Characteristics of seismic activity before the $M_s8.0$ Wenchuan earthquake*

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Abstract The characteristics of spatio-temporal seismicity evolution before the Wenchuan earthquake are studied. The results mainly involve in the trend abnormal features and its relation to the Wenchuan earthquake. The western Chinese mainland and its adjacent area has been in the seismically active period since 2001, while the seismic activity shows the obvious quiescence of $M \geq 7.0$, $M \geq 6.0$ and $M \geq 5.0$ earthquakes in Chinese mainland. A quiescence area with $M \geq 7.0$ has been formed in the middle of the North-South seismic zone since 1988, and the Wenchuan earthquake occurred just within this area. There are a background seismicity gap of $M \geq 5.0$ earthquakes and a seismogenic gap of $M_L \geq 4.0$ earthquakes in the area of Longmenshan fault zone and its vicinity prior to the Wenchuan earthquake. The seismic activity obviously strengthened and a doughnut-shape pattern of $M \geq 4.6$ earthquakes is formed in the middle and southern part of the North-South seismic zone after the 2003 Dayao, Yunnan, earthquake. Sichuan and its vicinity in the middle of the doughnut-shape pattern show abnormal quiescence. At the same time, the seismicity of earthquake swarms is significant and shows heterogeneity in the temporal and spatial process. A swarm gap appears in the $M 4.6$ seismically quiet area, and the Wenchuan earthquake occurred just on the margin of the gap. In addition, in the short term before the Wenchuan earthquake, the quiescence of earthquake with $M_L \geq 4.0$ appears in Qinghai-Tibet block and a seismic belt of $M_L \geq 3.0$ earthquakes, with NW striking and oblique with Longmenshan fault zone, is formed.

Key words: Wenchuan earthquake; background seismicity gap; seismogenic gap; earthquake swarm; seismic belt; quiescence

CLC number: P315.5

Document code: A

1 Introduction

A great earthquake with $M_s8.0$ occurred in Wenchuan, Sichuan at 14:28:04 on 12 May 2008. The earthquake caused over 69 000 people death and over 18 000 people missing. The economic loss is 845.1 billion RMB Yuan.

Zhang et al (2008) obtained the moment tensor solutions and optimized double-couple solutions of the Wenchuan earthquake using the broadband and long-period seismic waveform data from the Global Seismographic Network (GSN). The focal mechanism of the Wenchuan earthquake shows that it occurred in

the main fault of the Longmenshan fault zone with predominantly thrusting and minor right-lateral strike-slip component. The scalar seismic moment of the earthquake is 4.4×10^{21} N·m, and the moment magnitude is $M_w8.3$. The rupture process lasted for 60–80 s.

A lot of studies have been made on great earthquakes (Ma et al, 1982; Mei et al, 1982, 1996; Guo and Ma, 1988; Song et al, 1999). Mei et al (1996) systematically studied the characteristics of seismic activity before 16 great earthquakes in Chinese mainland and the results showed that the seismic activity are obviously strengthened and doughnut-shape patterns of earthquakes are formed several decades before all of the great earthquakes. In the strengthening area, the seismic activity appears stage feature. Song et al (1999) reported that the seismic strengthening area universally appears before a strong earthquake by studying seismic strength-

* Received 17 February 2009; accepted in revised form 9 April 2009; published 10 October 2009.

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ening areas before 85 earthquakes with $M \geq 6.0$. In addition, he explained the phenomenon qualitatively and half-quantitatively based on the strong body earthquake generating model and the inclusion theory. However, due to the restriction of historical earthquake catalogue, the previous researches above related little to the seismic activity of minor-moderate earthquakes in the middle-short period or short term of great earthquakes.

The great Wenchuan earthquake occurred in the middle of the North-South seismic zone, where occurred numerous historical and present earthquakes. This paper studied the characteristics of seismic activity in different spatio-temporal domain before the $M_S 8.0$ Wenchuan earthquake using the Chinese historical earthquake catalogue (Department of Earthquake Hazard Prevention, State Seismological Bureau, 1995; Department of Earthquake Hazard Prevention, China Earthquake Administration, 1999), as well as the monthly and the quick bulletin of earthquake catalogue from <http://www.csndmc.ac.cn/newweb/>. And the data of active blocks and faults referred to Zhang et al (2003) and Deng et al (2003).

