Characteristics of seismic activity before several large Sumatra, Indonesia, earthquakes*

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Two great earthquakes of $M_s 8.5$ and $M_s 8.3$ determined by the China Earthquake Networks Center (CENC) occurred successively on September 12 and 13, 2007 in the sea area to the south of Sumatra, which is another group of large earthquakes after $M_s 8.7$ event on December 26, 2004 and $M_s 8.5$ event on March 29, 2005. The magnitudes of these earthquakes determined by the National Earthquake Information Center of USA (NEIC) are $M_w 9.0$ (26 December 2004), $M_w 8.7$ (29 March 2005), $M_w 8.4$ (12 September 2007) and $M_w 8.1$ (13 September 2007), respectively.

Many researches about the two earthquakes of 2004 and 2005 have been developed (Chlieh *et al.*, 2007; Ammon *et al.*, 2005; ZHANG *et al.*, 2005). XUE *et al.* (2005a) studied the characteristics of seismic activity before the $M_w 9.0$ and make comparison between the two great earthquake sequences of 2004 and 2005 (XUE *et al.*, 2005b). When analyzing spatial distribution of the two sequences, XUE *et al.* (2005a) found a seismic gap with 400 km long and thought the seismic gap maybe a potential strong earthquake region taking historical earthquake activity there into account. It is interesting that the two earthquakes of 2007 just occurred in the seismic gap. Moreover the abnormal phenomena of the global and regional seismicity before the two earthquakes are similar to those before the large earthquake of 2004. In this paper, we will contrastively analyze the characteristics of seismic activity before the four large earthquakes and try to find the common features.

The data used in this paper are from global earthquake catalog given by NEIC^① and the global earthquake catalog with $M_s \geq 7.0$ obtained by CENC^② respectively. The earthquake catalog of NEIC can also cover earthquakes with $M \geq 4.8$ in Sumatra and its neighboring region (XUE *et al.*, 2005a).

1 Tectonic background and seismic activity

There were three great earthquakes with $M_s \geq 8.5$ occurred in three years since 2004 in Sumatra region, which suggests that the large earthquakes in this area is characterized by clustering. The group of earthquakes were caused by the rupture of Sunda-Andaman underthrust fault; the India and Australian plates subduct northeastward beneath the Sunda Shelf along the fault and the convergence direction is nearly orthogonal to the plate boundary in

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^① [Http://earthquake.usgs.gov/regional/neic/](http://earthquake.usgs.gov/regional/neic/)

^② [Http://www.csndmc.ac.cn/newweb/](http://www.csndmc.ac.cn/newweb/)

Java Island, southeast of Sumatra at a rate of about 63~68 mm/a (Michel *et al.*, 2001; Bock *et al.*, 2003). Along the Sunda trench, the direction of convergence becomes oblique to the trench. In the epicentral area of December 2004 rupture, the slip rate normal to the trench is about 40 mm/a; while in the region north to 8°N, that is between 14 mm/a to 34 mm/a (Subarya *et al.*, 2006).

The level of historical seismic activity was high in the region of Sunda trench. In the past 200 years many large earthquakes occurred in this area. XUE *et al.* (2005b) found that there was a rupture gap with 1 000 km long from 1°N to 12°N to the east of Sunda trench and the earthquakes of 2004 and 2005 just occurred there. The source rupture of $M_W 9.0$ in 2004 is unilateral rupture along the Andaman fault the rupture area with 1 200~1 300 km long and 150 km wide (Ammon *et al.*, 2005). The latter is bilateral with rupture length about 300 km (Walker *et al.*, 2005), both of which occurred in seismic region in 1861. Moreover, the two earthquakes of 2007 occurred in the source area of 1833 and distance between the two earthquake epicenters is about 200 km, the aftershocks distributed in a area of 380 km long and 130 km wide striking in NW direction.

