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Analysis of seismic strain releases related to tidal stress before the 2008 Wenchuan earthquake

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Abstract

Tidal stresses could load or unload the focal media and trigger small to moderate earthquakes around the epicentral area before a large or great earthquake. Based on the Preliminary Reference Earth Model, we calculated the time series of the tidal Coulomb failure stress (TCFS) acting on the focal fault plane of the Wenchuan earthquake. For the earthquakes ($2.5 \leq M_L \leq 4.0$) that occurred around the epicentral area from January 1990 to April 2008, we calculated the rate of TCFS, ΔTCFS, at the occurrence time of each earthquake. These earthquakes are divided into two categories on the basis of the sign of ΔTCFS: One is positive earthquakes (PEQs) occurring at times of ΔTCFS >0 and the other negative earthquakes (NEQs) occurring at times of ΔTCFS <0. Firstly, we obtained the cumulative seismic strain release (CSSR) curve for NEQs and PEQs respectively, and found that two curves almost overlapped before September 2004 and then began to diverge increasingly with time. We employ a parameter R_p, the propotion of the seismic strain release of PEQs, to reveal the effect of TCFS on the occurrence of eartquakes, and found that R_p was significantly higher than 0.5 about six months before the Wenchuan event at the 99% confidence level, indicating a significant correlation betwen the occurrence of earthquakes and the increasing TCFS.

Furthermore, we worked out the slope k (time rate) of the CSSR curve vs. time for PEQS and NEQs respectively. It shows that several years before the Wenchuan event the seismic strain release accelerated when TCFS increased, while it decelerated when TCFS decreased. R_k, the ratio of k for PEQS to that for NEQs, was used to depict quantificationally the difference of the time rate of seismic strain release between PEQS and NEQS. We found that R_k remained stable, around 1.0, until it started to increase rapidly with time from the beginning of

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2005, reached its highest value of 2.7 just before the time of the occurrence of the the Wenchuan event. R_k could reveal the promoting and inhibiting effects of the tidal stresses on the release of seismic strain. The increase of R_k corresponds to the promoting effect when TCFS increases or the inhibiting one when it decreases. Both effects took place in the focal region before the Wenchuan mainshock.

When the tectonic stress in the crust increases, the *b*-value in the Gutenberg–Richter relation will decrease. We also calculated the temporal variation of the *b*-value in the study region. By comparing R_k with the *b*-value, we found that after the tectonic stress had increased for about two and a half years, the focal region started to become unstable and the tidal stress began to take effect. With the further increase in the tectonic stress, the effects of the tidal stresse were enhanced gradually. The increase of the tidal Coulomb failure stress might have promoted the occurrence of earthquakes, whereas its decrease had an opposite effect. This observation may provide an insight into the processes leading to the Wenchuan earthquake and its and precursors.

1 Introduction

The M_s 8.0 Wenchuan earthquake occurred on May 12, 2008, with an epicenter at (31.0°N，103.4°E) and a depth of 19km, rupturing along the Longmenshan fault (indicated by F in Fig. 1a) in the Sichuan province, China. It killed thousands of people, caused building damage, widespread landslides, floods (Zhu et al., 2012), and epidemic outbreaks(Yan et al. 2009; Cao et al., 2010), along with serious affection of the ecological environment(Huang et al., 2018). Scientists have reported their researches on the Wenchuan earthquake. Such as the co-seismic changes in water level and water temperature associated with the Wenchuan earthquake (He et al., 2016,2017; He and Singh, 2019), the changes in b-value (Zhao and Wu, 2008; Shi et al., 2018; Chen and Zhu, 2020), the tide-triggered earthquakes (Li and Chen, 2018) and correlation between the occurrence of earthquakes and the Earth’s rotation in the pre-mainshock (Chen and Li, 2019). Meanwhile, we focused on the seismic strain release related to the tidal stress before the 2008 Wenchuan earthquake in this paper.

