Correlation of giant earthquakes with the lunar phase in seven Indo-Pacific subduction zones and around Mongolia

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Correlation of giant earthquakes with the lunar phase in seven Indo-Pacific subduction zones and around Mongolia

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Abstract

Variation in the approximately semidiurnal tidal force affects earthquake occurrence. This paper statistically demonstrates that giant earthquakes occur at lunar phases specific to particular seismic zones. Careful observation during the lunar cycle, especially when seismicity is occurring, should significantly reduce the damage from giant earthquakes. A case study in which a giant earthquake occurred after seismicity was concentrated within the specific lunar phase is discussed.

Keywords

Giant earthquakes, Lunar phase, Subduction zones

INTRODUCTION

Several studies have suggested that the approximately semidiurnal tidal force variation affects earthquake occurrence (*e.g.*, Nakata *et al.*, 2008; Cochran *et al.*, 2012). These studies calculated the stress change due to the tidal force for the fault slip orientation for each earthquake and statistically demonstrated that tidal force variation affects earthquake occurrence. The tidal force variation is greatest around the spring tide when the Sun, Earth, and Moon are aligned along a straight line and the tidal forces from the Sun and Moon reinforce each other. Therefore, giant earthquakes are expected to occur around the spring tide.

From 1900 to the present, giant earthquakes, whose M_W (the moment magnitude) ≥ 8, were not random, but they did not always occur around the spring tide; instead, the earthquakes were correlated with different parts of the lunar cycle that were specific to each subduction zone (Fujii & Ozaki, 2012; Ozaki & Fujii, 2012). However, the lunar phase calculation in those studies was not very accurate and those studies lacked statistical analyses. Therefore, a more accurate lunar phase calculation and the results of such statistical testing are adopted in this paper, thereby providing updated data on giant earthquakes through November 15, 2016. The differences between the lunar phases in the previous studies and the present study are mostly within 6°. However, some big differences due to mistyping were found and corrected. A case study of the Tohoku 2011 earthquake is also shown.

The most important point of this research is that we divided the earthquakes by their locations. Hough (2018) carried out simple simulations and concluded that the occurrence of $M_W \geq 8$ earthquakes ~1900 onward had nothing to do with lunar phases. However, her conclusion is inadequate since she analyzed all events at the same time without considering their locations.

GIANT EARTHQUAKES AND LUNAR PHASES

Data on all earthquakes worldwide with an $M_W \geq 8$ between 1900 and November 15, 2016 were obtained from the Search Earthquake Archives of the United States Geological Survey (USGS) website (Table 1); their lunar phases were calculated using by the AA.ARC v5.5 developed by Stephen L. Moshier in 1998 downloaded from his web site titled Astronomy and Numerical Software Source Codes (http://www.moshier.net/). Most of the algorithms employed in AA.ARC are from the Astronomical Almanac published by the U.S. Government Printing Office. The lunar phases for the time of earthquake occurrences were calculated by reducing the ecliptic longitude of the Sun from that of the Moon first. Then the delay from the spring tide (Figure 1), which is identical to the lunar phase if it is less than 180° (new moon to full moon), while 180° is subtracted from the lunar phase if it is greater than or equal to 180° (full moon to new moon). To make a group of earthquakes, such as those with delays from the spring tide of 160° and 10°, –20° may be used instead of 160° when necessary. The tidal force amplitude is almost the same for the same delay from the spring tide if the lunar phase difference is 180°. The specific lunar phases during which giant earthquake occurrences were concentrated for each subduction zone were more readily found in the previous studies than by using the lunar phase itself (Fujii *et al.*, 2013).

For giant earthquakes in Peru (Figure 2a), there appears to be a specific lunar phase roughly between 30° and 50° (Figure 3a). However, the specific lunar phase should be determined objectively. Therefore, the following statistical test was performed. Assuming a random process for earthquake occurrences (the random null hypothesis), the probability h that an earthquake occurs in a fixed specific lunar phase relative to the spring tide with a duration of l degrees is $2l/360$. Then, probability p'' that m' earthquakes within n' earthquakes occur in a specific lunar phase is

$$p'' = h^{m'}(1-h)^{n'-m'} \times {}_{n'}C_{m'}\,, \qquad (1)$$

where $h^{m'}$ denotes the probability that all m' earthquakes occur in the specific lunar phase, $(1 - h)^{n' - m'}$ denotes the probability that all $n' - m'$ earthquakes do not occur in the specific lunar phase, and ${}_{n'}C_{m'}$ is the number of m'-combinations from n' elements

$${}_{n'}C_{m'} = \frac{n'!}{m'!(n'-m')!} \qquad (2)$$

that is required because any m'-combination can occur. The probability p' that m' or more of n'

earthquakes occur in a fixed specific lunar phase or phases is

$$p' = \sum_{j=m'}^{n'} \left\{ h^j (1-h)^{n'-j} \times {}_{n'}C_j \right\} \qquad (3)$$