2 Characteristics of seismic activity before several large earthquakes

2.1 Quiescence-swarming phenomenon of the global $M \geq 7.0$ earthquakes

There are two notable quiescence periods of seismic activity since 2003. One appeared in 2004 and the quiescence lasted 141 days. After the tranquility period, the earthquake frequency increased obviously and then the earthquake of $M_W 9.0$ took place. The other appeared in 2007 and lasted 121 days from April to July. The strong earthquake frequency increased quickly since 2 August 2007, five earthquakes with $M \geq 7.0$ occurred during 40 days showing phenomenon of quiescence-active (swarming); and then the earthquakes of 12 and 13 September 2007 occurred successively. It is noticed that there are abnormal phenomena not only in the regional area but also in global area before a large earthquake.

2.2 Strengthened earthquake activity of $M \geq 7.0$ in Sumatra

Figure 1 shows the distribution of earthquakes with $M \geq 7.0$ in Sumatra and its vicinity. It can be seen from Figure 1 that the seismicity level was low from 1973 to 1993, and only three $M_W \geq 7$ earthquakes occurred with the

Figure 1 Distribution of $M_W \geq 7.0$ earthquakes in Sumatra area and its vicinity (catalogue of NEIC)

○ and ● denote $M_W \geq 7.0$ earthquakes during 1973-01-01~1993-12-31 and 1994-01-01~2004-12-25, respectively; “⊙” denotes $M_W \geq 8.0$ earthquakes during 2004-12-26~2007-09-13

largest magnitude of 7; afterward the seismic activity was obviously strengthened and the strong earthquakes concentrated in the area of 5°N~5°S with 1 200 km long and 300 km wide along Sunda trench and Sumatra Island before $M_W 9.0$ earthquake in 2007, in which total eight $M_W \geq 7.0$ earthquakes occurred with the largest magnitude of 8.3. Four large earthquakes with $M \geq 8.0$ occurred in this area since December 2004. The strengthening phenomenon before large interplate earthquakes is similar to those before the intraplate earthquakes (MEI *et al.*, 1996).

2.3 Seismic gap formed by $M \geq 5.0$ earthquakes in epicentral area and its vicinity

Figure 2a shows the distribution of $M \geq 5.0$ earthquakes. A seismic gap with 750 km long and 300 km wide was formed around the epicenter of $M_W 9.0$ where the two large earthquakes of 2004 ($M_W 9.0$) and 2005 ($M_W 8.7$) occurred. In general, seismic activity level of the gap is relatively high and quiescence interval between $M \geq 5.0$ earthquakes is less than 300 days. However the quiescence time (from 16 September 2003 to 25 December 2004) reached 466 days before the $M_W 9.0$ earthquake. Similarly, another seismic gap appeared prior to the two large earthquakes of 2007. Figure 2b is the distribution of $M \geq 5.0$ earthquakes from 26 December 2004 to 11 September 2007. The figure shows a

seismic gap with 280 km long and 300 km wide located in the area from 2°S to 4°S striking in NW. On April 21, 2007, a $M_{\text{S}}5.0$ earthquake occurred there at the depth of 45 km and then there was no earthquake in the gap till the occurrence of two large earthquakes. The two earthquakes and their aftershocks occurred in the gap. The gap was distributed in the old focal zone of 1833, generally there were always some $M \geq 5.0$ earthquakes occurred in it. After the $M_{\text{W}}9.0$ earthquake, however, the old rupture area was locked. It shows that the two great earthquakes of 2004 and 2005 may trigger the great shocks of 2007.

Figure 2 Distribution of $M \geq 5.0$ earthquakes in Sumatra area and its vicinity (NEIC catalogue)
(a) 2003-09-16~2004-12-25; (b) 2004-12-26~2007-09-11