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The amplitude of stresses caused by solid Earth tides in the crust is ~1 kPa, much lower than the average earthquake stress drop (~10^3–10^4 kPa), and they cannot provide the energy released in earthquakes (Scholz, 2002). However, if tectonic stresses in the focal area reach a critical value, tidal stresses could trigger an earthquake(Rydelek et al., 1992). Numerous studies have examined correlations between Earth tides and earthquakes. Positive results for aftershocks, volcanic earthquakes, and small to large earthquakes were obtained (Hofmann, 1961; Ryall, 1968; Shlien, 1972; Kayano, 1973; Filson et al., 1973; Mauk and Kienle, 1973; Tamrazyan, 1974; Klein, 1976; Gao, 1981; Kilston and Knopoff, 1983; Rydelek et al., 1988; Wilcock, 2001; Stroup et al., 2007; Zhang et al., 2007; Li and Jiang, 2011a; Vergos et al., 2015), but there were some exceptions (Schuster, 1897; Knopoff, 1964; Shlien ,1972; Heaton, 1982; Rydelek et al., 1992; Tanaka et al., 2006). It seems that tidal triggering of earthquakes with dip-slip or oblique-slip focal mechanisms may be more significant (Heaton, 1975; Tsuruoka et al., 1995; Tanaka et al., 2002a; Cochran et al., 2004; Li and Zhang, 2011b; Bucholc and Steacy, 2016). Tidal stresses triggered shallow strike-slip earthquakes that occurred in or near mainland China, but oblique-slip or dip-slip earthquakes in the same area were not triggered by tidal stresses, nor were strike-slip earthquakes occurring in California, USA (Ding et al., 1983; Vidale et al., 1998). No statistically significant evidence for a focal mechanism-dependence on earthquake triggering was found in the NEIC catalog (Métivier et al., 2009). The effect of tidal Coulomb stress triggering is more significant for normal slip earthquakes in low and middle latitudes and reverse-slip earthquakes in middle and high latitudes and tidal stress triggering decreases with increasing latitude for strike-slip earthquakes (Xu et al., 2011). A high correlation between Earth tides and earthquake occurrence was detected around the epicenters in the several years before some moderate to large earthquakes (Chen and Ding, 1996; Chen et al., 1998; Tanaka et al., 2002b; Tanaka, 2010, 2012; Li et al., 2018).

The seismic strain (or moment) release acceleration near the epicentral area before a strong earthquake has engaged the attention of many researchers (Sykes and Jaumé, 1990; Bufe and Varnes, 1993; Brehm and Braile, 1998,1999; Bowman et al., 1998; Yang and Ma, 1999; Jiang et al., 2004,2009a,2009b,2009c; Zhang et al., 2014; Li et al., 2015; Qian et al., 2015). The accelerating seismic strain release before some strong earthquakes has been reported, but before some cases, the significant accelerating seismic strain release has not been found, even the seismic strain release decelerates. Usually, researchers investigated the accelerating seismic strain release before strong earthquakes though the method given by Bufe & Varnes (1993) based on the cumulative seismic strain release curve of small to medium earthquakes occurring near the epicenter during a certain period (often several years to tens of years) before the strong earthquakes and presented their results to show whether there exists the significant accelerating seismic strain release. They analyzed the shape of the seismic strain release curve as a function of time by considering the studied period as a whole. The curve of seismic strain release over a longer time can be viewed as a chain of straight lines with various slopes. When the seismic strain release accelerates, the slope of the straight lines will get greater and greater, and vise versa.

Based on this idea and considering the effects of the tidal stress, we will examine whether there was any difference in the seismic strain release when the tidal stress increased and when it decreased for earthquakes that occurred before the 2008 M_s 8.0 Wenchuan earthquake.

2 Study region and data used

Earthquakes used in this study were obtained from the China Earthquake Networks Center, China Earthquake Administration. The Wenchuan earthquake's aftershocks ($M_L \geq 3.0$) that occurred from May 12 to August 31, 2008, are plotted in Fig. 1a. The aftershocks extended ~350 km to the northeast. A very large part of fault slip during the occurrence of the Wenchuan mainshock took place within a region between the Maoxian county and the Dachuan town in the southwestern aftershock zone (Zhang et al., 2008), meanwhile larger values of seismic release for aftershocks from May 12 to 31, 2008 were located within the same region. This region, enclosed by a quadrangle with a length of ~140 km in Fig. 1b, was selected as the study region in this article due to its significant correlation with the occurrence of the Wenchuan mainshock.