2 Tectonic background and historical earthquake activity of Longmenshan seismic belt

According to Zhang et al (2008), the great Wenchuan earthquake occurred on the active overthrust Longmenshan fault zone with complex structure and tectonic background, forming a boundary fault zone of the Qinghai-Xizang (Tibet) plateau block and the South China block. The late Cenozoic tectonic deformation mainly took place along the Guanxian-Jiangyou fault (the range-front fault), Yingxiu-Beichuan fault (the middle range fault) and Wenchuan-Maowen fault (the back range fault) (Xu et al, 2005, 2008; Densmore et al, 2007). The Wenchuan earthquake occurred on the Yingxiu-Beichuan fault resulted from the southeast pushing and the clockwise shearing of the Longmenshan thrust-nappe.

Xu et al (2005, 2008) and Densmore et al (2007) indicated slow slip-rate across the Longmenshan fault zone since the late Quaternary. Pre-earthquake GPS measurements in the region (Zhang et al, 2008) show that the slip rate does not excess about 2 mm/a across the entire Longmenshan fault zone and not excess 1 mm/a across individual fault, which agrees with seismological studies and historical seismicity in Sichuan. The recurrence intervals of great earthquakes can be estimated at

2 000–6 000 years. The Longmenshan fault zone develops in the metamorphic rocks with great rupture strength, and has a high dipping angle (more than 50° – 60°) near surface and low-angle at the depth of 15–20 km. The fault zone itself shows “plow-shaped” or “shovel-shaped” structure in profile, which is helpful to strain or energy accumulation to trigger great earthquake. The 12 May 2008 Wenchuan earthquake is characterized by slow slip-rate, long recurrence-interval and immense damage power (Zhang et al, 2008).

The historical earthquake activity shows that the seismic activity level of Longmenshan fault zone is not high and no $M \geq 7.0$ earthquake occurs and only five earthquakes with magnitude 6.0 to 6.5 (the maximal one $M 6.5$ on 21 April 1654 in Wenchuan); while the neighboring Minjiang fault zone is very active in seismicity, and there occurred four earthquakes with $M \geq 7.0$.

Figure 1 is the M - t chart of earthquakes with $M \geq 5.0$ in the Longmenshan seismic belt (including the Longmenshan and Minjiang fault zone). Figure 1 shows there may be two active periods with $M \geq 6.5$ since 1550. The first active period is from 1630 to 1748, lasting 119 years, and four strong earthquakes with $M \geq 6.5$ took place with the maximal one the $M 7.0$ Maowen-Diexi earthquake on 25 August 1713. Huang et al (1994) reported that earthquake catalogue is basically complete for $M_S \geq 6.0$ since 1879 and for $M_S \geq 5.0$ since 1931, respectively. The second active period began at 1933. During the first 45 years (from 1933 to 1976), the seismicity level was very high, and 29 earthquakes with $M_S \geq 5.0$ occurred, with an average of 1.6 years for one earthquake. Among these earthquakes, three with $M_S \geq 7.0$, namely the Maowen-Diexi $M 7.5$ on 25 August 1933, Songpan-Pingwu $M 7.2$ on 16 August 1976 and Songpan-Pingwu $M 7.2$ on 23 August 1976. But during the following 32 years (from 1977 to 2007), the seismic activity level is very low and only two earthquakes, i.e., the $M 5.0$ Mianzhu earthquake on 14 September 1999 and the $M 5.0$ Anxian on 30 November 1999, occurred. It

Figure 1 M - t chart of $M \geq 5.0$ earthquakes in Longmenshan seismic belt.

means a 32-year anomalous quiescence appears in the active period before the great Wenchuan earthquake (Mei, 1960).

3 Characteristics of seismic activity for strong earthquakes in Chinese mainland

3.1 Characteristics of seismic activity for strong earthquakes in western Chinese mainland after the $M_{\geq 8.1}$ western Kunlun mountain pass earthquake

Figure 2 is M - t chart of $M_{\geq 7.8}$ earthquakes in the western China and its adjacent regions (namely the “Big Triangle Area”) since 1900. Figure 2 shows the obvious active-quiet-period alternation of strong earthquakes. The 2001 western Kunlun mountain pass $M_{8.1}$ earthquake ends the 31-year-long $M_{\geq 7.8}$ quiescence of earthquakes in this area, and it also terminates the 50-year-long $M_{\geq 8.0}$ quiescence of earthquakes in Chinese mainland, marking the beginning of a new seismic active period for the “Big Triangle Area”. This can be proved by the occurrences of $M_{7.9}$ earthquake in the boundaries among Russia, Mongolia and China on September 27, 2003 and the $M_{7.8}$ earthquake in Pakistan on

October 8, 2005.

