Characteristics of seismic activity before Chile M_w 8.8 earthquake in 2010*

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Abstract The tempo-spatial variation of seismic activity before great Chile M_w 8.8 earthquake on February 27, 2010 is studied. Some results are as follows: ① Two types of seismic gaps appeared before the Chile M_w 8.8 shock. One is background gap of $M_w \geq 8.0$ earthquakes with 360 km length since 1900, the other is seismogenic gap formed by $M \geq 5.5$ earthquakes with 780 km length five years before the Chile earthquake; ② There was only one M_w 7.1 earthquake in the middle and southern part of Chile from 1986 to 2010. The obvious quiescence of $M_w \geq 7.0$ earthquake is the long-term background anomaly for the Chile earthquake; ③ The quiescence of $M \geq 6.5$ earthquakes appeared in South American block and its vicinity during the period from 2007 to 2009, and the quietude state has been disappeared three months before the Chile M_w 8.8 earthquake; ④ The deep and intermediate-depth earthquake activity has been noticeably strengthened in the subduction zone of South American block since 1993; ⑤ The great Chile earthquake shows that global seismicity is still in the active period of $M_w \geq 8.5$ earthquakes since 2004. Based on the characteristics of the former two active periods, several great earthquakes with $M_w \geq 8.5$ would take place in a few years. In addition, the circum-Pacific seismic belt would be the main region for $M_w \geq 8.0$ earthquakes.

Key words: Chile earthquake; two types of seismic gaps; deep and intermediate-depth earthquake; South American block; circum-Pacific seismic belt

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1 Introduction

A great M_w 8.8 earthquake hit the coast of Chile (35.8°S, 72.7°W, focal depth of 33 km) at 14:34:16 (Beijing Time) on February 27, 2010, reported by China Earthquake Networks Center (CENC) (www.ceic.ac.cn), and triggered a tsunami. At least 507 people were killed, many were injured and at least 200 000 houses were damaged by the earthquake and tsunami in the Concepcion-Valparaiso area (<http://earthquake.usgs.gov/earthquakes/eqinthenews/2010>).

Based on the global earthquake catalogue from United State Geological Survey (USGS, <http://www.usgs.gov/>), the M_w 8.8 Chile earthquake is the fifth largest earthquake since 1900 and it is also the third greatest earthquake with $M_w \geq 8.5$ since 2004.

A lot of studies have been made on the great inter-plate earthquakes (Fedotov, 1965; Mogi, 1973, 1979, 1987, 1988, 1990). Fedotov (1965) firstly brought forward conception of background seismic gap, namely the first type of seismic gap, which refer to the gap between two great earthquakes. Mogi (1979) put forward the idea of two types of seismic gaps, and called the gap formed by lower magnitude earthquakes as the second type of seismic gap. Mogi (1973, 1987, 1988, 1990) reported several instances that great shallow earthquakes along the Kurile-Japan Trench, Tongal Trench and Mariana Trench were preceded by occurrence of noticeable deep seismic activity including large deep m_b 7 earthquakes. The gradually downward migration of seismic activity in the subducting slab before high deep seismic activity was pointed out in some regions.

Xue et al (2005, 2006, 2008) studied the characteristics of seismic activity before several large shallow earthquakes in Sumatra, found that the appearance of two types of seismic gaps is common phenomena and

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the seismic activity of deep earthquakes was obviously strengthened 10 years before the massive shallow shocks.

Two sets of worldwide earthquake catalogues are used in this paper. One is the catalogue of $M_W \geq 7.0$ earthquake by Engdahl and Villaseor (2002) for 1900–1999 and by Harvard University (<http://www.seismology.harvard.edu/>) for after 2000. The other is the global shocks since 1973 from National Earthquake Information Center (NEIC, <http://earthquake.usgs.gov/>). The tempo-spatial variation characteristics of seismic activity before the great Chile earthquake are studied from global seismic activity and the historical earthquakes and aftershocks in Chile.

In order to evaluate the completeness of the second earthquake catalogue, we made two pictures, one is the variation of annual frequency of $M \geq 5.0$ earthquakes (Figure 1a) and the other is Gutenberg-Richter relation (Figure 1b) in South American block and its surrounding area (60°S – 20°N and 120°W – 40°W). On average, there are 196 earthquakes with $M \geq 5.0$ every year in the region and the annual frequency of earthquakes varies from 158 to 234 since 1973. Fitting the data in the magnitude range from 5.0 to 8.0 in Figure 1b with a straight line using least square approach shows that the correlation coefficient R is 0.997 and b -value is 1.05, and there is no “roll off” at the lower magnitude end. So the catalogue with $M \geq 5.0$ earthquakes is complete in the area.

