The implications of regional microseismic activities: a lesson from 2008 Ms 8.0

Wenchuan earthquake

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Abstract

The Ms 8.0 Wenchuan earthquake has greatly perturbed the crustal stress in Longmenshan fault zone (LFZ) and its neighboring regions, and hence significantly changed the regional seismicity pattern. Convectional coulomb stress change model based on half-space dislocation source of layered elastic or viscoelastic crust can only provide brief reference to estimate the after-shock sequences roughly. In this study, we apply the Z-test statistical method to examine the earthquake catalogue five years before and after this event to detect the changes of regional seismicity intensity and their statistical significance in LFZ and its neighboring regions. We analyze changes of the Z values with respect to time and seismic magnitude in each region. Our results reveal that, after the Wenchuan earthquake, seismicity intensity has significantly increased in Eastern Kunlun fault, southern Longmenshan fault, Longquanshan

1 fault and Huayingshan fault in Sichuan basin, but has significantly decreased in northern and
2 central Longmenshan fault, vicinity of the Songpan-Minjiang fault, and Fubianhe fault in
3 Bayankala block, respectively. Seismicity rate change in northern and central
4 Anninghe-Zemuhe fault zone is not correlated with the Wenchuan earthquake. These results
5 remain within 99% confidence level of the Z-test statistical method. We compare our
6 statistical analysis results with calculations of coseismic Coulomb failure stress change due to
7 the Wenchuan earthquake from previous studies. In most of the regions and fault zones, the
8 sign of the seismicity rate change agrees with the sign of the Coulomb stress change.

9

10 Key words: Micro-seismicity; the Ms 8.0 Wenchuan earthquake; seismicity intensity analysis;
11 Coulomb stress change;

12

13 **1. Introduction**

14 On 12 May 2008, the great devastating Ms 8.0 Wenchuan earthquake struck the eastern
15 margin of Tibetan Plateau and significantly redistributed the regional stress in Longmenshan
16 fault zone (LFZ) and its neighboring regions (Parsons et al., 2008; Toda et al., 2008b).
17 Previous studies calculated the coseismic Coulomb stress change induced by this catastrophic
18 event and discussed the subsequent effects following this event on the seismicity along LFZ
19 and its neighboring fault zones (Liu et al., 2014; Luo and Liu, 2010; Parsons et al., 2008;
20 Toda et al., 2008a; Wan et al., 2009). These studies used either analytical elastic dislocation
21 model, or more complex 2-D and 3-D numerical models (Shan et al., 2009; Wan and Shen,
22 2010; Wu et al., 2013) to calculate Coulomb stress change, and proposed hastening or

1 retarding of the nucleation of earthquakes on its neighboring fault zones. They are mainly
2 based on simplified geological modeling and assumptions of parameters of heterogeneous
3 material, fault geometry, coseismic fault slip and fault rupture mechanism. Therefore,
4 different works may bring model variance and hence big difference, and may introduce
5 unacceptable artificial uncertainties to seismic hazard analysis and mitigation after this huge
6 and complex event.

7 Coulomb failure stress has been demonstrated to be an efficient tool to analyze the aftershock
8 nucleation (Geller, 1997; Stein et al., 1997; Stein et al., 1992). Due to insufficient constraints
9 and lack of reliable measurements during geological survey, the full tectonic stress field of the
10 crust still cannot be determined in advance to date. Thus, these models mentioned above can
11 only adopt the Coulomb failure stress change (ΔCFS) to quantitatively evaluate the influence
12 of the major event on the post-seismic nucleation and its triggering mechanism. According to
13 the Mohr-Coulomb theory and the Hook-Brown strength criteria (Gahalaut and Hassoup,
14 2012; King et al., 1994; Stein et al., 1992), ΔCFS on the existing fault plane is

$$15 \quad \Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta p) + \Delta\mu(\sigma_n + p), \quad (1)$$

16 where $\Delta\sigma_n$ is normal stress change on the fault plane, $\Delta\tau$ is shear stress change in slip
17 direction on the fault plane, μ is friction coefficient on the fault plane, p and Δp are the pore
18 pressure and its change on the fault plane, respectively. We also assume that seismogenic
19 upper crust stays within a critical state due to its long-term earthquake-cycle evolution and a
20 small amount of stress perturbation may induce failure of the seismogenic fault. We then
21 calculate ΔCFS to determine if a synthetic epicenter or the existing fault is more dangerous or
22 safer. Or the fault is prone to slip if ΔCFS is positive, but the fault becomes more stable if
23 ΔCFS is negative.

24 The problem is, however, the in-situ values of these critical parameters in Eq.(1) cannot be
25 determined accurately. For example, the $\Delta\mu$ in the third term of the right-hand side is too
26 difficult to be analyzed during the fault-slip procedure based on the existing effective

1 constraints and experimental conditions. Moreover, since the total background stress state is
2 unknown, as essentially required by the Coulomb-Mohr failure criterion (Byerlee, 1969), this
3 methodology cannot be considered as a reliable criterion for fault slip judgment eventually
4 (Kagan et al., 2012; Stein et al., 2012, 2013).

5 Then, one realistic question arises up: Can we practically figure out reliable constraints to
6 trace the stress migration and predict major seismic activities following large earthquake
7 event? Large earthquake may lead to regional seismicity change greatly (Toda et al., 2008b).

8 Post-seismic change of seismicity following the major event is a direct and visible indicator
9 of regional stress migration which can directly reflect the aftershock nucleation or triggering
10 of the future events (Brodsky and Lay, 2014; Gahalaut and Hassoup, 2012; King et al., 1994;
11 Stein et al., 1992). With the help of broadband seismicity observations and statistical methods
12 in recent decades, studies in statistical seismology have been making considerable progress. It
13 provides alternative insights into the mechanism of regional stress migration and aftershock
14 nucleation in the crust at depth. Statistical methods based on hypothesis tests, such as Z-test
15 (Habermann, 1981, 1983a), β -test (Wyss and Habermann, 1988), P-test and γ -test methods
16 (Marsan and Nalbant, 2005b), have been introduced to measure the significance of seismicity
17 rate changes before and after big earthquakes.

