Tidal triggering of earthquakes in Longmen Shan region: the relation to the fold belt and basin structures

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We found a distinctive pattern of tidal triggering of earthquakes related to the fold belt and basin structures. We studied the correlation between tidal variations and seismic events in the Longmen Shan region. We divided this region into two subregions: one is located in the Songpan-Garze Fold Belt which has a soft and weakened crust; the other is located in the Sichuan Basin which has a relatively rigid and strong crust. The results of Schuster's test show that there is a higher correlation in the subregion of the Songpan-Garze Fold Belt than in the subregion of the Sichuan Basin. The reason for this distinctive triggering pattern is that the rock failure mechanism is related to the mechanical properties of the rocks: under conditions of high stress, different kinds of rocks have a different nonlinear behavior of rock deformation and fracture patterns. The nonlinear behavior of rock deformation, which is the prerequisite for a critical stress state in which the tidal stress could trigger an earthquake, increases as the rigidity and the strength of rocks decrease. Therefore, this triggering pattern is closely related to the properties of the crustal rocks of the Songpan-Garze Fold Belt and the Sichuan Basin.

Key words: Tidal triggering of earthquakes, Schuster's test, fold belt and basin structures.

1. Introduction

The problem of the tidal triggering of earthquakes has, for a long time, been of scientific interest (Stroup *et al.*, 2007). Changes in tidal stress (Melchior, 1983; Wilcock, 2001) are significantly smaller compared with seismic stress drops (Kanamori and Anderson, 1975); however, in the majority of cases, their rates are much higher compared with the mean rates of changes in tectonic stress (Wilcock, 2001). Therefore, a small change in tidal stress has the possibility of triggering an earthquake when the stress reaches a critical state in the focal region.

An intriguing aspect of recent study is the location and timing pattern of the tidal trigger effects linked with the occurrence of some large seismic events. Research into the Tonga subduction zone has shown that high correlations were just seen in the few years previous to the 1982 South Tonga earthquake (M_w 7.5) near and in the coming fracture region of the great quake (Tanaka *et al.*, 2002b). Research into the Sumatra region has also shown that clear correlations were detected as long as ten years prior to some large seismic events (Tanaka, 2006, 2010). Besides, some studies by Tanaka *et al.* (2006) show that this observational result is not widespread and may change in time and space within a certain area.

However, this aspect has been little studied, and we do not know what the space-time pattern of the tidal triggering effect is in fold belt and basin structures, such as the Longmen Shan region. In the present study, we investigate the

correlation between the earthquake events in the Longmen Shan region, China, and the tidal variations. We concentrate on the spatial and temporal pattern of this effect in relation to the Wenchuan M 8.0 earthquake and the structural setting of this region.

2. Theoretical Tidal Stress

The tide comprises two constituents (Tanaka *et al.*, 2002a): one is the Earth tide affecting the solid strata, caused by the attraction of the Moon and the Sun, and the other is the ocean tide. Close to the ocean edges, the effect of ocean loading has to be taken into consideration due to the larger ocean tide effect when compared to Earth tides on solid strata at various times. Although the Longmen Shan region is slightly distant from the ocean edges, we have considered the effect of ocean loading for the sake of accuracy.

The Earth tide stress we use is calculated theoretically by using the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981; Tsuruoka *et al.*, 1995).

As to the stress components, some researchers use shear stress on the fault plane (Mohler, 1980; Heaton, 1982) and a stress tensor trace (Tsuruoka *et al.*, 1995) as the tidal stress components. Others use tidal compressional stresses at the regional tectonic stress orientations (Tanaka *et al.*, 2004), Coulomb stress amplitude (Cochran *et al.*, 2004), and so on (Stroup *et al.*, 2007; Métivier *et al.*, 2009), as tidal stress components. For the Longmen Shan region, focal mechanisms are available for only a few earthquakes. To obtain dependable tidal triggering statistics, we require a certain number of seismic events. According to the study by Tanaka *et al.* (2004), earthquakes are inclined to occur when the regional tectonic stress is superposed by the tidal stress. Thus, we use the tidal compressional stress at the

regional tectonic stress orientations (the azimuth of tectonic stress orientation of this region is 84° according to the study by Xu *et al.* (1989)) as the tidal stress components for the purpose of obtaining a sufficient number of seismic events for a statistical test.

3. Statistical Test

The method to search for the tidal triggering of earthquakes is as follows (Tanaka *et al.*, 2002b).

First, we allocate to each earthquake a phase angle of tidal stress based on the earthquake occurrence time. Using the maximum stress closest to the seismic occurrence time, we define the maximum as the tidal stress phase angle of 0° , and the preceding and following minimum as -180° and 180° , respectively. We linearly interpolate the time interval between these phases to define other phase angles.