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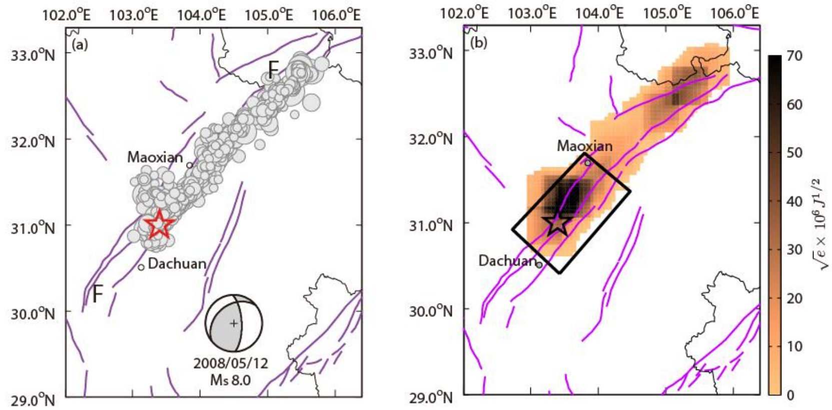

Figure 1 (a) Map showing the locations of aftershocks ($M_L \geq 3.0$) following the Wenchuan event from May 12 to August 31, 2008. The focal mechanism solution comes from the Global Centroid Moment Tensor catalog. "**F**" represents the Longmenshan fault. (b) The spatial distribution of seismic strain for the aftershocks that occurred from May 12 to 31, 2008. The star shows the epicenter of the Wenchuan event. The quadrangle shows the study region.

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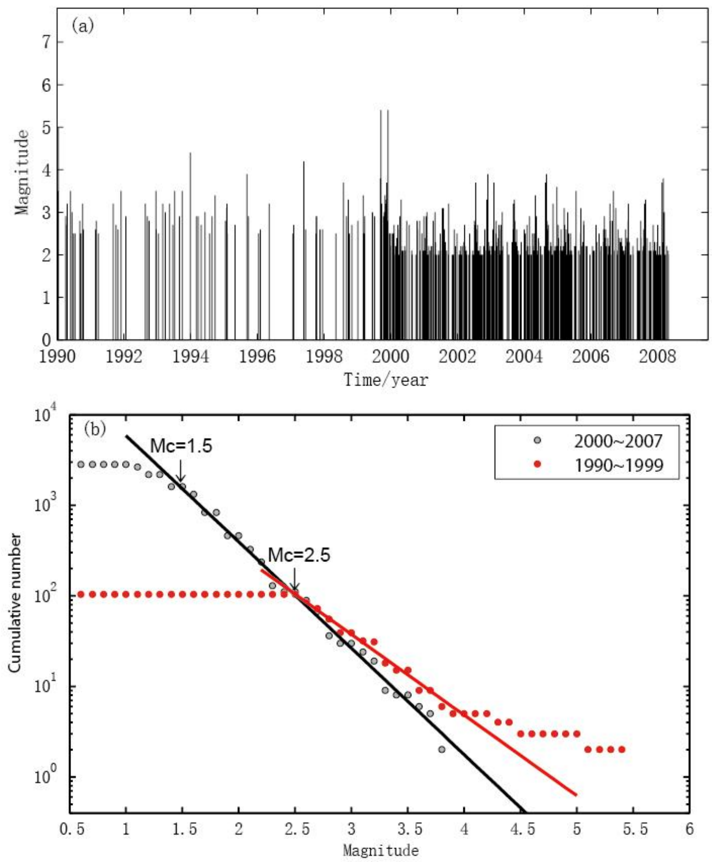

Figure 2 (a)Magnitude as a function of time for earthquakes ($M_L \geq 2.0$) occurring in the study region. (b) Cumulative number vs. magnitude for earthquakes in the study region.

The magnitudes versus time for earthquakes ($M_L \geq 2.0$) that occurred in the study region between January 1990 and April 2008 are plotted in Fig. 2a. It can be seen that fewer earthquakes with $M_L \geq 2.0$ occurred before 2000 resulting from the sparse seismic stations laid in and around the study region. The observed Gutenberg-Richter relationship is usually used for determinating the threshold of completeness of earthquake catalogue via inspection. The G-R relationships were plotted in Fig. 2b for earthquakes before and after 2000 respectively. The plot suggests the threshold of completeness to be Mc=2.5 before 2000 and Mc=1.5 after that. It can be also found from the G-R relationship that earthquakes with a magnitude M_L>4.0 does not obey the linear

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relationship. After we excluded those M_L>4.0 earthquakes, finally 217 earthquakes with a magnitude span of 2.5≤M_L≤4.0 were selected in the following analysis