18 After the great Ms 8.0 Wenchuan earthquake, the local seismicity pattern underwent
19 significant change along the seismogenic LFZ and its neighboring regions. Both the number
20 and their frequency of regional seismic events have sharply increased in some regions, but
21 also have dropped in some other regions. In this study, we adopt the well accepted Z-test
22 statistical method to analyze the earthquake catalogue before and after the Wenchuan
23 earthquake to examine the Wenchuan earthquake-induced seismicity rate change in LFZ and

1 its neighboring fault zones, and compare our results with the calculation results of Coulomb
2 stress change in previous studies. We have two primary objectives. The first one is to compare
3 and validate coseismic Coulomb stress change pattern induced by the 2008 great Wenchuan
4 earthquake with seismicity rate change pattern before and after this event in these fault zones.
5 The second one is to figure out to what extent are these seismicity rate changes correlated to
6 the 2008 great Wenchuan earthquake. To achieve these goals, we analyze Z-test value as a
7 function of time and seismic magnitude in different spatial-temporal windows.

8

9 **2. Method and data**

10 **2.1. Z-test method**

11 In recent years, many statistical methods for estimating seismicity rate change and
12 significance level have been developed. Marsan and Nalbant (2005a) introduced the P value
13 and γ value statistical methods, which suggest that the earthquake frequency change passes
14 the 95% confidence interval of hypothesis test when $|\gamma|=1.6$ (Marsan and Nalbant, 2005a).
15 Matthews and Reasenberg (1988) proposed the β -value statistics, obeying the Gaussian
16 distribution with mean value of 0 and standard deviation of 1. But it is inconvenient to be
17 utilized as the significance level of seismicity frequency change cannot be directly given by
18 the threshold of β interval. For each significance level, the Z-test has a single critical value
19 which makes it more convenient if the sample size is large or the population variance is
20 known. Therefore, the Z-test statistical method proposed by Habermann in statistical
21 seismology has been widely applied, which can assess the significance of deviations from a
22 stationary Poisson process in specific temporal and spatial windows(Habermann, 1983b;

1 Sarah et al., 2016). $|z|=1.96$ indicates that the earthquake frequency change passes the 95%
2 confidence interval of hypothesis test which is similar to the β -test statistical method
3 (Habermann, 1981, 1983b).

4 Therefore, in this study, we adopt the Z-test statistics to detect the notable change of the
5 seismic activity in a regional scale. Basically, this method is based on the central limit
6 theorem, is applied to compare the differences between the average values of two independent
7 samples from the same sequence (Habermann, 1987a; Meyer, 1975a). This theorem can be
8 briefly described as: given the arithmetic mean of a sufficiently large number of iterates of
9 independent random variables, each with a well-defined expected value and well-defined
10 variance, will be approximately normally distributed (Lawley, 1938). It is capable of
11 conveniently abstracting the complicated data sets from regional seismicity sequence by
12 different time and space windows, and identifying their significance with strict statistics
13 (Toda et al., 1998; Wyss and Habermann, 1988). Under the null hypothesis, the Z value is
14 defined as

$$15 \quad z = \frac{\mu_1 - \mu_2}{\sqrt{\sigma_1^2/n_1 + \sigma_2^2/n_2}} \quad (2)$$

16 where n_1 and n_2 are numbers of the events of two sets of earthquake clusters with μ_1 and μ_2 as
17 their mean values, which are normally distributed by central limit theorem, and their standard
18 deviations are σ_1 and σ_2 , respectively. The 90%, 95% and 99% significance levels correspond
19 to z values of 1.64, 1.96 and 2.57 (Habermann, 1981, 1987b; Meyer, 1975b; Wyss and
20 Habermann, 1988).

21

22 **2.2. Earthquake clustering**

1 We download and utilize microseismic catalogue data in Chuandian region (27° - 35° N,
2 99° - 106° E) from China Earthquake Networks Center affiliated to Chinese Earthquake
3 Administration (<http://www.csndmc.ac.cn/wdc4seis@bj/>). We then extract seismic data of ~5
4 years before and after the 2008 Ms 8.0 Wenchuan earthquake respectively to analyze regional
5 seismicity rate changes after this big event. We elaborately select the time window as January
6 1, 2003 to April 20, 2013, right before the Ms 7.0 Lushan earthquake occurred, as Lushan
7 earthquake is considered to be heavily impacted by the 2008 Wenchuan earthquake. Therefore,
8 during this nearly ten-year time window, no event greater than Ms 6.0 main shock has
9 occurred in our study regions. To avoid observation data uncertainties and to guarantee that
10 the statistical results are physically correlated to the regional stress migration before and after
11 the Wenchuan earthquake, we first partition LFZ and its neighboring fault regions with
12 different schemes, and we select the most reasonable spatial clustering according to the
13 geological settings, most importantly, fault systems, as well as spatial epicenter distribution
14 pattern of earthquake catalogue in the study region. The partitioned fault zones and their
15 correspondent earthquake clusters in our study region are shown in Fig. 1. Note that we
16 uniformly apply local magnitude M_L for data consistency.

Fig. 1. Earthquake clustering according to fault zones in our study region. The background colors show topography and the red solid curves show faults in this region. The red and blue spots represent epicenters of seismic events ~5 years before and ~5 years after Wenchuan earthquake, respectively. The two focal mechanism beach ball diagrams represent the epicenters of the 2008 Ms 8.0 Wenchuan earthquake and the 2013 Ms 7.1 Lushan earthquake, respectively. F1: eastern Kunlunshan fault zone; F2: Minjiang fault zone; F3: Huya fault zone; F4: Wubianhe fault zone; F5: Longmenshan fault zones; F6: Longquanshan fault zone; F7: Mabian-Zhaotong fault zone; F8: Huayingshan fault zone; F9: Zemuhe fault zone; F10: Xianshuihe fault zone; F11: Anwuhe fault zone; F12: Sanyanlong fault zone.

