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Tidal triggering of earthquakes in the Ning'er area of Yunnan Province, China

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ABSTRACT

To investigate the potential effect of tidal modulation on the seismicity in the Ning'er area, a seismically and geothermally active zone in Yunnan Province, China, we studied the correlation between Earth tides and the occurrence of $M \geq 6.0$ earthquakes dating back to 1970, as well as their aftershock sequences, using theoretically calculated tidal stresses and a statistical test. The results show a significant correlation between Earth tides and the occurrence of earthquakes. Six of seven main events occurred when the Earth tide increased the Coulomb failure stress on the source fault. Four main events occurred in a narrow range of phase angle corresponding to the maximum loading rate of tidal stress. Furthermore, the histories of the aftershock sequence as a function of the tidal phases demonstrate clear tidal modulation with a high significance. Thus, we conclude that Earth tides have a clear role in triggering (or modulating) the rupture of the fault systems in the Ning'er area.

1. Introduction

According to the Mohr–Coulomb failure criterion, an earthquake occurs as a result of a fast fault rupture when the Coulomb failure stress (*CFS*) acting on the fault exceeds a critical threshold value (Harris, 1998). Thus, any additional stress from non-tectonic loadings on a critically stressed fault may advance or delay the occurrence of imminent earthquakes (Emter, 1997). Changes in coseismic stress have been widely thought to be a major factor inducing aftershocks (Stein, 1999) and remote triggering (Lei et al., 2011). Compared with the static and dynamic stress changes induced by a nearby large earthquake, the amplitude of the periodic stress variation associated with the Earth tide, which is on the order of 10^3 Pa, is much smaller; typical stress drops of earthquakes are on the order of 10^5–10^7 Pa (Vidale et al., 1998). However, because the tidal stress rate is greater than the rate of tectonic stress accumulation, it has been argued that the tidal stress may be a triggering factor for earthquakes, including very large earthquakes, especially when the stress in the focal area approaches the critical value (Emter, 1997; Tanaka, 2012; Tanaka et al., 2002a).

Many studies have investigated the correlation between the Earth tide and the occurrence of earthquakes from this point of view (Contadakis et al., 2012; Schuster, 1897; Tanaka et al., 2004; Wilcock, 2001, 2009). Laboratory experiments and friction theory have been applied to analyze the effect of tidal stress variation on fault nucleation, which is considered to be an analogue to earthquakes, and the results suggest that the degree of the effect increases when the ratio of the tidal stress amplitude to the effective stress increases (Beeler and Lockner, 2003; Lockner and Beeler, 1999). Recently, increasing correlation between the tidal stress and the occurrence of earthquakes has been found prior to some large earthquakes in subduction zones, such as the 2011 $M_w = 9.1$ Tohoku-Oki earthquake (Tanaka, 2012) and the 2004 $M_w = 9.0$ Sumatra earthquake (Tanaka, 2010). Regarding global seismicity, a study using more than nine thousand $M \geq 5.5$ events demonstrated that reverse faults tend to show some tidal correlation, but strike-slip and normal faults appear to be less responsive (Tanaka, 2012; Tanaka et al., 2002a). Since there are a large number of events per tidal cycle in aftershocks following large earthquakes, the tidal triggering in aftershock sequences is thus an important issue in seismology (Kamal and Mansinaha, 1996; Datta and Kamal, 2012). Tidal triggering is an interesting but heavily debated issue that requires further investigation.

The Ning'er area is one of the most active seismic zones in Yunnan Province, China. Because the Ning'er area is located in the Yunnan–Tibet geothermal belt, the seismicity within this area may be affected by over-pressurized geothermal fluids. In this type of area, the seismicity may be particularly sensitive to external stresses

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from distant earthquakes (Lei et al., 2011) and tidal loading (Wu et al., 2005). In this study, we first analyzed the tidal correlation for all $M \geq 6.0$ earthquakes that occurred in the Ning'er area between 1970 and 2015. We then applied Schuster's statistical method to test whether the occurrence of their aftershock sequences is modulated by the tidal stress. Finally, we discuss the mechanisms to explain the observed tidal correlation.

2. Tectonic setting

As shown in Fig. 1, our study area lies in south Yunnan Province, corresponding to the east margin of the collision zone between the Eurasian Plate and the Indian Plate in the China (He et al., 2005; Huangfu and Qin, 2006; Leloup et al., 1995), where the tectonics are very complex and contain crisscrossing faults. This area belongs to the Wuliang Shan tectonic belt, which has a major strike in the NNW direction and right-lateral movement (Fig. 1). In addition, this area also features a series of small faults with left-lateral movement striking in the ENE direction (Guo et al., 1999; Mao et al., 2003; Zhang et al., 2009). Moderate earthquakes of $M \geq 5.0$ have occurred frequently in this area at intervals of several years (Mao et al., 2003; Zhang et al., 2009). Our study area surrounds a dead Ning'er volcano and shows extensive geothermal activity, such as hot spring activity. Most of the focal mechanism solutions of $M \geq 6.0$ earthquakes are consistent with the existing faults.