3 Analytical method

Based on the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981), the tide-generating stress components in the Earth's interior are calculated. The potential due to the attraction of the moon and sun at the point A(r,θ,λ) can be written as follow(Luo et al., 1986).

$$\left.\begin{aligned} V_m(A) &= \frac{3}{4} D \frac{C_m^3}{r_m} \frac{1}{R^2} \sum_{n=2}^{\infty} \left(\frac{r}{r_m}\right)^n P_n\,(\cos Z_m) \\ V_s(A) &= \frac{3}{4} D_s \frac{C_s^3}{r_s} \frac{1}{R^2} \sum_{n=2}^{\infty} \left(\frac{r}{r_s}\right)^n P_n\,(\cos Z_s) \end{aligned}\right\} \quad (1)$$

Where,

D is 26277cm^2·s^{-2},the Doodson constant;

D_s=0.45924D;

r_m is distance between the centre of the earth and the moon;

r_s is distance between the centre of the earth and the sun;

r is radius from the earth's centre;

Z_m is the geocentric zenith distances of the moon at the point A;

Z_s is the geocentric zenith distances of the sun at the point A;

R is the Earth's mean radius,taken to be 6371024m;

C_m is the average distance between the earth and the moon, equal to 3.844×10^{8}m;

C_s is the average distance between the earth and the sun ,equal to 1.496×10^{11}m;

λ is easterly longitude;

θ is colatitude.

The ratial,colatitudinal and longitudinal displacements caused by the potential are given by

$$\left.\begin{aligned} u_r(A) &= \sum_{n=2}^{\infty} \frac{H_n(r)}{g(r)} V_n(A) \\ u_\theta(A) &= \sum_{n=2}^{\infty} \frac{L_n(r)}{g(r)} \frac{\partial V_n(A)}{\partial \theta} \\ u_\lambda(A) &= \sum_{n=2}^{\infty} \frac{L_n(r)}{g(r)} \frac{\partial V_n(A)}{\partial \lambda} \end{aligned}\right\} \quad (2)$$

Where $V_n=V_m+V_s$, g(r) is the acceleration due to gravity.H_n(r) and L_n(r) are Love's numbers.

The strain components are obtained by

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$$\left.\begin{aligned}
\varepsilon_r &= \frac{\partial u_r}{\partial r}\\
\varepsilon_\theta &= \frac{u_r}{r} + \frac{\partial u_\theta}{r\partial\theta}\\
\varepsilon_\lambda &= \frac{u_r + u_\theta \cot\theta}{r} + \frac{\partial u_\lambda}{r\sin\theta\,\partial\lambda}\\
\varepsilon_{r\theta} &= \frac{\partial u_r}{r\partial\theta} + \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r}\\
\varepsilon_{r\lambda} &= \frac{1}{r\sin\theta}\frac{\partial u_\lambda}{\partial\lambda} + \frac{\partial u_\lambda}{\partial r} - \frac{u_\lambda}{r}\\
\varepsilon_{\lambda\theta} &= \frac{1}{r}\left(\frac{\partial u_\lambda}{\partial\theta} - u_\lambda \cot\theta\right) + \frac{1}{r\sin\theta}\frac{\partial u_\theta}{\partial\lambda}
\end{aligned}\right\} \quad (3)$$

The stress components are obtained by

$$\tau_{ij} = \lambda^{'}\Theta\delta_{ij} + 2\mu\varepsilon_{ij} \quad (4)$$

Where λ' and μ are Lame's coefficients, Θ is bulk strain and δ_{ij} is Kronecker operator.

According to the focal mechanism solution of the Wenchuan earthquake, the tidal stress components are projected onto its focal fault plane. The tidal normal stress σ_n and shear stress τ can be obtained, and then the tidal Coulomb failure stress (TCFS) acting on the focal fault plane can be obtained by applying equation (5):

$$TCFS = \tau + \mu\sigma_n \quad (5)$$

Where μ is the coefficient of friction, taken to be 0.6 (Chen, 1988). According to the global CMT catalog, the focal fault plane of the Wenchuan earthquake is a thrust-type one with the geometry of strike = 231° and dip = 35°. The rake is 138°. In calculation, the focal depth was taken to be 19 km. Fig. 3 shows the temporal variations of TCFS caused by the tide on the focal fault plane of the Wenchuan earthquake at a depth of 19 km.