2.3. The spatial distribution of completeness magnitude of earthquake catalogue

In seismicity studies, the basic premise is that the analysis method of adopting seismic catalogue data, while a critical factor influencing the quality of seismic catalogue data is the choice of minimum Magnitude of Completeness(M_c) (Wiemer and Wyss, 2000). M_c means that the all earthquakes have been completely and correctly recorded when their magnitudes are no less than M_c . Practically, a small variation in minimum M_c may lead to 25% change of earthquake catalogue volume when $b=1$. Therefore, the evaluation of M_c is of the most important for earthquake clustering analysis, for examples, the time-dependent seismic hazard analysis, the transient change of earthquake occurrence rate, and the static and dynamic earthquake triggering associated with stress and strain variance.

Therefore, in this study, picking of the minimum magnitude of the completeness of earthquake catalogue is an essential and complex task during data processing.

Underestimation of M_c may embrace irrelevant information and deliver non-objective or even wrong judgment. On the contrary, picking a larger M_c to guarantee the completeness may, however, bring about important information omission. Or more importantly, the total number of earthquake catalogue data will be insufficient to meet the minimum prerequisite of Gaussian distribution, and the credibility of statistical analysis will be affected eventually.

Due to the increasing of broadband seismic stations and technology improvement, obviously, M_c is a function of time, usually decreases with respect to time. Moreover, because that the layout of the seismic stations is not spatially evenly distributed, M_c value is uneven in the space subsequently, or namely varies with space. Subsequently, analyzing the temporal-spatial distribution of M_c in various spatial and temporal scales is significant for most seismicity

1 study.

2 Given a specific set of earthquake catalogue data, a variety of methods have been proposed

3 for calculating M_c , for examples, the Entire-Magnitude-Range(EMR) method (Woessner and

4 Wiemer, 2005a), the Maximum Curvature method (Wiemer and Wyss, 2000), Goodness-of-fit

5 test (GFT) method (Wiemer and Wyss, 2000), the Median-based analysis of the segment

6 slope (MBASS) method (Amorèse, 2007), and M_c by b-value stability (MBS) method (Cao

7 and Gao, 2002; Yi-Lei et al., 2016). Basically, these methods can be classified into two types:

8 the waveform-based method and statistical method. The waveform-based method, for

9 examples, comparison of amplitude-distance curves, signal-to-noise ratio and amplitude

10 threshold method(Gomberg, 1991; Sereno and Bratt, 1989), requires huge amount of work on

11 wave form analysis which are time-consuming and is not ideal for realistic application.

12 The statistical method analyze the relationship between magnitude and frequency. One of the

13 most frequently employed ones is based on the assumption that the Gutenberg-Richter (G-R)

14 power law distribution is suitable to the occurrence frequency of earthquake magnitudes no

15 less than M_c , as:

$$16 \qquad \lg N(M) = a - bM \qquad (3)$$

17 where N is the number of total events equal or above magnitude M , and a and b are constants

18 of G-R criterion. G-R power law, dominated by statistical method and as one of the basic

19 statistical law, is a universal empirical formula in seismology. The parameters in G-R power

20 law have rich and concrete physics origins. Meanwhile, the calculation method is simple.

21 Therefore, mapping the minimum magnitude of completeness in earthquake catalogues based

22 on the G-R power law is the most widely used and efficient method for seismicity analysis

1 (Gutenberg and Richter, 1944; Kafka, 2000; Wiemer and Wyss, 2000; Woessner and Wiemer,
2 2005a).

3 The Sichuan-Yunnan region exhibits strong and high frequent seismicity owing to its complex
4 geological settings and active fault systems. However, the estimated results of M_c will be
5 different with the different assumptions. Each method has its own benefits and drawbacks. In
6 order to overcome the uncertainty of using different data with the same method, this study
7 employs the Entire Magnitude Range method (EMR) to analysis the variations of regional
8 seismic completeness values.

9 For spatial distribution of M_c , EMR supposes that the frequency-magnitude distribution
10 conforms to G-R criterion for all events above seismic magnitude of M_c , and conforms to
11 normal distribution for events under seismic magnitude of M_c . So M_c is defined as the critical
12 point where the G-R power law begins to meet when Eq.(3) is calculated (Woessner and
13 Wiemer, 2005b).

14 In order to demonstrate spatial distribution of M_c value, we install a background grid with
15 node space of 0.1° over our study region. For each node, we scan earthquake catalogue data in
16 a radius of 50 km to calculate M_c . To guarantee the reliability statistically, we get rid of the
17 values on nodes whose number of valid data are less than 100. Spatial distribution of M_c
18 values clearly shows that they vary at a range of 1.42-2.31 (Fig. 2a), suggesting that regional
19 difference of M_c values among these regions cannot be neglected. For simplicity to discuss,
20 based on this result, we divide our whole study area into four regions A, B, C and D (Fig. 2a).
21 We calculate changes of M_c values with respect to time in each region. The M_c value
22 experiences a significant change from May, 2008 to January, 2010 in region A (red curve in

Fig. 2b), showing the significant effects of the 2008 great Wenchuan earthquake along on LFZ and its adjacent regions. In order to determine the average value of M_c values in each region, we neglect M_c values of region A from May, 2008 to January, 2010, because the performance of seismic activity does not significantly change before and after this period. Finally, the average value of M_c in these four regions is 1.5, 1.8, 1.8 and 1.9, respectively.

Fig. 2. The spatial distribution and changes of M_c values in the four regions over time. (a) Spatial distribution of M_c values in the study regions calculated by EMR. The blank areas are regions with grid points whose number of effective data are less than 100. The whole study region is divided into four regions (A, B, C, D) according to the regional difference of M_c values; (b) Changes of M_c values in the four regions with respect to time. Red, purple, blue and orange curves shows M_c values in regions A, B, C and D, respectively.

2.4. The temporal distribution of complete magnitude of earthquake catalogue

EMR method gives a moderate and stable M_c estimation, and it demonstrates superior performance when it is applied to realistic data from regional and global earthquake catalogues(Yi-Lei et al., 2016). But this method requires earthquake catalogue to be

1 tectonically correlated with the regional seismic activity history. Thus, one of the major
2 prerequisites of this method is that the amount of events is large enough and the tolerance of
3 missing events is relatively low.