2.4 Characteristics of moderate-deep earthquake activity

The subduction area of Australian and Sunda plates was divided into two parts: the east (3°S to 11°N, 108°E to 134°E) and the west (8°S to 6°N, 94°E to 108°E) by the longitude line of 108°E. Figure 3 describes the variation of focal depth of the moderate-deep earthquakes occurred in the two parts with time. It shows that all the $M \geq 5.2$ earthquakes in the west part from 1973 to 1988 were within the depth of 200 km, and the magnitude of those was less than $M7.0$. However the focal depth increased and the active level has strengthened gradually since 1989, especially the earthquake of 25 July 2004 with $M_{\text{W}}7.3$ which is the biggest and deepest one since 1973. After five months, the $M_{\text{W}}9.0$ earthquake took place. The seismic activity continued strengthening thenceforward and another unusual earthquake of $M_{\text{W}}7.5$ occurred on 9 August 2007 in the depth of 280 km near the Java Island. Thirty three days later, the two great earthquakes occurred one after the other on 12 and 13 September 2007. It seems that the two strong deep earthquakes may have prediction significance of moderate-short term for large shallow earthquakes (Figure 3a). In east region, the level of seismic activity is not high during the time of 1973 to 1993 and only two earthquakes with $M_{\text{W}} \geq 7.0$ occurred. Furthermore, strong deep earthquakes of $M \geq 6.0$ mainly occurred in two layers, the depth of 70~200 km and 440~620 km, with no earthquake in the middle layer. The seismic activity has obviously strengthened since 1994 and seven earthquakes with $M_{\text{W}} \geq 7.0$ occurred. Moreover, earthquakes in the upper layer (depth of 70~200 km) gradually migrated towards the deeper place, and two earthquakes of $M \geq 6.0$ occurred in the middle layer during the time of 2002 to 2003. The deep earthquake activity continued strengthening after the $M_{\text{W}}9.0$ earthquake, and especially a $M_{\text{W}}7.6$ earthquake (focal depth 397 km) occurred on 28 January 2006 in the middle layer where the active level is always low. The figure shows that the beginning time of deep earthquake abnormal activity in the west region is earlier than that of the east. In other words, the beginning time of deep earthquake strengthening near the great shallow earthquakes is earlier than that far from the large shallow earthquakes.

Figure 3 Focal depth variation of moderate-deep source earthquakes at western (a) and eastern (b) part of the subduction boundary zone of Australia-Sunda Plate (NEIC catalogue)

3 Discussion

Many significant research results about the interplate earthquakes have been obtained (Fedotov, 1965; Mogi, 1979, 1987, 1990). Fedotov first put forward the concept of seismic gap, namely the first type of seismic gap (the gap between two great earthquakes). Mogi (1979) suggested two types of seismic gap and named the gap formed by small earthquakes as the second type (Mogi, 1990). In this paper, two types of seismic gap were formed before the several great shallow earthquakes. It shows that the appearance of two types of seismic gap is the common phenomena in interplate area.

Mogi (1973, 1987) analyzed the characteristics of seismic activity before large shallow earthquakes in Tonga Trench, Mariana Trench and Japan area, and found that the deep earthquake activity strengthened obviously and the focal depth increased gradually before and after the great shallow earthquake. The same phenomena were found in this study in the sea area of Sunda trench. Furthermore, it is also showed that the strengthening of deep earthquake activity and migrated towards the deeper place not only appeared near the great shallow earthquakes, but also in the whole plate boundary belt, especially the strengthening is much outstanding in the middle layer of Wadati-Benioff belt (200~440 km) before the great shallow earthquake. In addition, the beginning time of the abnormal activity for the deep earthquake near the great shallow earthquake is earlier than that of far from it. It means that the significant strengthening of the deep earthquake activity, especially the occurrence of the unusual strong deep earthquakes with $M \geq 7.0$ can be regarded as a precursory phenomenon for large shallow earthquakes.

Shallow earthquakes occurred in the brittle layer of upper crust and their focal depth ends in the brittle-ductile transition zone (ZHANG *et al.*, 1996). While the deep earthquakes occurred in the cold plate which insert into the hot mantle. The strengthening of deep earthquake activity and the increasing of focal depth, especially the occurrence of unusual deep strong earthquakes with $M \geq 7.0$ make the lower crust with rheological features and the asthenosphere disturbed acutely, which is in favor of the stress accumulation in upper brittle layer and of the great shallow earthquake occurrence. Because of the intensification of asthenosphere disturbance, the affected area is not partial and local, but maybe the whole plate boundary belt and even the global area.

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