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# Correlations between solid tides and worldwide earthquakes $M_S \geq 7.0$ since 1900

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**Abstract.** Most studies on the correlations between earthquakes and solid tides mainly concluded the syzygies (i.e. new or full moons) of each lunar cycle have more earthquakes than other days in the month. We show a correlation between the aftershock sequence of the $M_L = 6.3$ Christchurch, New Zealand, earthquake and the diurnal solid tide. $M_S \geq 7$ earthquakes worldwide since 1900 are more likely to occur during the 0°, 90°, 180° or 270° phases (i.e. earthquake-prone phases) of the semidiurnal solid earth tidal curve ($M_2$). Thus, the semidiurnal solid tides triggers earthquakes. However, the long-term triggering effect of the lunar periodicity is uncertain. This proposal is helpful in defining possible origin times of aftershocks several days after a mainshock and can be used for warning of subsequent larger shocks.

## 1 Introduction

The correlation between solid tides and earthquakes has been suggested in other studies (Tanaka et al., 2002; Metivier et al., 2009; Klein and Einarsso, 1974; Klein, 1976). Previous research has mostly analyzed the correlations between earthquakes and lunar periodicity (i.e. lunar phase) (Lin et al., 2003; Iwata and Katao, 2006; Gackstatter, 2007) and the triggering of earthquakes by the tidal load (Tsuruoka et al., 1995). Semidiurnal periodicity has been less frequently considered as a contribution to the tidal components of solid tides and studies have lacked quantitative calculations (Tsuruoka et al., 1995; Lin et al., 2003; Iwata and Katao, 2006; Li, 2006; Gackstatter, 2007; Stroup et al., 2007; Wilcock, 2009). Therefore, the correlations between earthquake occurrence and solid tides were without reasonable explanations. The solid tides in this article are mainly discussed as the theoretical solid tides, which are the combined effect of the lunisolar gravitational perturbation and the rotation of the Earth.

## 2 Uncertain correlations between larger earthquakes and lunar phase

We used 420 747 $M_S \geq 4$ global earthquakes (Fig. 1a) to calculate large-scale statistics and systematically research the monthly lunar tidal phases to determine the influence of lunar phase on earthquakes.

Statistics on the earthquake origin time relative to the monthly tidal cycle show that earthquakes are relatively evenly distributed throughout the monthly solid tidal cycle (Fig. 1b). Therefore, the traditional belief that new and full moons are associated with larger numbers of earthquakes is incorrect.

The correlations between the lunar and solar orbits and $M_L \geq 7$ earthquakes since 1900 are uncertain, and the idea that earthquakes are triggered at the syzygies is not reasonable.

## 3 Research on the Earthquake ($M_L = 6.3$, New Zealand) as an example and worldwide earthquakes $M_S \geq 7.0$ since 1900

The $M_L$ 6.3 Christchurch earthquake occurred at 12:51 LT on 22 February 2011 at 5.9 km depth (Fig. 2). To research the triggering effect of the semidiurnal solid tide on the mainshock and its aftershocks, we calculated the theoretical solid tides before and after the mainshock using the George

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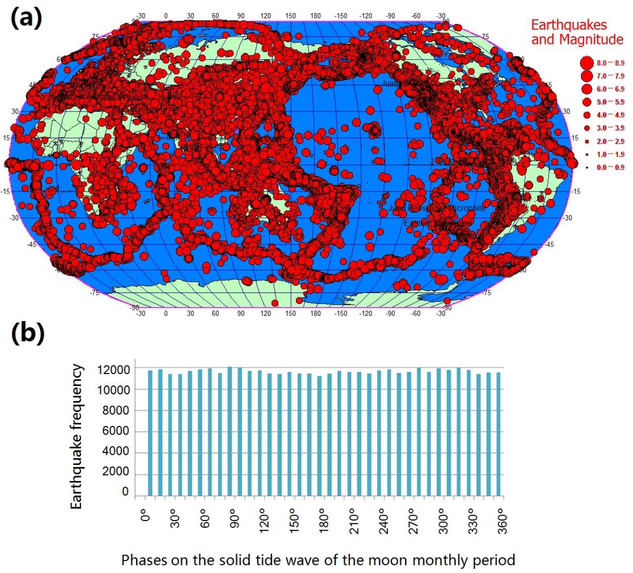


**Fig. 1.** Global epicenter distribution and earthquake frequency relative to the lunar solid earth tides. **(a)** Epicenter distribution of worldwide earthquakes. **(b)** $M_S \geq 4$ earthquake frequency distribution relative to the monthly lunar solid tide phases using 420 747 earthquakes. The difference between the lunar celestial longitude and the solar celestial longitude is used for counting the number of earthquakes.

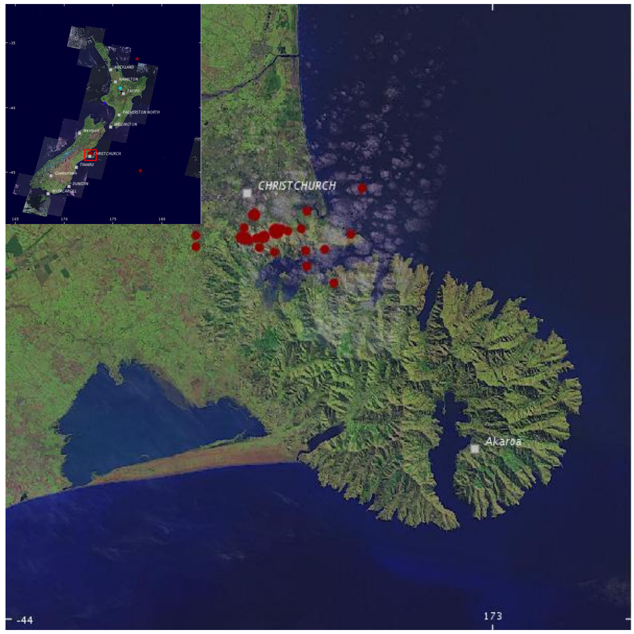


**Fig. 2.** The epicenter distribution map of $M_L \geq 4.5$ earthquakes of the aftershock sequence of the $M_L = 6.3$ New Zealand earthquake. Data are from the Earthquake Commission and GNS Science in New Zealand.