We calculated the time series of TCFS at the epicenter of each earthquake. Based on the time series, we calculated the TCFS rate (ΔTCFS) at the occurrence time of each earthquake. If TCFS increases, ΔTCFS >0 and vice versa. Earthquakes are divided into two categories: positive earthquakes (PEQs) occurring at times of ΔTCFS >0 and negative earthquakes (NEQs) occurring at times of ΔTCFS <0. On this basis, the characteristics of the seismic strain released during the time of positive and negative ΔTCFS can be analyzed.

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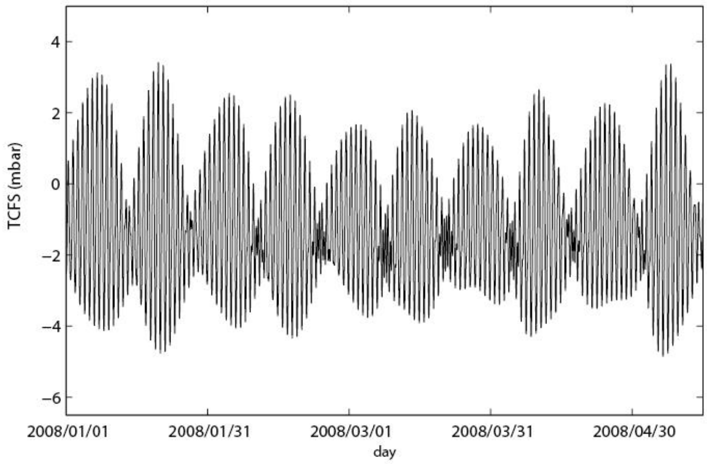

Figure 3 Temporal variations of TCFS caused on the focal fault plane of the Wenchuan earthquake at a depth of 19 km.

In seismology, the seismic strain release ε is represented by the Benioff strain obtained by taking the square root of seismic energy E_S calculated from equation (6) (Gutenberg and Richter, 1956). For earthquakes in mainland China, M_S in Equation (6) can be obtained from M_L by Equation (7) (Fu and Liu, 1991). We arranged the earthquakes in chronological order and then obtained the cumulative seismic strain release (CSSR) versus time by accumulating their Benioff strains.

$$Log\ E_s = 1.5M_s + 4.8 \quad (6)$$

$$M_s = 1.13M_L - 1.08 \quad (7)$$

4 Analysis of seismic strain release

Fig. 4a shows the CSSR curves of NEQs and PEQs. The grey circle represents the CSSR curve for PEQs and the cyan square for NEQs. It can be found that the two curves almost overlapped before September 2004. However, after that, they began to diverge increasingly with time. This divergence indicates that the seismic strain release of PEQS was higher than that of NEQs.

We calculated the propotion of the seismic strain release of PEQs R_p applying a moving 5-year time window moved by 3 months. R_p is defined as

$$R_p = \frac{\varepsilon_p}{\varepsilon} \quad (8)$$

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Where ε is the total seismic strain release of PEQs and NEQs, and ε_p *is* the seismic strain release of PEQs.

