form

$$\log L\,(\text{km}) = 0.51 M_w - 1.88, \quad r = 0.91, \tag{1}$$

where r is the correlation factor. The dependency obtained for l looks like

$$\log l\,(\text{km}) = 0.37 M_w - 1.04, \quad r = 0.86. \tag{2}$$

Note that L values grow with magnitude much faster than l values. The $\frac{L}{l}$ ratio for data covering 10 events varies within the range of 0.9 to 3.5, being on average 1.8 ± 0.8. This parameter shows an uptrend with growing M_w (against a background of a big data scatter).

For the data on 9 events (excluding the earthquake of June 4, 2000), linear dependences of the threshold magnitudes on M_w are again observed for shallow and deep rings. The linear regression equations are as follows:

$$M_{n1} = 1.92 + 0.38 M_w, \quad r = 0.90, \tag{3}$$

$$M_{n2} = -0.02 + 0.60 M_w, \quad r = 0.92. \tag{4}$$

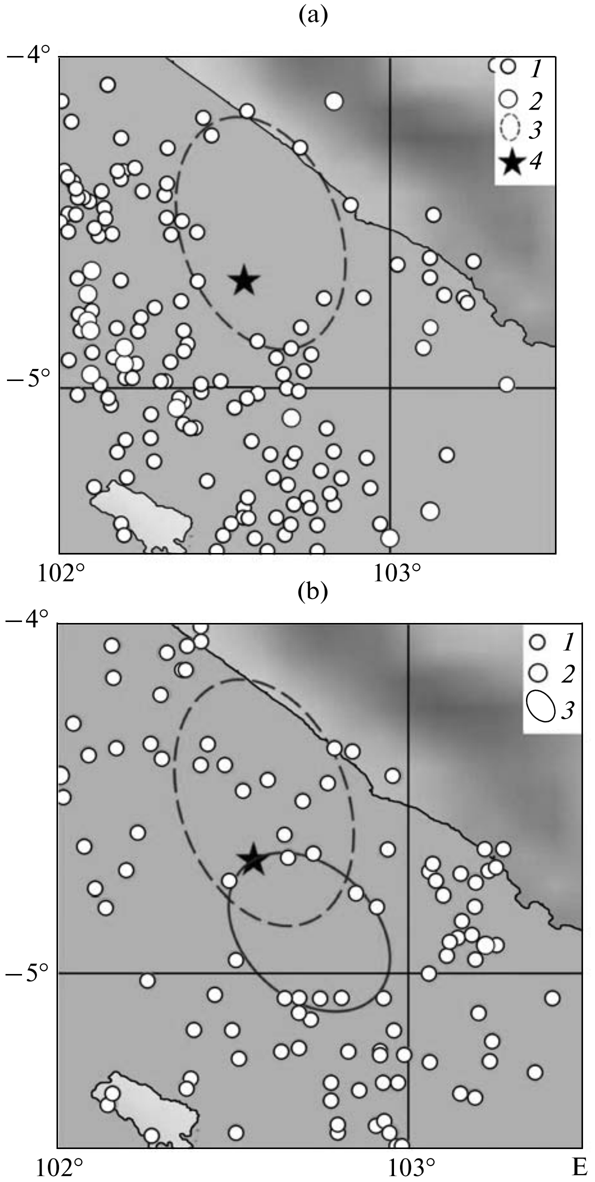

Fig. 1. Ring seismicity before the February 13, 2001, Sumatra earthquake. (a) Depth range 0–33 km; (*1, 2*) epicenters of earthquakes with $4.8 \leq M < 6.0$ (*1*), $M \geq 6.0$ (*2*), (*3*) shallow ring, (*4*) epicenter of the main event. (b) Depth range 34–70 km; (*1, 2*) epicenters of earthquakes with $4.5 \leq M < 6.0$ (*1*), $M \geq 6.0$ (*2*), (*3*) deep ring.

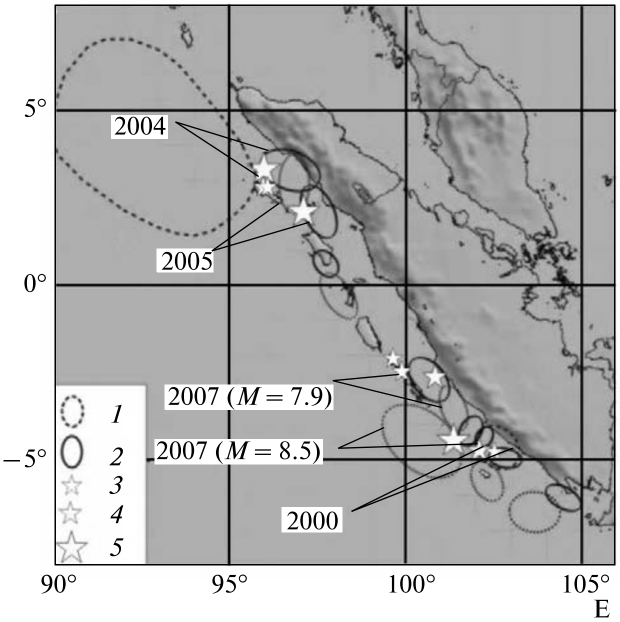

Fig. 2. Characteristics of ring seismicity before great earthquakes in the Sumatra region. (*1, 2*) Seismicity rings: (*1*) shallow, (*2*) deep; (*3–5*) epicenters of the largest earthquakes: $M = 7.0–7.4$ (*3*), $M = 7.9$ (*4*), $M = 8.5–9.0$ (*5*). Rings marked by arrows correspond to the given earthquakes. Rings without arrows correspond to seismic gap zones.