Figure 2 also illustrates that there are three active periods, i.e., 1902–1912, 1920–1934 and 1946–1957 from 1900 to 2000. Each active period lasts over ten years, during which several great earthquakes occurred. The Wenchuan earthquake took place in the fourth active period which began at 2001.

In addition, the grouping seismic activity is an important feature of strong earthquakes in Chinese mainland (Li et al, 1994, 1995; Fu et al, 2005). Seven $M_{\geq 8.0}$ earthquakes occurred from 1900 to 2000, which can be separated into three groups (Table 1). The shortest time interval between two great earthquakes in the same group is one year and the longest is seven years. The

Figure 2 M - t chart of $M_{\geq 7.8}$ earthquakes in the western Chinese mainland and its adjacent regions.

Table 1 Earthquakes with $M_{\geq 8.0}$ in Chinese mainland since 1900 and their occurring time interval

No. of group	a-mo-d	Location	M	Epicenter		Time interval /mo
				Long./°E	Lat./°N	
1	1902-08-22	Artux, Xinjiang	8.3	76.20	39.90	43
	1906-12-23	Shawan, Xinjiang	8.0	85.00	43.50	
2	1920-12-16	Haiyuan, Ningxia	8.5	104.90	36.70	76
	1927-05-23	Gulang, Gansu	8.0	102.20	37.70	
	1931-08-11	Fuyun, Xinjiang	8.0	89.80	47.10	
3	1950-08-15	Zayu, Xizang	8.6	96.70	28.40	14
	1951-11-18	Damxung, Xizang	8.0	94.40	31.10	
4	2001-11-14	Western Kunlun mountain pass	8.1	90.90	36.20	77
	2008-05-12	Wenchuan, Sichuan	8.0	103.40	30.95	

Wenchuan earthquake and the $M_{8.1}$ western Kunlun mountain pass earthquake belong to the fourth group with the interval of seven years.

3.2 Characteristics of seismic activity for $M_{\geq 7.0}$ earthquakes in western Chinese mainland since 1988

The spatial distribution of $M_{\geq 7.0}$ earthquakes in Chinese mainland shows that shocks mainly occur in the eastern tectonic syntaxis of Indo-Eurasia collision zone from January 1988 to February 1996, suggesting the characteristic of high seismic activity level in Southwest China and low in Northwest China (light circles in Figure 3). After March of 1996, the distribution of strong

earthquakes changed significantly. Shocks with $M_{\geq 7.0}$ mainly took place around the west tectonic syntaxis of Indo-Eurasia collision zone and also extended to the western part of Qinghai-Tibet block. The main active area focused on the Kunlun mountain fault zone and its vicinity. A huge earthquake belt with striking EW is then formed (gray circles in Figure 3). The middle part of the North-South seismic zone was seismically quiet, where the $M_{8.0}$ Wenchuan earthquake occurred (Figure 3).

Figure 4 shows the quasi-period feature of $M_{\geq 7.0}$ earthquakes in South-North seismic zone of Chinese mainland. Averagely, the active period lasts about 18

years. The seismic activity level is high at the beginning of each period and then decreases gradually (China Earthquake Networks Center, 2007). The most recent active period began on 6 November, 1988 ($M7.6$, $M7.2$ Lancang-Gengma earthquake in Yunnan), and lasted for 20 years. By 2007, 26 earthquakes with $M\geq 6.0$, five earthquakes with $M\geq 7.0$ occurred with the largest one $M7.6$. The Wenchuan earthquake ended the 12-year long earthquake quiet and began a new active period.

Figure 3 Distribution of earthquakes with $M\geq 7.0$ in western China and its adjacent region since 1988. Light circles and gray circles denote earthquakes during 1988-01-01–1996-02-29 and 1996-03-01–2008-05-11, respectively.

Figure 4 M - t chart of earthquakes with $M\geq 7.0$ in the North-South seismic belt.

Another feature is strong earthquakes with $M\geq 7.0$ in North-South seismic zone migrate from the south to the north (China Earthquake Networks Center, 2007). Three migration patterns appeared from 1900 to 1987. The fourth migration pattern began at 1988 when two groups of earthquakes occurred in the southern section and in the vicinity of latitude 27°N (Lancang-Gengma shock with $M7.4$, $M7.2$ in 1988, Menglian $M7.3$ in 1995 and Lijiang $M7.0$ event in 1996). It is deduced that the middle and northern section of the North-South seismic zone will be the seismic risk regions. The occurrence of the Wenchuan earthquake obeys the rules above.