4 In this study, we not only obtain different M_c for different regions, but also analyze the
5 temporal distribution of M_c . The M_c is obtained by adapting the specified time windows of
6 different regions of our study area to the range of the event magnitude. For each tectonic zone
7 in space, we select the earthquake frequency-magnitude distribution at all earthquake
8 magnitude ranges within the corresponding time windows. M_c value is then achieved through
9 the determination of the tectonic zone in which the Gutenberg–Richter law is verified in a
10 separate manner. Therefore, the time window also isolates the magnitude range that meets the
11 best local seismicity and local record capacity. But the disadvantage is this scenario is that the
12 earthquake catalogue records are truncated if they are not included in the specified time
13 window. If the time duration is not long enough, it may lead to incomplete or sparse catalogue
14 data, and the G-R law describing the earthquake frequency-magnitude distribution may not
15 hold over the entire magnitude range, and small areas may exhibit artificial types of seismicity,
16 especially in regions of low seismicity frequency.

17 Due to these aforementioned drawbacks, this study employs the Maximum Curvature method
18 (MAXC) and the GFT method with 90% (GFT-90%) and 95% (GFT-95%) good-of-fit
19 confidence level to analysis the regional seismic completeness and its changes as a function
20 of time, or namely as the temporal distribution of M_c in this study. MAXC places M_c value at
21 the point where the derivative of magnitude-rate curve reaches its maximum(Hashash et al.,
22 2001; Momayez et al., 1991). We choose this method because it has been successfully applied

1 to regional earthquake catalogue analysis and it showed better stability for small-scale sample
2 size over other methods (Mignan et al., 2011; Wiemer and Wyss, 2000). Hence, it is suitable
3 for the regional earthquake catalog, especially the sparse catalog data.

4 Compared with other methods, MAXC has good stability and can provide the initial M_c than
5 other methods due to the lower M_c value. GFT method obtains the minimum magnitude of
6 completeness M_c through repeatedly adjusting the initial magnitude to fit the G-R power law
7 distribution, or give a certain evaluation criterion (the goodness-of-fit value R in this study) to
8 estimate the goodness of fit between the observed and synthetic distribution, i.e., at this M_c ,
9 the results will meet the evaluation criterion. For example, GFT-90% means that we define
10 M_c as the point at which a G-R power law with the assumed a , b and M_c value can explain 90%
11 of the data variability.

12 Despite its robustness and easy applicability, more importantly, combination of MAXC and
13 GFT methods displays excellent performance in both the cumulative and non-cumulative
14 frequency-magnitude distribution. Thus, the empirical cumulative distribution functions (such
15 as exponential, lognormal, normal and exponential decay) to fit the incomplete part of
16 realistic earthquake catalogue are no longer as required. In practice, it is suitable to our
17 investigation very much (Vorobieva et al., 2013).

18 We establish the priorities of $\text{GFT-95\%} > \text{GFT-90\%} > \text{MAXC}$ to choose the calculable and the
19 highest priority M_c value as the final result of M_c . The first step for estimating M_c is to
20 obtain the initial M_c by MAXC method. With the magnitude interval of 0.1, we adopt M_c by
21 MAXC method as the initial fitting magnitude of GFT. We set the initial M_c plus 1.5 as the
22 upper magnitude bound, and the initial M_c minus 0.9 as the lower magnitude bound,

1 respectively. We use a maximum likelihood estimation to determine a and b values, and
 2 compute a synthetic G-R distribution with the same a, b and M values. To estimate the
 3 goodness of the fit between the observed and synthetic distributions, we choose a fitting
 4 criteria function R as

$$5 \quad R(a_i, b_i, M_i) = 100 - \left\{ \frac{\sum_{M_i}^{M_{max}} |B_i - S_i|}{\sum_i B_i} \times 100 \right\}, \quad (4)$$

6 with

$$7 \quad S_i = 10^{a_i - b_i M_i} \quad (5)$$

8 Where, B_i is the observed earthquake cumulative frequency of events i th magnitude bin with
 9 $M \gg M_i$, S_i is the predicted earthquake cumulative frequency of events in i th magnitude bin
 10 based on the G-R power law. R is the normalized fitting evaluation function. Finally, we
 11 choose the calculated Mc value of the highest priority as the final result based the setting
 12 priorities of GFT-95%>GFT-90%>MAXC.

13 Moreover, to analyze the seismicity rate changes over time in different regions, we also
 14 introduce a function of AS(t), where t is time. This function gives the ratio of seismicity rates
 15 within a period of time (time window) before and after a mainshock. A change in seismicity
 16 rate with a sharp onset can cause a sharp peak in function AS(t). Here we use function AS(t)
 17 to denote the typical time when seismicity changes in highest significance. We utilize the
 18 ZMAP package developed by M. Wyss et al (Wyss and Habermann, 1988) to fulfill our
 19 calculation and map generation.

20

21 **2.5. The aftershock exclusion**

22 It must be emphasized that the seismicity occurrence processes at different regions or fault

1 systems may obey different statistical distributions following big earthquake events. Z-test is
2 based on the assumption that the earthquake sequence is of independent and smooth process.
3 Apparently, aftershocks may greatly lead to uncertainties or even erroneous judgment. Hence
4 it is necessary to exclude the aftershock events from original earthquake catalogue data. In
5 order to measure the significance level of regional seismicity rate changes after the Ms 8.0
6 Wenchuan earthquake by Z-test method, the data independence needs to be satisfied in
7 advance. Therefore, we note that, when we calculate these average values of M_c , we also
8 exclude aftershock data accordingly (Meyer, 1975b; Molchan and Dmitrieva, 1992).
9 Catalog completeness is believed to suffer during time windows of highly aftershock active. It
10 is worth mentioning that earthquake catalogue clustering and aftershock exclusion are of a
11 very delicate process, and the criterion to distinguish aftershocks may introduce uncertainties
12 to results. Statistically, the procedure of earthquake occurrence is an extremely complex
13 non-stationary process. In most seismological research, the earthquake occurrence is assumed
14 to follow a relatively simplified distribution model. Basically, there are two approaches to
15 deal with the non-stationary difficulty. One is to exclude the aftershocks, after which the
16 earthquake process can be considered as a stable Poisson process. The other is, however, to
17 build a model to simulate the earthquake frequency change over time (Daniel et al., 2008;
18 Freed, 2005; Peng et al., 2012).
19 In this study, we just simply exclude events for specified periods of time when it is likely that
20 events are less completely cataloged. We have no attempt to remove all aftershock events
21 following moderate to large earthquakes completely or to decluster the aftershocks to generate
22 one namely well-distributed frequency-magnitude catalogue. The major reasons are that we

1 don't believe that the aftershocks are intrinsically unsuitable as target events, nor it is
2 necessarily desirable because there is often no clear physical distinction to justify aftershocks
3 and nature events.