Second, using the phase angle previously mentioned, we examine whether or not seismic events occur indiscriminately within the half daily tidal periodic variation by applying Schuster's test (Schuster, 1897; Heaton, 1982; Tsuruoka *et al.*, 1995; Wilcock, 2001; Tanaka *et al.*, 2002a). Schuster's test introduced a parameter p , whose value represents the probability of a random earthquake phase distribution. Therefore, a lesser p -value corresponds to a stronger correlation between tidal variations and earthquake occurrence. In this study, we use $p \leq 5\%$ as the limit for significant correlation between tidal variations and seismic occurrence (Tanaka *et al.*, 2002a; Stroup *et al.*, 2007).

4. Data

We analyzed the correlation between tidal variations and earthquake occurrence in the Longmen Shan region of China, which is a seismically active region around the Longmen Shan fault belt. At 14:28 on May 12, 2008, Wenchuan County, located in the Longmen Shan region, was struck by a $M 8.0$ earthquake. The epicenter distribution of events occurring from 1978 to 14:28, May 12, 2008, in the Longmen Shan region (a total of 1788 earthquakes) is shown in Fig. 1(a) (data extracted from the earthquake catalogue of the China Earthquake Administration). The epicenter distribution of events (which are mostly the aftershocks) occurring from 14:29, May 12, 2008, to April 12, 2010 (a total of 1987 earthquakes) is shown in Fig. 1(b). Since clustering can confuse the analysis results (Young and Zurn, 1979), the clustered earthquakes were eliminated using the Reasenberg method (1985). The completeness magnitude estimated after performing a Gutenberg-Richter analysis is 2.4.

5. Results

5.1 The temporal pattern of the p -value in the Longmen Shan region

In our research on the temporal pattern of the p -value in the Longmen Shan region, we followed analysis methods used in Tanaka's works (Tanaka *et al.*, 2002b; Tanaka, 2006, 2010). By using the concept of a sliding window, we can calculate the temporal evolution of the p -value. Figure 2(a) details the variation with time of the p -value in the Longmen Shan region. A sliding window length of 1000 days and a step length of 100 days were used

Fig. 1. (a) Epicenter distribution of events occurring from 1978 to 14:28, May 12, 2008, in the Longmen Shan region (a total of 1788 earthquakes). (b) Epicenter distribution of events occurring from 14:29, May 12, 2008, to April 12, 2010, in the Longmen Shan region (a total of 1987 earthquakes).

before the Wenchuan $M 8.0$ earthquake. After the main shock, a window length of 700 days was used. As can be seen from the figure, the p -value fluctuated more than 20% for the period of 11000 days to 2800 days before the Wenchuan $M 8.0$ earthquake. The p -value began to diminish 2700 days before the earthquake. The least value it achieved before this event was 2.2%. After this earthquake, it abruptly increased, achieving a relatively high value of 31.1%. This result indicates that there is an obvious distinction in phase angle choice between the preceding, and after, seismic event periods with respect to the Wenchuan $M 8.0$ event. Figure 2(b) details the phase angle frequency variations for the time period of 1800 days before the Wenchuan $M 8.0$ event. The data set includes 239 earthquakes occurring in this period. The result of Schuster's test shows a small p -value of 3.4%. We note that the maximum phase angle frequency is close to 0° , at which the tidal compressional stresses at the regional tectonic stress orientations

Fig. 2. (a) Change of p -value with time. The sliding window length of 1000 days, denoted by a horizontal line, is moved by 100 days before the Wenchuan M 8.0 earthquake. (b) Phase angle frequency variation for seismic events in the period 1800 days before the Wenchuan M 8.0 earthquake. The fine solid curve denotes a function of sinusoidal least squares fit to the variation.

are at their highest values, enhancing earthquake occurrence. This signifies that the observed small p -value before the Wenchuan M 8.0 earthquake can be attributed to the changes in the tidal compressional stresses at the regional tectonic stress orientations.

5.2 The time-space variations of p -value according to the geological features of Longmen Shan region

In order to obtain more valuable results, we have further investigated the time-space variations of the p -value according to the geological features of this region.

The Longmen Shan region, shown in Fig. 1, can be divided into two major tectonic units (Burchfiel *et al.*, 1995; Liu *et al.*, 2009): one is the Songpan-Garze Fold Belt, which has a soft and weakened crust (Liu *et al.*, 2009); the other is the Sichuan Basin, which has a relatively rigid and strong crust (Liu *et al.*, 2009). The Longmen Shan Fault Belt, which consists of three faults, forms the boundary between the Songpan-Garze Fold Belt and the Sichuan Basin on the surface of the ground (Chen and Wilson, 1996). The three faults extend together in the deep Earth crust and form

Fig. 3. Two subregions: Subregion 1 is located in the Songpan-Garze Fold Belt, while Subregion 2 is located in the Sichuan Basin.

Fig. 4. Change of p -value with time in the two subregions for the period 11000 days preceding the Wenchuan M 8.0 event. The sliding window length of 1000 days, denoted by a horizontal line, is moved by 100 days. The small circles indicate the p -value in Subregion 1, while the asterisks indicate the p -value in Subregion 2.

the convergent boundary where the Songpan-Garze Fold Belt and the Sichuan Basin collide (Teng *et al.*, 2009), and where the Wenchuan M 8.0 earthquake occurred. Taking this convergent boundary as a boundary line, we divide the above region into two subregions: Subregion 1 is mainly located in the Songpan-Garze Fold Belt, while Subregion 2 is mainly located in the Sichuan Basin. In order to eliminate the effect of the location of the boundary between these two subregions on the observed results, the location of the collision boundary is avoided (see Fig. 3).