The data for the June 4, 2000, earthquake manifestly fall outside of the above dependences: the M_{t1} and M_{t2} values for this earthquake exceed their averages for $M_w = 7.9$ by as much as 0.58 and 0.78, respectively. For the sake of comparison, note that the rms's of these quantities over 9 events are 0.14 and 0.19, respectively. From this it follows that the data for the given earthquake fall outside the 4σ limits.

Identification of ring structures in the seismic gap regions (Fig. 2) suggests a hypothesis implying that foci of new large earthquakes are shaping up there. Using formulas (1), (2), we can estimate probable magnitudes of the forthcoming events (Table 2). For the three zones considered (from north to south) we obtain, respectively, $M_w = 8.1$, 8.0, and 8.2. With these known quantities it is now possible, using Eqs. (3) and (4), to find the prognostic values M_{t1}, M_{t2} and deviations of the real values from these estimates (ΔM_{t1}, ΔM_{t2}). From Table 2 it follows that the maximum values ΔM_{t1} and ΔM_{t2} (0.5 and 0.7, respectively) are obtained for the second zone located in the South Sumatra region.

New data confirm, on a wider database, the conclusion inferred in [1, 2] about the epicenters of most of the great earthquakes in subduction zones to be associated with the regions of shallow and deep ring overlap or their close proximity. (Maximum spacing of the main event epicenter from the area of ring overlap corresponds to the September 12, 2007, earthquake with $M = 7.9$; however, relations $\frac{\Delta r}{L} \ll 1$, $\frac{\Delta r}{l} \ll 1$ hold even in this case.) As was mentioned earlier, this effect can be explained rather by the uprise of deep fluids through the ring boundaries, which results in formation of a thicker two-phase layer with connected pores in those regions and stress concentration at the top of the layer [1, 2]. Recently, data were obtained that could be indicative of the fluid uprise in the sub-

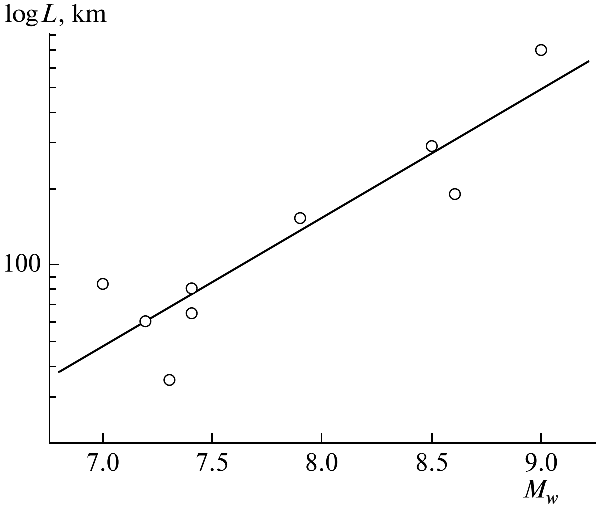

Fig. 3. logL as a function of M_w for the Sumatra region.

duction zones mostly through the ruptures formed during earthquakes [4].

From [1, 2] it follows that by generalization of the data for different subduction zones, no distinct correlation of the ring sizes with magnitude was found. At the same time, for the Sumatra region, linear dependences of ring sizes on magnitude with sufficiently high correlation coefficients are revealed. Comparison with the data presented in [1, 2] shows that for other regions different dependences should hold rather.

The severe overestimation of M_{t1} and M_{t2} values for the June 4, 2000, earthquake, in our view, may result from the following circumstances. To judge from the recent data [5, 6], of equal importance in the processes of a large earthquake preparation are both the stress field in the lithosphere and the content of fluids in the future focal area that considerably decrease the friction at a forming rupture. The last large earthquake with $M_w > 7.5$ before 2000 in the Sumatra region occurred as far back as 1935 ($M_w = 7.8$) [4]. From this it follows that the June 4, 2000, earthquake was an independent event that required a relatively high fluid content at the boundary of the submerging lithospheric plate to drive the motion at the source of earthquake. This requirement had just been met owing to sufficiently high values of threshold magnitudes (we can assume that the increase in focal sizes of seismic events in regions of the ring structures ensures the growth in the total volume of the uprising fluids). At the same time, after the June 4, 2000, earthquake, a redistribution of stresses in the neighboring regions occurred associated with stress accumulation in focal zones of large and great events that took place in 2001–2008 (Table 1) [3]. Therefore, a lower fluid content and, hence, lower M_{n1} and M_{n2} values in regions of ring structures were required to trigger motions in these earthquakes.

Estimates for ΔM_{n1} and ΔM_{n2} obtained for the seismic gap zones suggest that the preparation process of a large earthquake has gone farthest in the second zone (approximately between 4.5° and 6° S).

The sources of large earthquakes in the subduction zones are known to correspond usually to the slip events of submerging oceanic plate segments, whereas the ring structures are associated rather with the dehydration of plate material that results in the uprise of mantle fluids [5–7]. Seismicity rings that develop before large earthquakes are a manifestation of geodynamical self-organization processes, the formation of so-called dissipative structures that can exist far from equilibrium only if supported by sufficient mass and energy fluxes [8]. It is just the fluids uprising from the upper mantle and heated up to several hundred degrees Celsius that support the survival of these fluxes.

The results of our work can be used for the purposes of seismic zoning and intermediate-term forecast in different subduction zones and, first of all, in those regions where no large earthquakes with $M \geq 7.5$ have occurred for a long time.

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