4 More specifically, we exclude target earthquakes for 1 month following the events with
5 magnitude between 6.0-6.6, 2 months following the events with magnitude between 6.6-7.0,
6 and 3 months following the events with magnitude bigger than 7.0. We also exclude target
7 events if they follow an event of $M \geq 4$ within 3 days and within 150 km at distance.

8 Eventually, the total number of seismic events involved in calculation of our study is 72627.

9 After exclusion of aftershocks, the total number of events above M_c reduces to 18229. In Fig.

10 1, the red spots show that the epicenters of earthquakes occurred during ~5 years before the
11 2008 Wenchuan earthquake, while blue spots show earthquakes occurred during ~5 years
12 after the Wenchuan earthquake. Note that the spots are evenly distributed with less clusters
13 after exclusion of aftershocks. This improves data quality and provides a guarantee to
14 reliability and stability of the subsequent calculations. We then apply Z-test method to the
15 pre-processed data for the sake of examining the statistical significance of the seismicity
16 change in the surrounding regions of LFZ after the Wenchuan earthquake.

17

18 **3. Results of Z-test method**

19 We have used Z-test method to address seismicity rate changes in adjacent regions of LFZ ~5
20 years before and ~5 years after the 2008 great Wenchuan earthquake. The two sets of data
21 required in Eq. (2) are those preprocessed data within ~5 years before the Wenchuan
22 earthquake, and within ~5 years after this event, respectively. The data sampling interval n is

1 14 days. In Eq. (2), positive Z value represents seismicity decrease, and on the contrary,
2 negative Z value indicates seismicity increase. The significance level is positively correlated
3 with absolute value of Z ($|Z|$).

4 We place a grid with node space of 0.05° over the whole study area. For each node, we use the
5 data of over 100 events within a range of 50 km in radius to calculate Z value. To guarantee
6 the reliability statistically, we get rid of the values on nodes whose number of valid data are
7 less than 100. Previous studies have ratified that the approach keeping the number of data
8 fixed and changing the scale of statistical spatial window is more effective than the opposite
9 way (Wiemer and Wyss, 1994). For convenience, we pick eight fault zones, in which Z value
10 is purely positive/negative in order to compare our Z -value calculation results with results of
11 Coulomb stress change in previous studies.

12 Our calculated Z value changes in different fault zones (Fig. 3), indicating that seismicity
13 changes significantly in different fault zones after the Wenchuan earthquake. Seismicity in
14 regions A, B, C, and D has increased (negative Z value in Fig. 3). The fault zones with
15 seismicity increase include southern Longmenshan thrust fault, eastern Kunlun fault,
16 Longquanshan fault and Huayingshan fault (negative Z value in Fig. 3). Nevertheless,
17 seismicity in regions E, F, G, and H has decreased (positive Z value in Fig. 3). The fault zones
18 with seismicity decrease include northern Longmenshan thrust fault, Songpan-MinJiang fault,
19 Fubianhe fault in the east of Bayankala block, and northern and central Anninghe-Zemuhe
20 fault (positive Z value in Fig. 3).

Fig. 3. Calculated spatial distribution of Z value. The Z value distribution shows spatial distribution of seismicity changes after the Wenchuan earthquake. If the Z value is positive, the seismicity decreases. If the Z value is negative, the seismicity increases. The polygonal regions (A-H) represent eastern Kunlun fault (region A), southern Longmenshan fault (region B), Longquanshan fault in Sichuan basin (region C), Huayingshan fault in Sichuan basin (region D), northern and central Longmenshan fault (region E), vicinity of the Songpan-Minjiang fault (region F), Fubianhe fault in Bayankala block (region G), northern and central Anninghe-Zemuhe fault zone (region H), respectively.

Coulomb stress changes due to the 2008 Wenchuan earthquake calculated by Parsons et al.

(2008) and Wan et al. (2009) showed the increase of Coulomb stress in eastern Kunlun fault (region A in Fig. 3) and southern Longmenshan thrust fault (region B in Fig. 3), and the decrease of Coulomb stress in northern and central Longmenshan thrust fault (region E in Fig. 3) and Songpan-Minjiang fault (region F in Fig. 3). Qian and Han (2011) suggested that the Coulomb stress in northern Longquanshan fault (region C in Fig. 3) increased significantly after the Wenchuan earthquake, and the increment gradually decreased from north to south along the fault. Shan et al. (2009) showed that the Wenchuan earthquake induced Coulomb stress drop along Fubianhe fault (region G in Fig. 3).

All these previous studies above are consistent with our calculation results of Z value. However, some regions have coseismic Coulomb stress changes by the 2008 Wenchuan earthquake contradicting our statistical results. For example, calculations of Coulomb stress changes from many researchers (Luo and Liu, 2010; Parsons et al., 2008; Wan et al., 2009) showed that the Coulomb stress in southern Xianshuihe fault increased significantly, but in our work, the value of Z at the same place is positive, indicating a seismicity drop. On Anninghe-Zemuhe fault zone, our Z value calculation results contradict with the results of coseismic Coulomb stress changes calculated by some studies. For example, Wan et al. (2009) suggested that the Wenchuan earthquake almost had no effect on Anninghe-Zemuhe fault, but northern Anninghe-Zemuhe fault has significant seismicity decrease (region H has positive Z value in Fig. 3). However, our results coincide with calculations of Coulomb stress changes by Luo and Liu (Luo and Liu, 2010), which show the decrease of Coulomb stress along Anninghe fault.