This equation is for the case in which the specific lunar phase is fixed. However, $n = n' - 1$ and $m = m' - 1$ should be used instead of n' and m' because the study arbitrarily assumes a specific lunar phase depending on the lunar phase of earthquakes. Finally, the probability p of the random null hypothesis can be calculated as

$$p = \sum_{j=m}^{n} \left\{ h^j (1-h)^{n-j} \times {}_{n}C_j \right\}. \qquad (4)$$

Usually, a random null hypothesis is statistically rejected when $p < 0.05$, which means that the occurrence of giant earthquakes does not follow a random process; *i.e.*, there is a specific lunar phase in which giant earthquake occurrences concentrate.

First, p was calculated for all of the events in Fig. 3a. Assuming that the specific lunar phase is between –16.24° and 50.21°, so n' and m' comprise five events and $p = 0.019$. Therefore, the assumed specific lunar phase is statistically significant because $p < 0.05$. However, an attempt was made to narrow the specific lunar phase because it would be too wide for practical applications. In this attempt, the left-most (#31) or right-most (#56) event was assumed to be outside the specific lunar phase. This time, m' is four events, the assumed specific lunar phase was between 32.33° and 50.23° or –16.24° and 40.32°, and $p = 0.00098$ or 0.031, respectively. Note that the specific lunar phase between 32.33° and 50.23° is more significant than before excluding #31. The same process was repeated setting $m' = 3$ for the assumed specific lunar phases of between 32.33° and 40.32° (excluding #31 and #56) or 35.04° and 50.23° (excluding #31 and #75); $p = 0.0019$ or 0.0071, respectively. These were statistically less significant and the specific lunar phase between 32.33° (L_S) and 50.23° (L_E) was determined to be the best for Peruvian earthquakes (the red bar in Figure 3a and Table 3).

Assuming the occurrence of the next giant earthquake, namely setting $n' = 6$ and $m' = 5$, then $p = 0.05$ when the duration of the specific lunar phase is 61.66° (ΔL). Therefore, statistically, it can be said that the next giant earthquake will occur between –11.43° ($L_E - \Delta L$) and 93.99° ($L_S + \Delta L$) (the blue bar in Figure 3a). However, this range is too wide to be of practical use. Therefore, the prediction of the next giant earthquake for $p = 0.01$ (duration, 39.97°) is also shown as the green bar in Figure 3a.

Using the above procedure, no significant specific lunar phase was found for the earthquakes in Chile (Figure 2a). The result for giant earthquakes in Southern Chile only is shown (Figure 3b, Table 3). The events #48–#50 were regarded as one earthquake because they occurred in 33 hours. The specific lunar phase was determined for Alaska (Figures 2b, 3c, Table 3) with a relatively large *p*-value. Specific lunar phases for the Japan Trench (Figures 2c and 3d) and Mongolia (Figures 2d and 3e), which is not a subduction zone, were also determined (Table 3). The events #2 occurred 14 days after #1 and they were treated as two events.

The events #91 in Sumatra occurred just two hours after #90. Regarding the two events as one event, a specific lunar phase for giant earthquakes in Sumatra (Figure 2d) was not determined (Figure 3f) because $p = 0.0641$. A specific lunar phase was determined for giant earthquakes in the Kuril Islands (Figures 2c and 3g). However, no specific lunar phase was determined for Samoa and Tonga (Figures 2e and 3h) because $p = 0.250$.

Figure 4 summarizes the specific lunar phases. Giant earthquakes occur around the spring tide in Peru, Southern Chile, and Alaska, when the tidal stress is greatest. However, giant earthquakes occur at times other than around the spring tide around Mongolia, in the Japan Trench and the Kuril Islands. The mechanism underlying this phenomenon has not been clarified, although our research group is examining the strain rate (Fujii *et al.*, 2013 and 2015; Wang *et al.*, 2016).

CONSIDERATION OF THE LOWER LIMIT OF MAGNITUDE

The above analyses were performed only for giant earthquakes ($M_W \geq 8$), mainly because it is desirable to predict giant earthquakes that can cause significant damage. However, there were too few earthquakes in the above analyses to achieve good statistical power. Using a slightly smaller lower limit produces better results for earthquakes in Peru.

The number of earthquakes is increased by lowering the lower limit of magnitude, as shown in Figure 6. A specific lunar phase can be observed for the case where $M_W \geq 7.5$ and p is approximately a fifth the value compared with $M_W \geq 8.0$ (Figures 3a and 6a, Table 2). For $M_W \geq 7.0$, the concentration of earthquakes in a specific lunar phase is vague and no lunar phase range with p of less than 0.05 was not found (Figure 6b). Therefore, the lower limit of $M_W = 7.5$ is considered to be the best for Peru earthquakes.