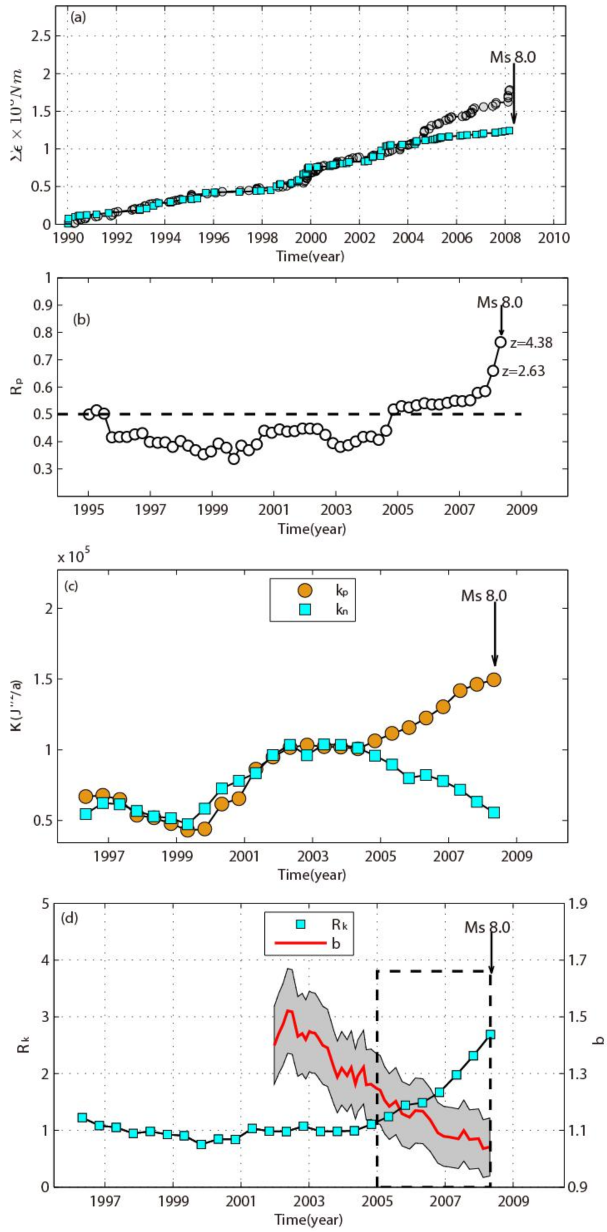

Figure 4 (a) Cumulative seismic strain release curve. The line with "○" for PEQs, and the line with "□" for NEQs. (b) R_p vs. time A moving 5-year time window moved by 3 months. (c) The time rate *k* of CSSR vs. Time for both PEQs and NEQs. The orange circle shows the time rate *k* for PEQs and the cyan square for NEQs. A

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moving 5-year time window moved by 3 months. (d) R_k (cyan square) and b value(red line) as a function of time.The grey area indicates the 95% confidence limit of b value. The downward arrow shows the occurrence of the Wenchuan earthquake.

R_p vs. time is shown in Fig. 4a. It changed between 0.3 and 0.6 before October 2007,and then become over 0.66. As the length of time with ΔTCFS>0 is almost the same as that with ΔTCFS<0, The normal value of R_p is 0.5 if the tidal Coulomb failure stress does not have a significant effect on the occurrence of earthquakes. If increasing TCFS indeed influences the seismic strain release, R_p should be significantly larger than 0.5, which can be evaluated using its z-values (Ge and Wang, 2006). The z-value of *N* earthquakes can be calculated according to equation (9).

$$z = (2R_p - 1)\sqrt{N} \qquad (9)$$

where *N* is the total number of earthquakes used to calculate R_p. The critical *z*-value is denoted by z_α, for which values at different significance levels are shown in Table 1. For the last two values of R_p in Fig. 4b, their z values are 2.6 and 4.4 respectively, indicating a significant difference between the two values of R_p and 0.5 at the 99% confidence level. It means that the seismic strain release was significantly related to the increasing tidal Coulomb failure stress.

Table 1. The values of z_α at different significance levels.

α	z_α		α	z_α
0.001	3.29		0.01	2.575
0.002	3.09		0.02	2.336
0.005	2.81		0.05	1.96

The time rate of seismic strain release can be mirrored by the slope, *k,* of the CSSR curve. If the slope increases, the seismic strain release accelerates and vice versa. The observed slope as a function of time was obtained by fitting the data with straight lines within a moving 5-year time window,that moved by 3 months' steps. Let k_p denote the slope for PEQs and k_n for NEQs. Both are shown in Fig. 4c using the orange circle "●" for k_p and the cyan square "■" for k_n, respectively. The seismic strain release accelerates for PEQs when k_p increases, and for NEQs when k_n increases.

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It can be seen from Fig. 4c that k_p and k_n had almost the same value at the same time and in phase before 2005. Thereafter, they changed out of phase, and k_p increased with time, whereas k_n decreased. Therefore, even several years before the Wenchuan event the seismic strain release accelerated when the tidal Coulomb failure stress increased, while it decelerated when the tidal Coulomb failure stress decreased.

We analyzed the difference between k_p and k_n using their ratio, R_k. The ratio R_k is defined as

$$R_k = \frac{k_p}{k_n} \tag{10}$$

R_k vs. time is shown in Fig. 5d. It increased rapidly from the beginning of 2005, and reached its highest value just before the time of the occurrence of the Wenchuan earthquake. This means that the seismic strain release rate for PEQs increased sharply before the Wenchuan earthquake, compared with that for NEQs. k_p reached ~2.7-fold greater than k_n just before the Wenchuan event occurrence.