1

2 **4. Regional seismicity versus time**

3 We have computed the significance level of seismicity rate changes in major fault zones of
4 southeastern Tibetan Plateau before and after the Wenchuan earthquake, but we still have
5 uncertainties regarding whether these seismicity rate changes and their relationship to
6 Wenchuan event. To better explain the relationship between seismicity rate changes and the
7 Wenchuan earthquake, we calculate the value of $AS(t)$ with respect to time. As shown by red
8 curve in Fig. 2(b), a change in seismicity rate with a sharp onset corresponds to a sharp peak
9 in $AS(t)$ just while the great 2008 Ms 8.0 Wenchuan earthquake happened. We also calculate
10 the changes of cumulative number of earthquakes in case that $AS(t)$ cannot perform well
11 when the number of sample size is insufficient.

12 We first focus on the four regions where seismicity increases (negative Z value in Fig. 3). In
13 regions A and B, shortly after the great 2008 Ms 8.0 Wenchuan earthquake, slope of
14 cumulative number of seismic events occurs a sudden change (solid curves in Figs. 4a and 4b),
15 and $AS(t)$ shows a minimum or trough (dashed curves in Figs. 4a and 4b). In region C, the
16 slope of cumulative number increases significantly around 2008, but the $AS(t)$ curve does not
17 have a trough at this time (Fig. 4c). This is different from results in regions A and B. The most
18 possible reason leads to the difference is that in region c, the number of events before 2008 is
19 much less than that after 2008. Hence the contribution of data before 2008 is neglected when
20 compute $AS(t)$, and this causes a roughly horizontal line and low values before 2008 (Fig. 4c).
21 Seismicity rate changes in the three regions above (regions A, B and C) are highly correlated
22 with the 2008 Wenchuan earthquake. However, $AS(t)$ in region D does not reach a minimum

1 in 2008 (dashed curve in Fig. 4d), indicating that the increase of seismicity in region D is not
2 caused by the 2008 Ms 8.0 Wenchuan earthquake. It is worth mentioning that $AS(t)$ in regions
3 A, B and C reaches a maximum point around 2011 (see dashed curves in Figs. 4a-4c), and this
4 suggests that the effects of the Wenchuan earthquake may vanish in the whole area after
5 ~2011.

6 We then analyze the four regions where seismicity decreases (positive Z value in Fig. 3) in the
7 same way. $AS(t)$ in regions E, F and H shows a relatively sharp peak shortly after May, 2008
8 (dashed curves in Figs. 4e, 4f and 4h), suggesting a strong correlation between seismicity in
9 these regions and the Wenchuan earthquake. In region G, it is difficult to decide whether a
10 peak exists or not, but $AS(t)$ does reach a maximum around 2008. Therefore, we suggest that
11 in region G, to some extent, regional seismicity is related to the Wenchuan earthquake. We
12 observe that the peak values of $|AS(t)|$ at the occurrence of main shock (if exists) in all the
13 cases discussed above are larger than 2.57, and this indicates that our conclusions have passed
14 the 99% confidence limit according to Z-test method.

Fig. 4. Changes of cumulative number of seismic events and the $AS(t)$ curves over time in the eight regions A-H (a-h). Locations of these eight regions are shown in Fig. 3. The solid curves represent changes of cumulative number (see left axis). The dashed curves represent function $AS(t)$ (see right axis). The occurrence time of the 2008 great Wenchuan earthquake is marked by arrows. The regions A-D have the increasing seismic frequency (a-d). The regions E-H have the decreasing seismic frequency.

In previous studies (Wiemer and Wyss, 2000; Wyss, 2000), it has been demonstrated that, by average, a major earthquake tends to turn on the seismicity of neighboring volumes rather than to turn off it. We find a similar trend in our study. The $AS(t)$ curves of regions E-H seem

1 to be more undulant, and the peaks at the occurrence of main shock look less distinctive
2 (compare dashed curves in Figs. 4e-4h with those in Figs. 4a-4c). These results suggest a
3 weaker correlation between seismicity in regions E-H and the 2008 Ms 8.0 Wenchuan
4 earthquake than that between seismicity in regions A-C and this event. However, many
5 reasons and factors may lead to the similar features, so it is difficult to make a decisive
6 conclusion herein. For example, one possible reason is that the data size is too small in
7 regions of F and H, causing undulant AS(t) curves (Figs. 4f and 4h). Another possible reason
8 is that, after data of seismic events below M_c are cut off, the ratio between small and large
9 events changes in favor of large events, probably leads to some variations to features of the
10 AS(t) curve. To address this issue comprehensively, the relationship between Z value and
11 seismic magnitude will be discussed specifically in next section.

12

13 **5. Seismicity versus seismic magnitude**

14 Besides time factor, the change of seismicity rate following a big earthquake also depends on
15 and correlates with the seismic magnitude range: seismicity rate increases sharply within a
16 certain seismic magnitude range, but drops in another range (Eneva et al., 1994; Habermann,
17 1983a). In Fig. 5, we plot three sub-figures for each of the eight regions. The first two
18 sub-figures show the relationship between seismic magnitude and seismicity rate, and the
19 third one shows relationship between seismic magnitude and the Z value. If the earthquake
20 catalogue is complete at all magnitude ranges, we can just look at the b-value changes to
21 examine the rate changes with respect to different magnitudes. However, if seismic rate
22 changes are caused by artificial factors such as observation network capabilities or improper

1 selection of M_c , seismic rate changes for small events should be much more significant than
2 those for big events, neither they can reflect the realistic physics. If seismic rate changes are
3 induced naturally by an earthquake, seismic rate changes should be distributed evenly through
4 the whole range of seismic magnitude, not depending on small or big events. Compared with
5 seismic rate changes for big events, seismic rate changes for small events might be more
6 significant, because our statistical calculation includes much more small-event samples than
7 big-event samples. We show the seismicity rate changes with seismic magnitude for the eight
8 regions in Fig. 5.