4 Characteristics of seismic activity for moderate-strong earthquakes in Chinese mainland before the Wenchuan earthquake

4.1 Notable $M\geq 6.0$ and $M\geq 5.0$ earthquake quiescence

On the basis of statistics, 756-day long quiescence of $M6.0$ earthquakes from 9 April 2005 to 4 May 2007 is the longest quiet time since 1900. Five notable quiescences with the quiet time more than 500 days appeared since 1900 (Table 2). Within one year after three of the anterior four seismic quiescences, there were earthquakes with $M\geq 7.0$ in Chinese mainland. For the other one, although there no $M\geq 7.0$ earthquake occurred in Chinese mainland, a $M8.3$ event occurred in Mongolia, 300 km away from China. The Yutian $M7.3$ shock on 21 March 2008 and the Wenchuan $M8.0$ event on 12 May 2008 occurred one year after the $M6.1$ Ritu-Gaize earthquake on 5 May 2007 in Tibet, which ended the fifth outstanding seismic quiescence with 756-day long.

A group of moderate-strong earthquakes occurred from May to July 2007 after the ending of the 756-day long quiescence of $M6.0$ earthquake, but 172-day long $M5.0$ earthquake quiescence appeared from July 20, 2007 to January 8, 2008 (Figure 5). There are only eight

Table 2 Statistics on the quiescence time over 130 days of shallow earthquakes with $M\geq 5.0$ in Chinese mainland

No.	Quiet interval	Lasting duration/d	The ending earthquake	Succeeding earthquake in one year
1	1968-05-15–1968-12-22	221	$M5.4$ Hualong, Qinghai	Bohai $M7.4$ in 18 July 1969
2	1969-02-12–1969-07-18	156	$M7.4$ Bohai	Tonghai, Yunnan, $M7.8$ in 5 January 1970
3	1978-10-08–1979-03-02	145	$M5.3$ Guzhen, Anhui	No
4	1983-06-29–1983-11-06	130	$M6.0$ Ulan Ul lake, Qinghai	No
5	1984-05-21–1984-11-23	186	$M5.3$ Lingwu, Ningxia	Wuqia, Xinjiang, $M7.1$ in 23 August 1985
6	1994-02-16–1994-06-30	133	$M6.3$ Tanggula mountain, Qinghai	Menglian, Yunnan, $M7.3$ in 12 July 1995
7	2001-12-08–2002-06-04	178	$M5.7$ Burang, Xizang	No
8	2007-07-20–2008-01-08	172	$M6.9$ Zhongba, Xizang	Yutian, Xinjiang, $M7.3$ in 21 March 2008 Wenchuan, Sichuan, $M8.0$ in 12 May 2008

obviously seismic quiescences that the quiet time is over 130 days since 1950. Six of the anterior seven seismic quiescences were ended by $M5.3$ – 6.3 earthquake and during one year after four of them $M\geq 7.0$ earthquakes occurred in Chinese mainland, but the magnitude does not excess $M7.5$. There is only one special phenomenon that 156-day long quiescence was ended by Bohai $M7.4$ shock and after half a year Tonghai $M7.8$ earthquake took place. The Gaize $M6.9$ event in January of 2008 finished the outstanding 172-day long $M5.0$ earthquake

quiescence and in the short time of four months, Yutian $M7.3$ and Wenchuan $M8.0$ occurred one after another.

It is noticed that six earthquakes with $M\geq 5.0$ in 2007 occurred, which is the least annual earthquake frequency since 1950 (excluding aftershocks). The average annual number of shocks with $M\geq 5.0$ is 20 in Chinese mainland since 1950. On the basis of statistics, there are four cases with annual frequency lower than eight, that is, eight earthquakes in 1968, seven in 1984, seven in 2002 and six in 2007. Within one year after the

Figure 5 M - t chart of shallow earthquakes with $M\geq 5.0$ in Chinese mainland since 2001.

Figure 6 Distribution of earthquakes with $M\geq 4.6$ before (a) and after (b) the 2003 Dayao earthquake and M - t chart of earthquakes in the quiescence area delineated in subfigure (b) since 1988 (c). In subfigure (a), the light circles denote earthquakes during 2001-11-14–2003-07-20. In subfigure (b) the light circle and the gray circle denote earthquakes during 2003-07-21–2008-02-26 and 2008-02-27–2008-05-11, respectively.

first three cases, Bohai $M7.4$ in 1969, Wuqia $M7.4$ in 1985 and $M7.9$ in 2003 at the boundary of China, Russia and Mongolia occurred respectively in or around Chinese mainland.