Figure 1 Annual frequency of $M \geq 5.0$ earthquakes (a) and the G-R relationship (b) in South American block and its surrounding area.

2 Historical earthquakes and two types of seismic gaps

The Chile earthquake, occurring as thrust-faulting on the interface between the Nazca and South American tectonic plates, with the Nazca plate moving down and landward below the South American plate, is located at the boundary between the two plates, which are converging at a rate of 80 mm per year (Melnick et al, 2008).

Coastal Chile has a history of very large earthquakes. There have been eight events of magnitude 8.0 or greater since 1900. The magnitude of 9.6 earthquake in May, 1960, is the largest earthquake worldwide in the last 200 years or more. This giant earthquake spawned a tsunami that engulfed the Pacific Ocean. An estimated 1 600 lives were lost in the 1960 earthquake and tsunami in Chile, and the 1960 tsunami took additional 200 lives among Japan, Hawaii, and the Philippines. Approximately 870 km to the north of the February 27, 2010, earthquake is the source region of the magnitude 8.5 earthquake of November, 1922. This great quake significantly impacted central Chile, killing several hundred people and causing severe property damage.

2.1 The first type of seismic gap

Figures 2 and 3, Table 1 show the source rupture distribution and length variation of earthquakes with $M_W \geq 8.0$ since 1900. The information of source ruptures from 1900 to 1972 is presented by Beck et al (1998), Kelleher (1972) and Melnick et al (2008). The others based on aftershock areas are also given by this paper. Figure 3 shows the temporal variation of the ruptures.

From Figures 2 and 3, the source region about 1 000 km length of $M_W 9.6$ earthquake in May, 1960, being unilateral rupture, lies at the south to $M_W 8.8$ shock on February 27, 2010. Approximately 400 km length of the 1906 $M_W 8.5$ earthquake appears to the north to 2010 $M_W 8.8$ earthquake. Between the source regions of the 1906 and 1960 earthquake, there is a 360 km long rupture gap where no $M_W \geq 8.0$ earthquake occurred before 2010. The $M_W 8.8$ earthquake on February 27, 2010, ruptured this part of the South American subduction zone separating the above two massive historical earthquakes. And the aftershocks not only filled in the rupture gap, but also stretched to the source region of the 1906 earthquake and to the north part of the 1960 event. The aftershock area of the $M_W 8.8$ earthquake is about 650 km long.

Figure 2 Distribution of source ruptures of $M_w \geq 8.0$ earthquakes in Chile coast since 1900. Circles and triangles denote mainshock and aftershocks, respectively.

Table 1 Source ruptures of $M_w \geq 8.0$ earthquakes in Chile coast since 1900

Date a-mo-d	Location		M_w	Source rupture/km	Information source
	ϕ°	λ°			
1906-08-17	33.00°S	72.00°W	8.5	400	Beck et al, 1998
1922-11-11	28.55°S	70.75°W	8.7	470	Kelleher, 1972
1943-04-06	30.75°S	72.00°W	8.2	360	Kelleher, 1972
1960-05-21	37.83°S	73.38°W	8.2	1000	Melnick et al, 2008
1960-05-22	38.29°S	73.05°W	9.6		
1985-03-03	33.14°S	71.76°W	8.0	210	aftershock area
1995-07-30	23.34°S	70.26°W	8.0	220	aftershock area
2001-06-23	17.28°S	72.71°W	8.4	410	aftershock area
2010-02-27	35.95°S	73.15°W	8.8	650	aftershock area

since 1973 (Figure 4b). Both $M_w 8.8$ earthquake and its aftershocks were in the gap (triangles in the ellipse area in Figure 4a).

It is also shown in Figure 4a that there is only one earthquake with $M_w 5.9$ occurred on 23 November, 2009

Figure 3 Variation of source rupture lengths of $M_w \geq 8.0$ earthquakes with time.

It is noticed that an $M_w 8.0$ quake with 210 km long fault occurred in the source rupture region of the 1906 event on March 3, 1985, indicating that the recurrence period of great earthquakes may be about 80 years in Chile coast.

Figures 2 and 3 also show that there is a 450 km long rupture gap in northern part of Chile coast from 18.0°S to 22.7°S, where a potential $M_w \geq 8.0$ earthquake might occur in the future.