TOHOKU 2011 CASE

Let us examine whether the Tohoku 2011 earthquake could be anticipated using the specific lunar phase concept. For the Japan Trench, the specific lunar phase is 49.23° to 95.71° (Table

2). Excluding the Tohoku 2011 earthquake (#89), *i.e.*, setting $n' = 6$ and $m' = 5$, the same specific lunar phase was determined for the right five events, with a slightly greater $p = 0.018$ (Figure 7). The lunar phases for the next giant earthquake were determined as shown in Figure 7.

On March 9, 2011, an M_W 7.2 foreshock occurred during the specific lunar phase for the next giant earthquake with $p = 0.01$ (Figure 8). A tsunami watch (≤ 0.5 m) was issued and then lifted (Table 3). Subsequently, another large foreshock (M_W 6.6) occurred in the specific lunar phase. A tsunami watch was again issued and lifted. However, small foreshocks continued to occur, and the mainshock occurred 31 h later, within the specific lunar phase for giant earthquakes which could have been determined before the mainshock. The lunar phase for the next giant earthquake with $p = 0.05$ is too wide and it would be impractical to have people remain evacuated until it ended. However, if people had known that there was a specific lunar phase for the next giant earthquake with $p = 0.01$, and had remained evacuated for another 31 hours, the number of victims would have been greatly reduced.

CONCLUDING REMARKS

Statistically, giant earthquakes can occur during the specific lunar phases to some of the subduction zones or around Mongolia. Heightened attention during the dangerous portion of the lunar period in each seismic zone, especially when seismicity is occurring, should reduce the damage from giant earthquakes. An example in which a giant earthquake occurred in the specific lunar phase after seismic activity in the lunar phase for the next giant earthquake, was discussed. It is necessary to clarify the mechanisms underlying why giant earthquakes occur around the neap tides in some seismic zones and to examine additional case studies to show the effectiveness of the specific lunar phase concept.

DECLARATIONS

Abbreviations

M_W: the moment magnitude

USGS: the United States Geological Survey

Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no conflict of interest.

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Authors' contributions

Conceptualization: YF and YT; data collection and analysis: YT; writing and original draft preparation: YF and JK ; review and editing: JK and DF All authors read and approved the final manuscript.