The obviously seismic quiescence of $M7.0$, $M6.0$ and of $M5.0$ indicates that the seismic activity level of Chinese mainland is rather low after the 2001 western Kunlun mountain pass $M8.1$ earthquake.

4.2 Characteristics of the seismic evolution for $M \geq 4.6$ earthquakes after the 2001 western Kunlun mountain pass $M8.1$ earthquake

Figure 6 shows the epicentral distribution of earthquakes with $M \geq 4.6$ before and after the 2003 Dayao earthquake in Qinghai-Tibet block. As shown in Figure 6, earthquakes are mainly distributed in the aftershock zone and its vicinity in 20 months after the 2001 $M8.1$ western Kunlun mountain pass earthquake, while the seismic activity level of the North-South seismic zone is rather low and there was only one earthquake, the $M5.3$ Xinlong event on 8 August 2003 (Figure 6a).

Beginning with the Dayao earthquake, the seismic activity obviously strengthened. It is noticed that a doughnut-shape pattern of $M \geq 4.6$ earthquakes is formed in the middle and the southern part of the North-South seismic zone. Located in the middle of the doughnut-shape pattern, Sichuan and its vicinity are abnormally quiescent, while 22 earthquakes with $M \geq 4.6$, including three with $M \geq 6.0$, took place with the biggest one the $M6.3$ Ning'er event on 3 June 2007 in the ringed area. Two and more months prior to the great Wenchuan earthquake, the $M4.6$ Kangding event occurred on 27 February 2008, 170 km away from the epicenter of Wenchuan $M8.0$ shock, ending the 4.5-year long seismic quiescence. To some extent, it may be regarded as a signal event for occurrence of the Wenchuan earthquake (Wang et al, 2004). Many active fault zones, such as Longmenshan, Xianshuihe, Anninghe and Zemuhe fault zones, are distributed in the seismic quiescence area (Figure 6b). The $M-t$ chart of earthquakes in the quiet area (Figure 6c) illustrates that the seismic activity level of this area is high from 1988 to 2002, in which the Lijiang $M7.0$ shock occurred in 1996. But it is noticed that there was no earthquake with $M \geq 4.6$ in 4.5 years before the Wenchuan $M8.0$ earthquake.

5 Background and seismogenic gap of the Wenchuan earthquake

5.1 Background seismicity gap

Figure 7 shows the distribution of earthquakes with $M \geq 5.0$ in Sichuan and its vicinity. The seismic activity level was high from 1930 to 24 February 1970 (light circles in Figure 7a), while there was no earthquake on the Longmenshan fault and its neighboring area from 25 February 1970 to 13 September 1999, and a NE-striking, 400 km long background gap (dashed oval area in Figure 7a) was formed. Figure 7b is the $M-t$ chart of earthquakes in the background seismicity gap, and it shows that the 38-year long quiescence of $M \geq 5.0$ earthquakes is the most outstanding phenomenon since 1930 (Figure 7b). The $M5.0$ Mianzhu shock on 14 September 1999 and the $M5.0$ Anxian event on 30 November 1999 occurred in the gap, and from then on there was no earthquake with $M \geq 5.0$ until the $M8.0$ Wenchuan earthquake occurrence (Figure 7a).

Figure 7 Background gap with $M \geq 5.0$ earthquakes (a) and $M-t$ chart of earthquakes in the seismic gap (b). In subfigure (a), light circles, gray circles and solid circles denote $M \geq 5.0$ earthquakes during 1930-01-01–1970-02-24, 1970-02-25–1999-09-13 and 1999-09-14–2008-05-11, respectively.

5.2 Seismogenic gap with $M_L \geq 4.0$

Distribution of $M_L \geq 4.0$ earthquakes in Sichuan and its vicinity (Figure 8a) shows that a NE striking seis-

mogenic gap with 400 km long was formed from 1 September 2001 to 10 March 2007. In normal time, moderate earthquakes are active in the gap and the 5.5-year long quiescence is outstanding since 1988 (Figure 8b).