3. Data and methods

3.1. Earthquake data

In this study, we used the catalog of earthquake sequences from 1970 to 2015 provided by the Earthquake Administration of Yunnan Province, China. We first reviewed all main events of $M \geq 6.0$ that occurred in the Ning'er area, which is bounded by 100.5°E < longitude < 101.5°E and 22.5°N < latitude < 23.5°N (Fig. 1). We then tested the completeness of the aftershock sequences of these $M \geq 6.0$ earthquakes by calculating their magnitude–frequency distributions. As shown in Fig. 2, we used the 1993 earthquake sequence as an example and obtained the cut-off value of completeness magnitude (M_c) to be 1.5.

Using the same method, the cut-off values of completeness magnitude were found to be 1.9, 1.5, 2.5, 1.5, 1.7, 2.0 and 2.0 for the sequences of the 2007, 1993, 1979, 1973, 1971 (*M* 6.2), 1971 (*M* 6.7), and 1970 earthquakes, respectively. Except for the 1970 earthquake sequence, which had 76 events, most sequences had more than 100 events with magnitudes of M_c or greater. For the 1971 and 1973 cases, portable stations were installed a few days after the main event occurred, and thus only data collected by the portable stations are available.

3.2. Tidal stress

In this study, the program GOTIC2 (Matsumoto et al., 2001) was used to calculate the strain tensor caused by both the solid Earth tides and the ocean loading, and the tidal normal stress σ_n, shear stress τ, and Coulomb failure stress (CFS = $\tau + \mu'\sigma_n$, where μ' is the effective coefficient of friction) on a given fault plane, which is estimated from focal mechanism solution data and other geological conditions, were then calculated (Table 1). When the fault plane is uncertain, we use the nodal plane, which is almost consistent with the strike direction of the nearby fault. In this paper, tensional stresses are positive. The stresses were calculated in the shallow media with μ' = 0.3. The shear modulus is assumed to be 3.2×10^{10} N m^{-2}.

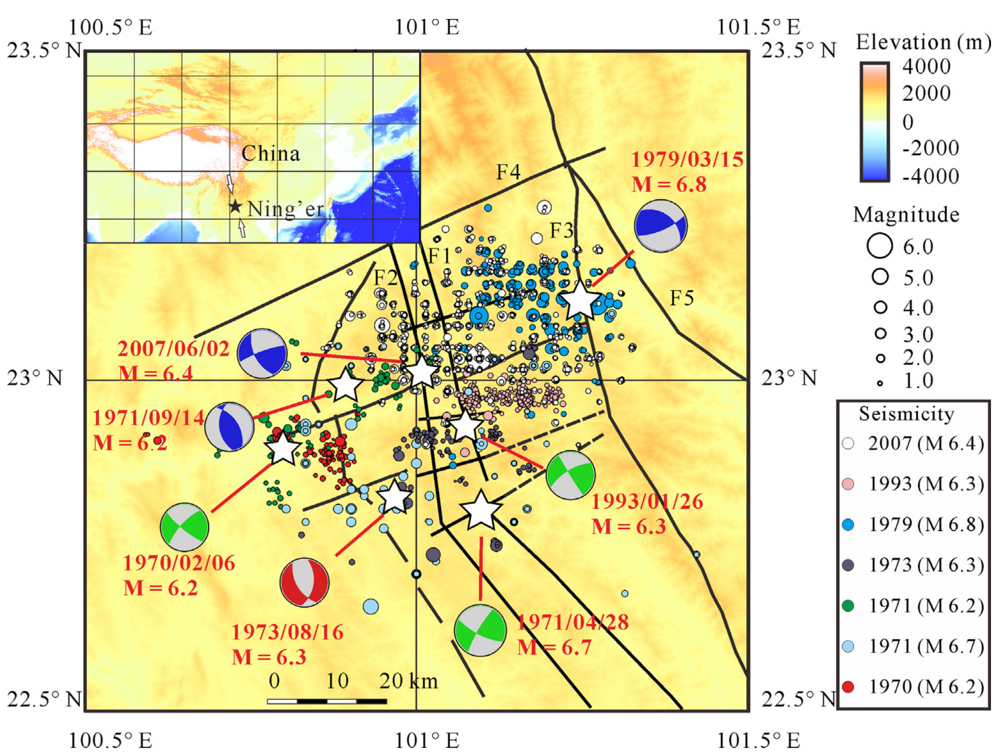

Fig. 1. Map showing the distributions of earthquakes and active faults (black lines, derived from studies by Deng (2007), Xie et al. (2007), and Guo et al. (1999)). The background topography is based on Shuttle Radar Topography Mission Version 3 (SRTM3) digital elevation model (DEM) data (http://srtm.csi.cgiar.org/SRTM3). Stars indicate the epicenters of all $M \geq 6.0$ earthquakes. Hypocenter locations of the seven earthquake sequences are color coded by time and scaled by magnitude, as indicated. F1 and F2 are the eastern and western segments of the Pu'er fault, respectively; F3 is the Mohei fault; and F4 is the Zhendong–Mengxian fault. F1, F2, F3, and F4 belong to the Wuliang Shan tectonic belt. F5 is the Babianjiang fault. In the inset map, the arrows show their regional stress orientations, and the black star is the Ning'er area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)