9 Region A is eastern Kunlun fault (As shown in Figs. 1 and 3). Seismicity rates for all the
10 magnitudes have increased after the Wenchuan earthquake along this fault (middle panel in
11 Fig. 5a). The cumulative seismicity after the Wenchuan earthquake is 1.7 times higher than
12 that before this event (top sub-figure in Fig. 5a). The Z value curve indicates that seismicity
13 rate changes for $M_s < 3.0$ pass 95% significance level (bottom sub-figure in Fig. 5a). The
14 reason why seismicity rate changes for larger events get a lower significance level would be
15 that events with $M_s > 3.5$ are few for Z-test method.

16 In region B, or southern Longmenshan fault (Figs. 1 and 3), yields an increase of 55% in
17 cumulative seismicity (Fig. 5b). We stress that the Wenchuan earthquake occurred in the
18 central and northern segments of this fault and ruptured 3/7 of its total length (Wen et al.,
19 2009). The cumulative seismicity curve tells us few events with $M_s > 4.0$ within 5 years before
20 the Wenchuan earthquake. Hence, the significance of seismicity rate changes for $M_s > 4.0$
21 cannot be tested. After the Wenchuan earthquake, events with $M_s > 4.0$ began to occur, and the
22 M_s 7.1 Lushan earthquake is the largest one.

1 Region C is Longquanshan fault (Figs. 1 and 3) in Sichuan basin, a rigid block with low
2 seismicity. Before the Wenchuan earthquake, only several events in this region occurred and
3 the seismic magnitudes of all events were below M_s 2.5. This region stays in a relatively
4 stable state, because it is located inside the rigid block, Sichuan basin. After the 2008
5 Wenchuan earthquake, seismicity in this region increases significantly and hundreds of events
6 have occurred. The Z value curve clearly shows that seismicity rates for $M_s < 2.5$ have
7 changed significantly, and the seismicity rate changes for $M_s > 2.5$ can also be observed
8 through the cumulating seismicity curve (Fig. 5c).

9 Region D is Huayingshan fault (Figs. 1 and 3). It is also inside Sichuan basin, but seismicity
10 in this region is somehow active and the seismicity curve in this region behaves like that of in
11 region B (Figs. 5d and 5b). We have demonstrated in the previous section that seismicity rate
12 change in region D is not correlated with the Wenchuan earthquake (Fig. 4d). Hence, we do
13 not discuss region D here.

14 Region E is northern and central Longmenshan fault (Shown in Figs. 1 and 3). The energy
15 release by the Wenchuan earthquake significantly decreases the number of small events, but
16 on the contrary, the number of large events increases. The cumulating seismicity per year
17 reduces by 35% after the Wenchuan earthquake (top sub-figure in Fig. 5e). We need to
18 mention that this region stays in the aftershock zone of the Wenchuan earthquake and our
19 calculation has excluded all the aftershock data as described in section 2. It is quite difficult to
20 decide whether a large event is aftershock or not, hence some uncertainty may exist in our
21 calculation results, but the overall seismicity in this region has decreased (Fig. 5e).

22 Situations of regions F, G and H are quite similar. Seismicity rates in these three regions

- 1 decrease significantly for almost all the seismic magnitudes (Figs. 5f-5h). This shows that
- 2 seismicity of Songpan-Minjiang fault, Fubianhe fault and Anninghe-Zemuhe fault is
- 3 suppressed by the Wenchuan earthquake.

4

Fig. 5. The relationship between seismicity rate and seismic magnitude before and after the Wenchuan earthquake in the eight regions A-H (a-h) calculated by our statistical method. Locations of these eight regions are shown in Fig. 3. Each region has three sub-figures. In the top and middle sub-figures, dashed curves show the relationship between seismicity rate and seismic magnitude before the Wenchuan earthquake, and solid curves show that after this event. In the bottom sub-figure, the Z value plot is divided into two parts by a vertical solid line, and the solid curve on the left side shows the Z value of earthquakes smaller than the corresponding seismic magnitude, but the solid curve on the right side shows the Z value of earthquakes greater than the corresponding seismic magnitude. The horizontal dotted line points to ± 1.96 , indicating that the Z value is corresponding to significance level of 95%.

In most of the regions discussed above, seismicity rate changes for $M_s > 3.0$ have passed 95%

1 significance level. Besides, turning on or off seismicity by the Wenchuan earthquake is
2 reflected for most of the seismic magnitudes. Therefore, seismicity changes calculated by our
3 statistical method are not caused by artificial factors, or in another word, our calculation
4 results are reliable.

5

6 **6. Discussions and conclusions**

7 Earthquake triggering is the procedure by which stress migration and change are associated
8 with a big earthquake occurred. It can escalate or decelerate seismicity in its surrounding
9 regions or even trigger earthquake at great distance. On May 12, 2008, Wenchuan Ms8.0
10 earthquake struck the Longmenshan fault zone, where is one of the most seismicity active
11 regions around the global. Obviously, it had a significant impact on seismicity pattern of this
12 region. Following this event, in some its surrounding regions, earthquake cumulative
13 frequency increased significantly, while some other areas had reduced earthquake cumulative
14 frequency. Therefore, an important practical issue is to quantitatively or statistically justify the
15 rate changes of earthquake occurrences at regional scale, in particular, for operational
16 forecasting and risk evaluation by checking whether such changes are actually statistically
17 significantly correlate to the occurrence of Wenchuan Ms8.0 earthquake or not. In this paper,
18 for the first time, we examine the complete seismicity catalogue in Sichuan-Yunnan region of
19 China, to detect the significance of these changes before and after Wenchuan Ms8.0
20 earthquake.