In the process of the gap evolution, seismic activity of the peripheral area (it may be regarded as the area by enlarging the gap into a bigger one, 1.3 times of the old one and then subtracting the old gap) was strengthened and the curve of strain release began to go up from 2004 to 2007 and then turned to flat (Figure 8c). During this period the $M_{5.2}$ Minxian, Gansu on 13 November 2003,

the Minxian $M_{5.0}$ on 7 September 2004, and the Wenxian $M_{5.0}$ event on 21 June 2006 occurred in the peripheral area. Among them, the noticeably event is the Barkam earthquake swarm in Sichuan. The swarm began on 14 December 2004 and ended on 30 October 2007, in which 309 $M_L \geq 2.0$ earthquakes occurred, and the number of $M_L 3.0-3.9$ and $M_L 4.0-4.9$ is 41 and 5 respectively with the biggest magnitude $M_L 5.0$. Based on the above analysis, this gap is a seismogenic gap (Lu et al, 1982, 1983).

Figure 8 Seismogenic gap of the Wenchuan earthquake (a), the $M-t$ chart of earthquakes in the gap since 1988 (b) and strain release for the area near the gap (c). In subfigure (a) light circles and gray circles denote the earthquakes during 2001-09-01–2007-03-10 and 2007-03-11–2008-05-11, respectively.

It is noticed that the seismic activity in the two ends of the seismogenic gap increased markedly from 11 March 2007 to occurrences of the Wenchuan earthquake. The successive occurrences of the $M_L 4.2$ Qingchuan shock on 11 March 2007, the $M_L 4.3$ Songpan event on 27 April 2007, the $M_L 4.3$ Hanyuan shock on 31 July 2007, the $M_L 4.4$ Kangding shock on 16 February and the $M_L 4.6$ Kangding event on 27 February 2008 narrowed the gap, which maybe a signal that the preparation of the $M_{8.0}$ Wenchuan earthquake is in the middle-short term phase (Lu et al, 1982, 1983).

6 Characteristics of seismic activity for small earthquake before the $M_{8.0}$ Wenchuan earthquake

6.1 Seismicity of small earthquake swarms

Jiang and Chen (1983) and Xue and Mei (1999)

suggested that the high seismic swarm activity can be regarded as a significant feature of middle-short term before great earthquakes. According to the principles of selecting earthquake swarms by Jiang and Chen (1983), we select 55 swarms with $M_L \geq 3.0$ in Qinghai-Tibet block since 2002. The 83.6% of them are distributed in the southern and the middle part of the North-South seismic zone. Figure 9a shows the distribution of swarms from 21 July 2003 to 11 May 2008. It illustrates that swarms mainly occur in the brim of the seismic quiet area of $M \geq 4.6$ earthquakes; moreover, most of the swarms concentrate in the western Yunnan and the eastern boundary area of Yunnan and Sichuan, forming a swarm belt with NE striking. The marked swarms are $M_L 5.0$ Barkam on 14 November 2004, the $M_{5.1}$ Ludian on 15 November 2003, the $M_{5.3}$ Huize on 5 August 2005 and the $M_{5.1}$ Yanjin on 22 July 2006.

Figure 9a also shows that a swarm gap is formed in

the seismic quiet area of $M \geq 4.6$ earthquakes. The $M 8.0$ Wenchuan earthquake occurred at the brim of the gap. There was only one swarm, the $M_L 3.3$ Kangding, in the gap from 21 July 2003 to the end of 2006; while the $M_L 4.1$ Kangding and $M_L 3.1$ Xinlong swarm occurred in 2007, and the $M_L 3.8$ Zipingpu swarm, which is 20 km away from the epicenter of the Wenchuan earthquake, occurred on 14 February 2008 in the gap (gray circles in Figure 9a). It demonstrates the activity of swarms around the Wenchuan earthquake was strengthened with the increased stress field before the great Wenchuan shock.

Figure 9 Distribution of earthquake swarms in Qinghai-Xizang block (a) and variation of swarm frequency (N) with time (b). In subfigure (a), light circles and gray circles denote earthquakes during 2003-07-21–2006-12-31 and 2007-01-01–2008-05-11, respectively.

As shown in Figure 9b, the curve of the swarm frequency (six-month long sliding window and one-month long sliding step) indicates that the average frequency value of annual earthquake swarms is 4.5 in Qinghai-Tibet block and there are three peak values since 2002. The first peak may be related with the 2001 western Kunlun mountain pass $M 8.1$ earthquake. The second peak value, 8.0, appeared in January of 2005, which is mainly caused by the $M_W 9.0$ Sumatra earthquake. The third peak value, 10, the most outstanding

one compared with the two other peak values, appeared during November to December of 2007. Four months after the anomalous high value, it returned to normal, then the great Wenchuan earthquake occurred.