2.2 The second type of seismic gap

Figure 4a shows that a 780 km long seismogenic gap elongating NNE-SSW was formed from 14 April 2005 to 26 February 2010 (the ellipse area in Figure 4a). Generally, medium to strong earthquakes are active in the region and a 4.8 years long quietude is outstanding

to the south of the seismogenic gap since 14 April 2005. In despite of low seismic activity level, it is considered that the possibility of occurrence of $M_w \geq 8.5$ earthquakes is low in few years because the 1960 $M_w 9.6$ event took place in the region and the elapsed time is short.

Figure 4 Distribution of $M \geq 5.5$ earthquakes in Chile and its vicinity (a) and M - t plot of earthquakes in the seismogenic gap (the ellipse area in Figure 4a) since 1973 (b). In Figure 4a, open circles, gray circles and triangles denote the shocks during 1973-01-01–2005-04-13, 2005-04-14–2010-02-26 and 2010-02-27–2010-03-23, respectively. The sizes of circles and triangles denote magnitudes of earthquakes, the magnitudes of earthquake sized by open circles are as the same as that by gray circles.

Similar to the patterns of the several large earthquakes in Sumatra from 2004 to 2009, there are two types of seismic gaps before the Chile $M_w 8.8$ earthquake.

The concept of two types of seismic gaps is useful to large earthquake forecasting (Xue et al, 2008). In addition, we have done tempo-spatial scanning on the seismogenic gap of $M \geq 5.5$ earthquakes in Chile coast and its adjacent regions. The result shows that there is a 420 km long seismogenic gap in the middle and northern part of Chile (23.2°S – 27.0°S) since 2001 (Figure 5a). Figure 5b is the M - t plot of earthquakes in the gap, and it indicates that the nine years quiescence of $M \geq 5.5$ earthquakes is notable. The $M_w 8.0$ earthquake in 30 July 1995 occurred in the north of the gap and its source rupture is about 220 km long. There is 1922 $M_w 8.7$ quake in the south of the gap. Assuming an 80 years recurrence period for large earthquakes, the focal rupture of 1922 $M_w 8.7$ event may have been relocked, and this area may be a potential seismic hazard region of a large earthquake.

3 Seismicity in South American block before the Chile earthquake

3.1 $M_w \geq 7.0$ earthquake quiescence in the south of Chile coast

Figure 6a shows distribution of $M_w \geq 7.0$ earthquakes in South American block and its vicinity since 1900. The seismicity level was high in this region, and the largest is the 1960 $M_w 9.6$ event. There were 44 $M_w \geq 7.0$ earthquakes in the south of Chile coast (24.7°S – 45.7°S) from 1900 to 1985, i.e., the annual frequency of $M_w \geq 7.0$ earthquakes is 0.5 averagely. However, there was only one shock, $M_w 7.1$ on 15 October 1997, from 1986 to 26 February, 2010. Namely there is a notable $M_w \geq 7.0$ earthquake quiescence 24 years before the Chile shock (Figure 6b).

3.2 $M \geq 6.5$ earthquake quiescence in South American block and its adjacent regions

Figure 7a shows the distribution of earthquakes with $M \geq 6.5$ in circum-Pacific seismic belt since 1973. The seismicity was active in normal times, while there was no strong shock of $M \geq 6.5$ from 17 November 2007 to 12 November 2009. The about two year's long quietude of $M \geq 6.5$ earthquakes before the Chile earthquake is the longest quiet time since 1973 (Figures 7b and 7c). Three and more months prior to the great Chile earthquake, an event with $M_w 6.5$ occurred on 13 November 2009 (the triangle in the dashed area in Figure 7a), 1 800 km away from the epicenter of Chile $M_w 8.8$ shock. This earthquake ended the two years long seismic quietude. To some extent, the quiescence may be regarded as a medium-short term anomaly pattern for the Chile earthquake.

4 Analysis of global deep and intermediate-depth earthquakes

4.1 Distribution of global deep and intermediate-depth earthquakes

Earthquakes can be traditionally divided into three types: shallow (focal depth less than 70 km), intermediate

-depth (depth between 70 and 300 km) and deep earthquake (depth over 300 km) by focal depth. Based on the worldwide earthquake catalogue from NEIC, the largest event is $M_W 8.2$ earthquake in South American block on 9 June 1994 (the depth is 631 km) and the shock of $m_b 5.5$ in Fiji on 23 October 1985 is the deepest one of the world (the depth is 700 km) since 1973.

Figure 5 Distribution of $M \geq 5.5$ earthquakes in Chile and its vicinity (a) and the $M-t$ plot of earthquakes in the seismogenic gap, (the rectangle area in Figure 5a) since 1973 (b). In Figure 5a open circles and gray circles denote the shocks in the period of 1 January 1973 to 31 December 2000 and 1 January 2001 to 24 March 2010, respectively. The magnitudes of earthquake sized by open circles are as the same as that by gray circles.