Because the aftershocks of the Wenchuan M 8.0 earthquake are mostly located in the collision boundary (see Fig. 1(b)), we have focused on the variation of the p -value for the period before the main shock in the following studies of the two subregions.

Fig. 5. (a) Phase angle frequency variation for seismic events in the period 2300 days before the Wenchuan M 8.0 earthquake in Subregion 1. The fine solid curve denotes a function of sinusoidal least squares fit to the variation. (b) Phase angle frequency variation for seismic events in the period 1000 days (i.e. the most strongly-triggered period) before the Wenchuan M 8.0 earthquake in Subregion 1. The fine solid curve denotes a function of sinusoidal least squares fit to the variation. (c) Phase angle frequency variation for seismic events in the period between 2300 to 11000 days before the Wenchuan M 8.0 earthquake in Subregion 1. The fine solid curve denotes a function of sinusoidal least squares fit to the variation.

Fig. 6. (a) Phase angle frequency variation for seismic events in the period 1600 days before the Wenchuan M 8.0 earthquake in Subregion 2. The fine solid curve denotes a function of sinusoidal least squares fit to the variation. (b) Phase angle frequency variation for seismic events in the period 1000 days (i.e. the most strongly-triggered period) before the Wenchuan M 8.0 earthquake in Subregion 2. The fine solid curve denotes a function of sinusoidal least squares fit to the variation. (c) Phase angle frequency variation for seismic events in the period between 1600 to 11000 days before the Wenchuan M 8.0 earthquake in Subregion 2. The fine solid curve denotes a function of sinusoidal least squares fit to the variation.

Figure 4 shows the time-space variations of the p -value in these two subregions for the period 11000 days before the Wenchuan M 8.0 earthquake, where a time window of 1000 days is moved by 100 days. The time variations of the p -value in Subregions 1 and 2 are denoted by circles and asterisks, respectively. Comparing the p -value in Subregion 1 with that in Subregion 2, we find that the p -value in Subregion 1, on the whole, is smaller than the p -value in Subregion 2: the average of the former is 14.7%, while the average of the latter is 47.6%. Further studies indicate that there are great differences in the p -values between Subregion 1 and Subregion 2. First, the low- p ($p \leq 5\%$) period in Subregion 1 is longer than in Subregion 2: the former is 2300 days, while the latter is 1600 days. Second, as can be seen in Figs. 5(a) and 6(a), the p -value for the low- p period in Subregion 1 is much smaller than that in Subregion 2: the former is 1.8% while the latter is 4.35%. Third, the smallest p -value in Subregion 1 is much smaller than that in Subregion 2: the former is 0.22%, while the latter is 4.1% (see Figs. 5(b) and 6(b)). Lastly, as can be seen in Figs. 5(c) and 6(c), the p -value for the non-low- p ($p > 5\%$) period in Subregion 1 is much smaller than that in Subregion 2: the former is 23.6% while the latter is 53.1%. From the above-mentioned differences, we deduce that there is a higher correlation between tidal variations and earthquake occurrences in Subregion 1 than in Subregion 2.

Obviously, the above phenomena are not random. They can be explained by the mechanism of the rock failure and the different mechanical properties of the crustal rocks of these two subregions.

6. Discussion and Conclusions

Our research on the correlation between tidal variations and earthquake occurrence in the Longmen Shan region has demonstrated that a high correlation appeared about 5 years before the Wenchuan M 8.0 earthquake. In the pre-seismic periods, a peak of the tidal phase angle distribution appeared near 0° , in which tidal compressional stresses at the regional tectonic stress orientations are at their highest values enhancing earthquake occurrence. This signifies that the observed small p -value before the Wenchuan M 8.0 earthquake can be attributed to changes of tidal compressional stresses at the regional tectonic stress orientations.

The results of a statistical analysis of the two subregions indicate that there is a higher correlation between tidal variations and earthquake occurrence in Subregion 1, located in the Songpan-Garze Fold Belt, than in Subregion 2, located in the Sichuan Basin. The reason for this distinctive pattern of tidal triggering of earthquakes is that the mechanism of rock failure is related to the mechanical properties of the rocks: under conditions of high stress, different kinds of rocks show a different non-linear behavior of rock deformation and fracture patterns because they have different stress-strain relationships (i.e. constitutive relations) (Lockner and Beeler, 2002; Ge *et al.*, 2004); the non-linear behavior of rock deformation, which is the prerequisite for a critical stress state (Yin and Yin, 1991) in which the tidal stress could trigger an earthquake, increases as the rigidity and strength of rocks decrease (Jiao *et al.*, 2003). Therefore, this triggering pattern is closely related to the properties of

the crustal rocks of the Songpan-Garze Fold Belt and the Sichuan Basin.

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