6.2 Seismicity of small earthquakes in short term before the Wenchuan earthquake

Based on scanning, there are two obvious quiescence of $M_L \geq 4.0$ earthquakes in Qinghai-Tibet block. One is that the marked 103-day long quiescence of $M_L \geq 4.0$ earthquakes appeared in Qinghai-Tibet block from 2 October 2007 to 12 January 2008 (the dashed circle in Figure 10a). The quiescence state was broken by the $M 4.6$ Kangding event. Before the Wenchuan earthquake the quiescence region reduced to Bayan Har block (the shadow area in Figure 10a) from 12 January 2008 to May 11, and the great Wenchuan shock occurred just in the east boundary zone of the block (Figure 10a).

The other is that the notable 107-day long quiescence of $M_L \geq 4.0$ earthquakes appeared from 2 October 1972 to 17 January 1973 and then the quiet region reduced to Sichuan-Yunnan rhombic block and its vicinity. The 1973 $M 7.6$ Luhuo earthquake occurred in the northeastern boundary zone 19 days after the quiescence state was broken (Figure 10b).

Form the two obvious quiescences before the Wenchuan and Luhuo earthquakes, a similar evolvement process can be found. A large quiet area appeared around several active blocks in the short term before great earthquakes, with the strengthening of the seismic activity, and the quiet area is gradually narrowed to the block where the great earthquake occurred.

Figure 11 shows the distribution of $M_L \geq 3.0$ earthquakes in Sichuan and its vicinity from January 22 to May 11, 2008. A seismic belt with NW striking, oblique to the Longmenshan fault zone, is formed in the seismogenic gap, three months prior to the Wenchuan earthquake. It is noticed that an unusual earthquake swarm with $M_L 3.8$ occurred in the area of Zipingpu reservoir in the seismic belt on 14 February 2008.

7 Discussion and conclusions

According to the results above, some characteristics of seismic activity in different spatio-temporal domain before the great Wenchuan earthquake are obtained, which may be significant for prediction of great earthquakes.

1) The seismic activity of $M \geq 7.8$ earthquakes in the western China and its vicinity has been in the active

Figure 10 Distribution of $M_L \geq 4.0$ earthquakes in Qinghai-Xizang block and its vicinity before the Wenchuan earthquake (a) and before the Luhuo earthquake (b). In subfigure (a), light circles and gray circles denote earthquakes during 2007-10-02–2008-01-12 and 2008-01-13–2008-05-11, respectively; in subfigure (b) light circles and gray circles denote earthquakes during 1972-10-02–1973-01-17 and 1973-01-28–1973-02-05, respectively.

Figure 11 Distribution of earthquakes with $M_L \geq 3.0$ in Longmenshan seismic belt and its vicinity from 22 January to 11 May 2008.

stage since 2001, while the seismic activity level of Chinese mainland become lower and lower during the same time. The 6.5-year long quiescence of $M \geq 7.0$ earthquakes, the 756-day long quiescence of $M \geq 6.0$ shocks and the 172-day long quiescence of $M \geq 5.0$ events appeared in succession, which is an important feature of seismic activity in Chinese mainland before the great Wenchuan earthquake.

2) The quiescence of $M \geq 7.0$ earthquakes in the

North-South seismic belt has lasted twelve years since the 1996 $M7.0$ Lijiang event and a new active period will begin. Historical earthquake activity indicates that the magnitudes of earthquakes at the beginning of the active periods are relative large. Another feature of earthquakes with $M \geq 7.0$ in this region is the migration from south to north in space distribution. The occurrence of the great Wenchuan earthquake, being in full compliance with the spatio-temporal characteristics of historical earthquakes, has started a new active period.

3) The space distribution of $M \geq 7.0$ earthquakes indicates that a notable quiet area, where the great Wenchuan earthquake occurred, appeared in the middle part of the North-South seismic zone since 1988.

4) The seismic activity was obviously strengthened and a doughnut-shape pattern of $M \geq 4.6$ shocks was formed in the middle and the southern part of the North-South seismic zone after the 2003 $M6.2$ Dayao event. Sichuan and its vicinity, the middle of the doughnut-shape pattern, are markedly quiet. At the same time, earthquake swarm activity is also very significant, and shows heterogeneity in the temporal and spatial process. A swarm gap appears in the $M4.6$ seismically quiet area, and the great Wenchuan earthquake occurred in the brim of the gap. Swarm frequency curve shows high anomaly eight months before the Wenchuan earthquake, exceeding twice RMS. And the great earthquake occurred four months after the high value anomaly ended.