21 Firstly, assessing the magnitude of completeness M_c of earthquake catalogue is an essential
22 and compulsory step for any seismicity analysis. We verify the effectiveness of combining

1 standard statistical methods (setting priorities as $GFT-95\% > GFT-90\% > MAXC$) of addressing
2 the spatial and temporal changes of M_c . The results show minimum magnitude of
3 completeness M_c of Sichuan-Yunnan region earthquake catalogue varies with respect of time
4 and space. During the January 1, 2003 to April 20, 2013, the smallest magnitude M_c
5 fluctuates from 2.1 to 1.3(Fig2b), and the spatial distribution of consistency is good. When
6 analyzing the changes of seismicity rates before and after Wenchuan Ms8.0 earthquake, we
7 choose the relatively higher value of M_c during the study period, ensuring the reliability of
8 earthquake catalogues used in the entire study period.

9 The Z-test statistical method has been applied to examine the seismicity rate changes and its
10 significance in eight fault zones ~5 years before and ~5 years after the Wenchuan Ms8.0
11 earthquake, identify the triggering and quiescence patterns following the 2008 Wenchuan
12 Ms8.0 earthquake. We find seismicity rate increasing in some regions, while in other regions
13 seismicity rate decreasing. The change rate conforms to the Z-test with significance at 99%
14 confidence intervals in most areas. In most of the regions, the sign of the seismicity rate
15 change agrees with the sign of the Coulomb stress change of previous investigations.

16 In summary, our results propose that the seismicity in eastern Kunlun fault, southern
17 Longmenshan fault, Longquanshan fault and Huayingshan fault has been facilitated, but
18 seismicity in northern and central Longmenshan fault, vicinity of the Songpan-Minjiang fault,
19 and Fubianhe fault in Bayankala block has dropped significantly. Seismicity in northern and
20 central Anninghe-Zemuhe fault zone does not exhibit correlation with the Wenchuan Ms8.0
21 earthquake. Our statistical results coincide with seismicity change assessment based on
22 calculations of Coulomb stress change in previous studies for most of these regions except

1 Xianshuihe fault zone and Anninghe-Zemuhe fault zone, suggesting that these two fault zones
2 still stay in a state of interseismic locking.

3 To examine the time of a single seismicity rate change, the Z-test is applied to the data by a
4 function namely as $AS(t)$. Results show that, influenced by Wenchuan Ms8.0 earthquake, the
5 seismicity rates increased in East of Kunlunshan fault, South of Longmenshan fault and
6 Longquanshan fault; Seismicity rate decreased in Huya-Minjiang fault, Fubianhe fault and
7 North of An'ninghe-Zemuhe fault. We find seismicity rate decreases in seismicity are not as
8 noticeable as increases from the curves of earthquake accumulative frequency with time and
9 the values of AS .

10 It is common consensus that earthquake releases elastic energy potential in the lithosphere
11 under evolution. Therefore, the Coulomb stress change is naturally considered as an efficient
12 tool to predict the possible aftershock regions following big event. However, geophysical and
13 geological communities have to admit that our current understanding of the earthquake
14 occurrence mechanisms is far away from sufficient to forecast earthquakes. Many simplified
15 theories, models and idealized critical parameters applied to forecast future seismicity do not
16 agree with the observed data and geological evidence. For example, large earthquakes often
17 occur in the regions with low seismic risk indicated by hazard maps in orogenic belts or
18 continental seismology zones (Stein et al., 2012). In fact, the geophysical and geological
19 communities have also failed to answer if earthquake forecast (issuing reliable and accurate
20 alarms of imminent large and damaging earthquakes) was possible till present. One important
21 reason attributed to the introduced uncertainties when we determine the values of critical
22 parameters in these simplified models, leading these simplified models are not purely

1 deterministic eventually.

2 We found it necessary to figure out a new observation-based paradigm for aftershock
3 occurrence and subsequent nucleation of big seismic events. For example, we can assume that
4 the lithosphere is a well-connected system with the fault plane and slip distribution for each
5 earthquake, and magnitude of each earthquake is the result from an essentially stochastic
6 process rather than predetermined. We also should focus on the mechanism for storing elastic
7 energy in the lithosphere that has heretofore being considered as discrete and separate faults.

8 We recognize the existence of fundamental problems in present theories on earthquake
9 occurrence and earthquake forecast, and try to search for a new paradigm. We demonstrate
10 that statistical analysis of seismic data, with other conventional methods, for example,
11 calculations of Coulomb stress changes, can be integrated together to evaluate regional
12 seismicity and future earthquake hazards and their mitigation. Therefore, our methodology of
13 comprehensively preprocessing the earthquake catalogue data set proposed in this study,
14 together with the Z-test statistical method and results may serve as a particularly good
15 candidate to overcome current difficulties to justify the regional seismicity intensity following
16 large seismic events.

17 By calculating changing curves of accumulative seismic frequency with earthquake
18 magnitude and changing curves of z value versus earthquake magnitude of each zone, we can
19 find in the areas triggered or restrained by Wenchuan Ms 8.0 earthquake, the seismic
20 frequency of each magnitude has changed. Namely, the change of seismicity rates does exist,
21 which is not caused by the human factors, such as the level of seismic monitoring and so forth.

22 On the account of numerous medium and small earthquakes, which are less than 3.0

1 Magnitude, their changes of seismicity rates are more obvious, which can further infer the
2 changing feature of regional seismic activity. It's highly reliable to analyze seismicity rates of
3 each area with the instrumental earthquake catalogues, which should be paid more attention in
4 the future. By combining with the result of Coulomb stress, we can make more accurate
5 judgment on seismic hazard assessment.

6 Finally, the distribution of Z value versus seismic magnitude indicates that the significance of
7 seismic rate changes for large events is much lower than that for small events, mostly
8 probably because of small sample size of large events. Likewise, the AS(t) curves of nearly
9 half of the selected regions are severely undulated, leading to difficulties in determining the
10 correlation between seismicity rate changes and the mainshock. Hence, the applications of
11 statistical methods to seismology are basically limited by sample size properly reflecting the
12 physics. Even if data size of the original earthquake catalogue is large enough, it is also
13 difficult for the desired data to meet the requirements of hypothesis test after excluding
14 aftershocks and small events below M_c . Thus, some better and new statistical methods are
15 expected to overcome these difficulties in the future studies.

16

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7

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