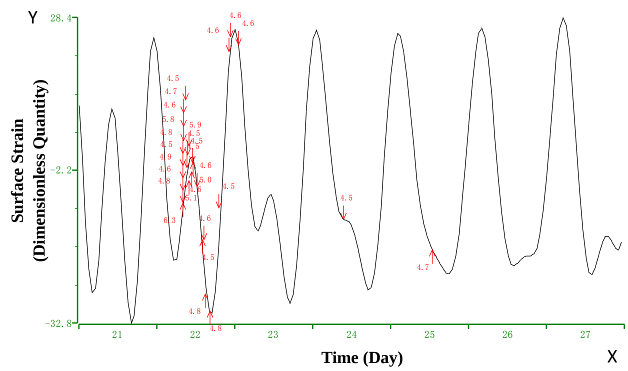


**Fig. 3.** The occurrence time distribution of earthquakes in the aftershock sequence of the $M_L = 6.3$, February 2011 New Zealand earthquake superimposed on the theoretical curve of the solid earth tide (UTC+8). The X-axis is time (day) from 21 February 2011 to 27 February 2011 and Y-axis is surface strain (dimensionless quantity). The surface strain can normally describe the changes of solid tides.

Darwin model (Darwin, 2009). Using the MapSIS software programmed by Professor Li at the Institute of Seismology of China Earthquake Administration, we modeled the theoretical curve of the solid tides based on the time sequence. We identified the origin times of the mainshock and aftershocks on the curve (Fig. 3) and determined the phases of the solid tides at the times of the earthquakes.

We find that the mainshock occurred close to the 0° phase of the semidiurnal solid tidal curve. Most of the larger aftershocks ($M_L \geq 4.5$ prior to 00:00 UTC on 28 February 2011) occurred close to the 0°, 90°, 180° and 270° phases, showing the triggering effect of the semidiurnal solid tide on larger aftershocks.

Prior to larger earthquakes, stress accumulates on the fault zone (Pollitz et al., 2001; Kato et al., 2006) and microfractures may appear (Kanamori and Cipar, 1974; Warwick et al., 1982; Ashby and Sammis, 1990; Kuksenko et al., 1996). The daily undulation in solid tidal loading forces critical terranes in the seismogenic zone to the breaking point (Elkhoury et al., 2006; Yin et al., 1995; Tsuruoka et al., 1995) and finally triggers an earthquake.

We calculated the theoretical waveform of the semidiurnal solid earth tide ($M_2$) (Department of Surveying Engineering in University of New Brunswick and Vaníček, 1973; Harrison, 1984; Melchior, 1983) for the location and time of each $M_s \geq 7$ earthquake since 1900 (a total of 2015 earthquakes as of the February 2010 $M = 8.8$ Chile earthquake). Figure 4 shows the solid tidal phases during earthquakes that caused large numbers of casualties. Statistics were calculated for the earth tidal phases at the origin times of these earthquakes. These findings show that the number of earthquakes that occurred near the 0°, 90°, 180° and 270° phases of the semidiurnal solid earth tide ($M_2$) exceeds the number that occurred during other phases (Fig. 4). In other words, earthquakes are more likely to occur during these four phases (i.e. earthquake-prone phases) of the semidiurnal solid earth tide ($M_2$).

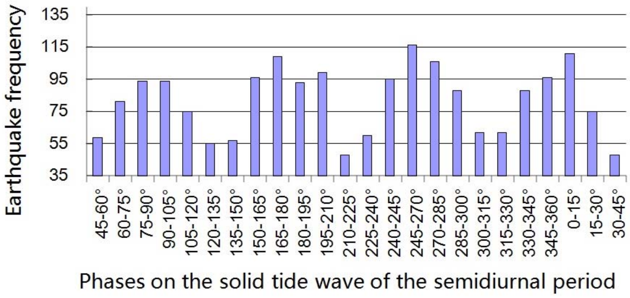


**Fig. 4.** $M_S \geq 7$ earthquake distribution relative to the phases of the semi-diurnal wave.

This proposal is helpful for determining the possible times of aftershocks and can be used to predict earthquakes. For instance, the 0°, 90°, 180° and 270° phases of the semidiurnal solid tide constitute approximately 8 h each day. The definition of these dangerous hours is helpful to avoid further damage and loss of life, and it can eliminate continuous panic caused by the threat of future earthquakes. Infrastructure improvement, such as power repair, gas safety, communication, security and other lifeline engineering, can be carried out in the days following a large earthquake during times that are predicted to be safer according to this method. Thus, this method can be used to mitigate earthquake disasters.

## 4 Conclusions

Direct correlations do not exist between the occurrence of earthquakes and the relative locations of the moon and the sun (lunisolar tides). The correlation between the 2011 Christchurch, New Zealand, earthquake sequence and the solid tides shows that the larger aftershocks were mainly triggered by the semidiurnal solid tides, and the most of earthquakes ($M_S \geq 7$ worldwide since 1900) are distributed near the 0°, 90°, 180° and 270° phases of the $M_2$ tidal constituent, which mainly describes the semidiurnal solid tides. This correlation can be helpful in determining possible times of subsequent aftershocks.

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