Figure 6 Distribution of $M \geq 7.0$ earthquakes in South American block and its adjacent regions (a) and the $M-t$ plot of $M \geq 7.0$ earthquakes in the south of Chile coast (the quietude area in Figure 6a) (b) since 1900. In Figure 6a, light circles and dark circles denote the shocks during 1900-01-01–1985-12-31 and 1986-01-01–2010-02-26 respectively. Triangle denotes the Chile $M_W 8.8$ quake. The magnitudes of earthquake sized by open circles are as the same as that by gray circles.

The distribution of global deep and intermediate-depth earthquakes from 1973 to February 2010 (Figure 8) shows that the deep and intermediate-depth

Figure 7 Distribution of earthquakes with $M \geq 6.5$ in circum-Pacific seismic belt since 1973 (a), the time interval (b) and M - t plot (c) of $M \geq 6.5$ shocks in South American black and its adjacent regions (the quietude area in Figure 7a). In Figure 7a, open circles and gray circles denote earthquakes during 1973-01-01–2007-11-16 and 2007-11-17–2010-02-26, respectively. The sizes of circles denote magnitude of earthquakes. The magnitudes of earthquake sized by open circles are as the same as that by gray circles.

earthquakes are not in everywhere of the world, and they mainly lie in South American block (No.2 region), the northwestern part (No.3 region) and the south-west part of the circum-Pacific seismic belt (No.4 region), and the western part of the northern boundary zone of Australian plate (No.1 region). Next there are intermediate-depth events in the north part of the circum-Pacific seismic belt, Myanmar arc and Hindu Kush area etc.

4.2 Enhancement of the deep and intermediate-depth earthquakes in South American block and its adjacent regions

Figure 9 shows the focal depth of earthquakes (focal depth over 100 km) varies with time in South American block and its vicinity since 1973 (No.2 region

in Figure 8). It is shown that the quakes mainly occurred in the depth range of 100–300 km and 500–600 km. The seismicity level is lower and there were 15 shocks with $M \geq 6.5$ during 1973–1992. Moreover, the largest one is $m_b 6.9$ and the annual frequency is 0.65 averagely. After 1993, there are 30 earthquakes with $M \geq 6.5$, including 11 events of $M \geq 7.0$, and the largest is $M_w 8.2$ on 9 June 1994 in Bolivia. On average, the annual frequency is about 1.8. Thus, the background of the Chile $M_w 8.8$ earthquake occurrence is the 17-year enhancement activity of the deep and intermediate-depth earthquakes.

The feature of strengthening of deep and intermediate-depth earthquake activity is also found before the

Figure 8 Distribution of global deep and intermediate-depth earthquakes from 1973 to February 2010. Open and gray circles denote the intermediate-depth (between 70–300 km) and deep (over 300 km) earthquakes, respectively. The magnitudes of earthquake sized by open circles are as the same as that by gray circles.

Figure 9 Earthquakes with depth over 100 km varies with time in South American block and its adjacent regions (No.2 region in Figure 8).

great Sumatra $M_W 9.0$ event (Xue et al, 2005). Therefore, over ten years enhancement of deep and intermediate-depth earthquakes may be a regional or a global indicator before great earthquakes. The worldwide deep earthquake activity is divided into four regions: the western part of the north boundary zone of Australian plate, South American block, the northwestern part and the southwestern part of circum-Pacific seismic belt (Figure 8). Figure 10 shows the M - t plot of the deep and intermediate-depth earthquakes in the four regions. The seismic activity strengthened synchronously from 1993 or 1994 in the four regions.

On the basis of the enhancement feature of deep and intermediate-depth earthquakes, the large shallow Sumatra $M_W 9.0$ shock occurred in the No.1 region and the Chile $M_W 8.8$ quake in the No.2 region respectively, since 2004. We may believe that there would be great

shallow quakes in the Nos.3 and 4 regions in future.

5 Activity of worldwide $M_W \geq 8.5$ events

The M - t plot of global $M \geq 8.5$ earthquakes since 1900 (Figure 11) shows that there may be three active and two quiet periods. The active periods are 1905–1923, 1950–1965 and the present time from 2004. These active periods last 18.6, 14.5 and 5.3 years, with six, seven and three great earthquakes, respectively. The two quiet periods lasted about 27 and 38 years, respectively. As shown in Table 2 and Figure 11, the period of the global large earthquakes is about 50 years. Compared with the first two active periods, the third one would still last about ten years and there would be three or four great shocks with $M_W \geq 8.5$.