5) According to the historical earthquake activity, there were no $M \geq 7.0$ events on Longmenshan fault zone before the great Wenchuan earthquake. A background seismicity gap with $M \geq 5.0$ earthquakes was formed in Longmenshan seismic belt 38 years before the Wenchuan earthquake. A seismogenic gap of $M_L \geq 4.0$ shocks with 400 km long and NE striking was formed in the same area 6.5 years prior to the shock. It is noticed that one year before the shock, the successive occurrence of some particular earthquakes with $M_L 4.0-5.0$ in Longmenshan fault zone and its two ends caused the seismogenic gap narrowed.

6) The 103-day long quiescence of earthquake with $M_L \geq 4.0$ appeared in Qinghai-Tibet block seven months prior to the Wenchuan earthquake, then the quiet region reduced to Bayan Har block and the shock just occurred on the east boundary zone of the block. A seismic belt of $M_L \geq 3.0$ events with striking NW, oblique with Longmenshan fault zone, was formed in the seismogenic gap three months prior to the Wenchuan earthquake. It is noticed that an earthquake swarm of $M_L 3.8$ occurred in the area of Zipingpu reservoir in the seismic belt on 14 February 2008.

The analysis above indicates that a series of seismic activity anomalies appear in different spatio-temporal domain before the great Wenchuan earthquake. Most of them are noticed in daily seismic tendency tracing work, but some improper judgments were got. Reasons are as follows: ① For the outstanding quiescence anomalies of $M \geq 7.0$, $M \geq 6.0$ and $M \geq 5.0$ earthquakes, we thought that the seismic activity of Chinese mainland was in the relative seismic quiet period and it will be a process of gradually strengthening (China Earthquake Networks Center, 2007). It is completely unexpected that the $M 6.9$ Gaize shock on 9 January 2008, the $M 7.3$ Yutian event on 21 March 2008 and the great Wenchuan earthquake occurred one after another in such a short time of five months. ② It is imperipient for the seismic hazard of Longmenshan fault zone. Though the Longmenshan fault zone is the eastern boundary zone of the Bayan Har block, but its seismic activity level was greatly low and there were no $M \geq 7.0$ earthquakes before the great Wenchuan earthquake, resulting in, to some extent, the underestimation of the seismic risk. On the basis of these situations, some seismic anomalies appearing in the process of seismic tendency tracing were respectively attached to the seismic risk area, the juncture region of Tibet, Qinghai, Si-

chuan and Yunnan.

Because of the reasons above, we are imperipient for the large-scale quiescence of Sichuan and its vicinity since 2003, and do not synthetically take into account the seismic strengthening and the kinds of anomalous precursors which appeared in the juncture of Gansu, Qinghai and Sichuan and the eastern juncture of Sichuan and Yunnan provinces. In the process of actual work we took these anomalous precursors into two seismic risk areas.

This paper shows that seismic activity features in the preparation process of great earthquakes are different from those moderately strong shocks. For the great earthquake, the spatio-temporal scope involved in the preparation process is greatly large. Namely it involves thousands to hundreds of kilometers in space and at least lasts several decades, years to months in temporal process. The notable feature of seismic region and its vicinity is quiet and seismic activity anomalies of small and moderate earthquakes usually appear one year before the great earthquake. In short term, the features are only the $M_L \geq 4.0$ quiescence and the $M_L \geq 3.0$ seismic belt. Therefore it is difficult to give correct judgments if there is no correct earthquake tendency estimation. Consequently, it needs further study that how to give a correct earthquake tendency estimation, how to combine the anomalous precursors of the long-term, mid-term, short-term and impending-period and how to synthetically analyze all kinds of anomalous phenomena.

Judgment of the active and quiet period is important in the analysis process of earthquake tendency estimation. For a region, no matter how large or small, it should be separated into active or quiet periods, but in different time the judgment criterion is different. For the earthquake prediction research of Chinese mainland, the criterion is the activity of $M \geq 7.0$ earthquakes which is obviously factitious. It is more reasonable to judge active and quiet period by actual seismic activity.

Acknowledgements This research was supported by the Key Project of Chinese National Programs for Fundamental Research and Development (973 program, No. 2008CB425704 and 2004CB418406). This paper was accomplished based on the summarization and reflection for Wenchuan $M 8.0$ earthquake in earthquake prediction field. We are very grateful to many professors for their advice and assistance. We thank two anonymous reviewers for their valuable comments.

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