The decrease of parameter b in the *G–R* relationship $log\ N(M) = a - bM$ is interpreted as a stress increase in the crust before an approaching seismic event (Scholz, 1968; Wyss, 1973). For analyzing the relationship between R_k and the regional tectonic stress, we investigated the temporal changes in the crustal stress by *b*-value in the study region. The maximum likelihood method is applied to estimate *b*-value [Aki, 1965]

$$b = \frac{\log e}{\overline{M} - M_{\min}} \tag{11}$$

The 95% confidence standard deviation of *b* is

$$\sigma(b) = 1.96\frac{b}{\sqrt{N-1}} \tag{12}$$

where $\overline{M}$ represents the average magnitude of a group of earthquakes, $M_{\min}$ is the minimum magnitude in the group. Considering fewer eartquakes before 2000, we calculated the *b*-value as a function of time by using the earthquakes with $M_L \geq 1.5$ in the study region from January 2000 to April 2008. Calculations of *b*(t) were carried out in sliding time windows containing a constant number of 400 events which advanced in steps containing 30 events. The temporal changes of the

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b-value are shown by the red line in Fig. 5d, where the grey area indicates the 95% confidence interval. The *b*-value decreased by ~31.6% from 1.52 in May 2002 to ~1.04 immediately before the occurrence of the Wenchuan event, i.e., in a time period of ~6 years. It decreased by ~17.8% before 2005, and by ~13.8% in the latter three years and four months. During the former period when the *b*-value declined, R_k remained stable around 1.0, when the *b*-value dropped to ~1.25 at the end of 2004, R_k began to increase, and thereafter, the *b*-value continued decreasing, while R_k showed a rapid increase and reached ~2.7 eventually.

As stated above, the *b*-value can reflect the regional tectonic stress, and its decline corresponds to increasing regional tectonic stress. Therefore, during the early time of the regional tectonic stress enhancement, R_k remained stable,around 1, indicating that TCFS did not affect the seismic strain release. When the regional tectonic stress continued to biuld up, R_k increased rapidly, and reached the maximum value of 2.7 when the Wenchuan mainshock was impending (see the dashed black frame in Fig. 5d). This means that the rate at which the seismic strain was released during the time of TCFS increased 2.7-fold compared to that during the time of TCFS decreased when the focal source region of the Wenchuan event was approaching instability.

To sum up the above observations, the significant stress buildup was found around the epicentral area preceding the Wenchuan mainshock. During the latter phase of the stress buildup, the difference in the seismic strain release between the earthquakes occurring when TCFS increased and those occurring when TCFS decreased became increasingly noticeable, and reached its maximum just before of the occurrence of the Wenchuan mainshock.

5 Conclusions and discussions

In this article, we examined the difference in seismic strain release between earthquakes that occurred during the increase of the tidal Coulomb failure stress and that during the decrease preceding the Wenchuan earthquake. The obtained results are as follows:

(1) The propotion of the seismic strain release during the increase period of the tidal Coulomb failure stress was significantly higher than 0.5 at the 99% confidence level around the epicentral area about six months before the Wenchuan event, indicating a significant correlation betwen the occurrence of earthquakes and the increasing tidal Coulomb failure stress.

(2) The seismic strain release accelerated during the increase period of the tidal Coulomb

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failure stress and decelerated during the decrease one for the several years before the Wenchuan event.

(3) The ratio (R_k) of the time rate of seismic strain release during the increase time interval of the tidal Coulomb failure stress to that during the decrease one increased rapidly, reached ~2.7 at the time when the occurrence of the Wenchuan earthquake was approaching.

The *b*-value is related to the tectonic stress in the crust. From May 2002 until the occurrence of the Wenchuan event, the *b*-value had been declining. By comparing ratio R_k with *b*-value, it can be found that the tidal Coulomb failure stress had no effect on the seismic strain release in the early period of tectonic stress build up. However, with the further increase in the tectonic stress, the difference in seismic strain release between NEQs and PEQs became evident. The difference increased gradually with time, and the effect of the tidal Coulomb failure stress on the seismic strain release became more and more significant.

It can be concluded that within three years and more before the Wenchuan earthquake, the increase of the tidal Coulomb failure stress might have promoted the occurrence of earthquakes, whereas its decrease had an opposite effect. This observation may provide an insight into the processes leading to the Wenchuan earthquake and its precursors.

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Data Availability Statement

The Earthquakes catalog support the findings of this study are available in the China Earthquake Networks Center, China Earthquake Administration at [http://10.5.160.18/console/index.action]

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