Table 2 also shows that there are 13 earthquakes with $M_W \geq 8.5$ in the first two active periods, and among these events, 11 quakes are in the circum-Pacific seismic belt, accounting for 85% of all events. Namely the seismic activity level of the circum-Pacific seismic belt is far higher than that of Eurasian earthquake zone. There have been three $M_W \geq 8.5$ quakes in the third active period, in which two shocks occurred in Sumatra in the Eurasian seismic belt. The occurrence of the Chile $M_W 8.8$ earthquake shows that the circum-Pacific seismic belt enters into an active period of great earthquakes with $M_W \geq 8.5$. According to the feature of the first two active periods, there would be large shocks in the circum-Pacific seismic belt in several years.

There are 14 and 13 great earthquakes with $M_W \geq 8.0$ in the first and second active period respectively. Among them, 10 shocks occurred in the circum-Pacific seismic belt in each period, accounting for 74% of all the earthquakes. In the third active period, there are already 10 events of $M_W \geq 8.0$, of which seven events are located in

circum-Pacific seismic belt and three in the Eurasian seismic belt. Not only the number of earthquakes, but also the percentage, is less than in previous two active periods in the circum-Pacific seismic belt. So the circum-Pacific seismic belt is the main active region of $M_W \geq 8.0$ earthquakes in the future.

Figure 10 M - t plot of deep earthquakes. Focal depth of shocks is over 300 km in No.1 (a), No.3 (c) and No.4 (d) regions and the depth is over 100 km in No.2 (b) region.

Figure 11 M - t plot of global earthquakes with $M_W \geq 8.5$ since 1900.

In addition, the worldwide deep and intermediate-depth earthquakes strengthened in 1993, ten years before the enhancement of large shallow earthquakes with $M_W \geq 8.5$.

6 Conclusions

Firstly, the $M_W 8.8$ Chile earthquake in 2010 occurred in a background gap formed by $M_W \geq 8.0$ earthquake since 1900 and a seismogenic gap was formed by $M \geq 5.5$ shocks five years before. Because there are great earthquakes at south and north to the Chile $M_W 8.8$ earthquake, there may be little possibility to take place a great shock again in this region in recent years, while there is a 450 km long background gap of $M_W \geq 8.0$ earthquakes in the north part of Chile coastal region (18.0°S – 22.7°S) and a 420 km long seismogenic gap formed by $M \geq 5.5$ shocks in the north part of Chile (23.2°S – 27.0°S). These may be potential seismic hazard regions of large earthquakes.

Table 2 Statistics on global earthquakes with $M_W \geq 8.5$ since 1900

No.	Active period a-mo	Lasting time/a	Total number of earthquake		Number of earthquake in circum-Pacific seismic belt		Number of earthquake in Eurasian seismic belt	
			$M_W \geq 8.5$	$M_W \geq 8.0$	$M_W \geq 8.5$	$M_W \geq 8.0$	$M_W \geq 8.5$	$M_W \geq 8.0$
1	1905-07–1923-02	18.6	6	14	5	10	1	4
2	1950-08–1965-02	14.5	7	13	6	10	1	3
3	2004-12–2010-02	5.3	3	10	1	7	2	3

Secondly it is the long-term background anomaly that there was a notable quiescence of $M_W \geq 7.0$ earthquakes with 2 300 km long region 24 years before the

$M 8.8$ quake in the south part of Chile coastal region. Another anomaly is that there was an obvious quietude of $M \geq 6.5$ events in South American block and its adjacent

regions two years prior to the M_W 8.8 earthquake and the quietude state disappeared three months before the M_W 8.8 event. This is the medium- and short-term anomalous seismicity pattern of the Chile quake.

Next, it is similar to the great Sumatra M_W 9.0 shock in 2004, the seismic activity of deep and intermediate-depth earthquakes obviously strengthened 17 years before the Chile M_W 8.8 quake in South American block and its vicinity. The enhancement of deep and intermediate-depth earthquakes is a long-term background anomaly, and it is helpful for place forecast of large earthquakes. According to the anomalies, there would be large shallow earthquakes with $M_W \geq 8.5$ in the north-west part and south-west part of the circum-Pacific seismic belt.

Finally, the Chile M_W 8.8 earthquake shows that the global seismicity has entered into a new active period of $M_W \geq 8.5$ earthquakes since 2004. The active period would still last for about ten years and there would be several large earthquakes with $M_W \geq 8.5$ according to the features of the first and the second active periods. In addition, the circum-Pacific seismic belt will be the main active region of great quakes.

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