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Figures

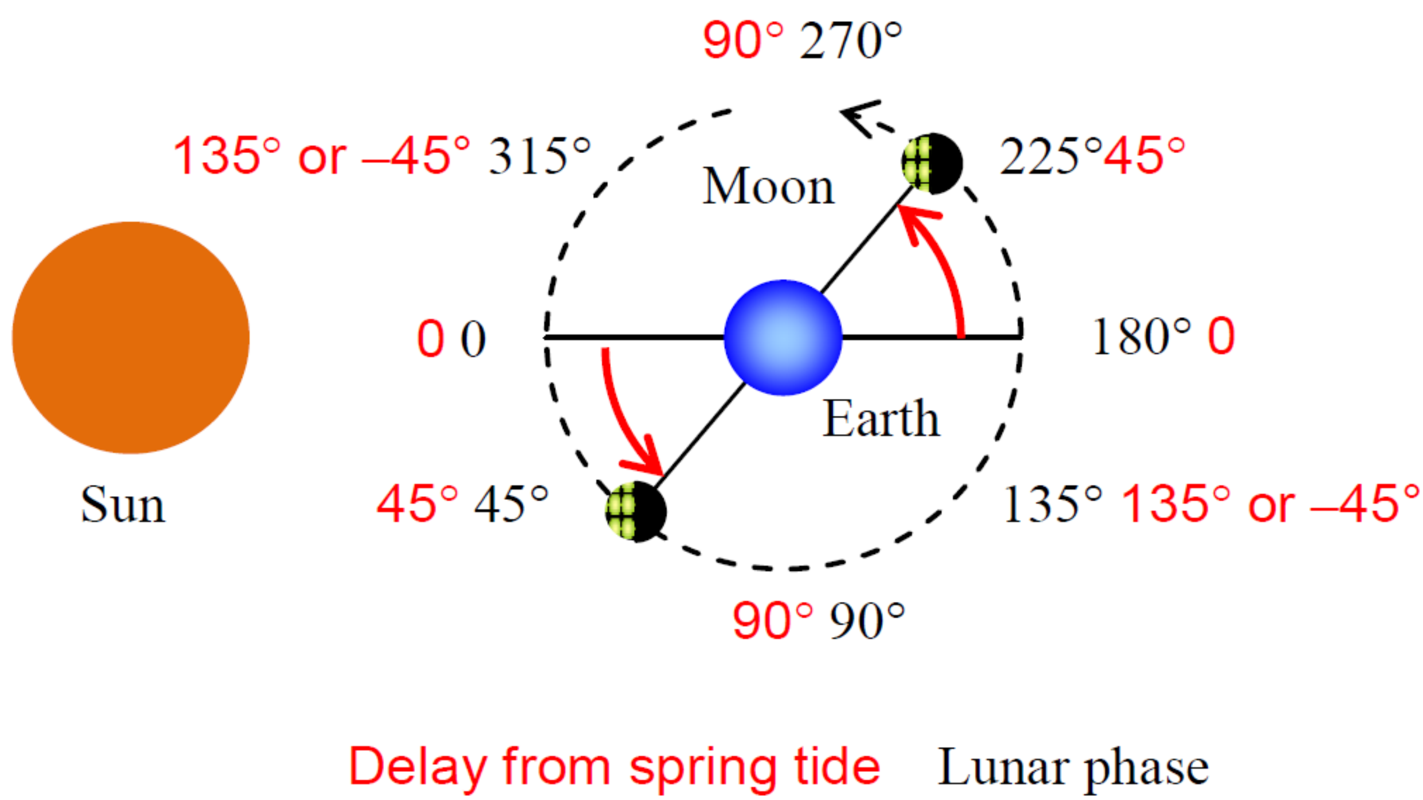


Figure 1

Lunar phase and delay from the spring tide. Not to scale.

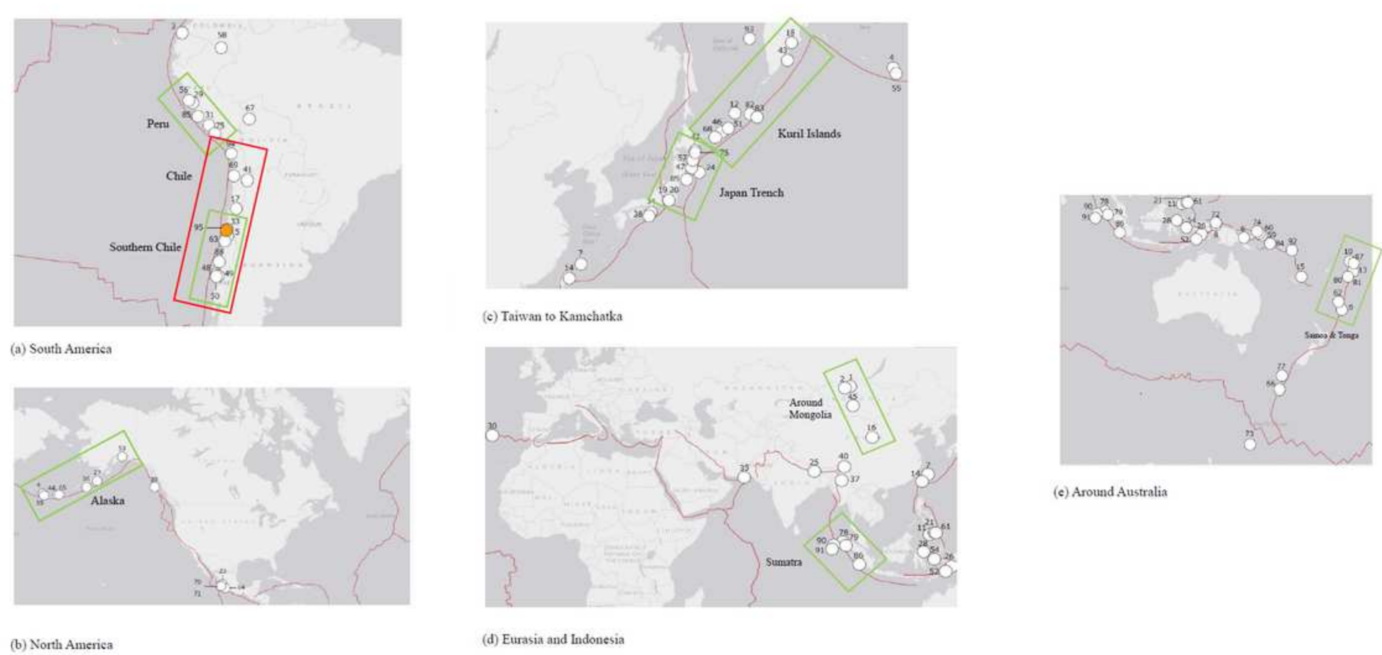


Figure 2

Giant earthquake distribution between 1900 and November 15, 2016 using the Search Earthquake Archives at the United States Geological Survey (USGS) Website.

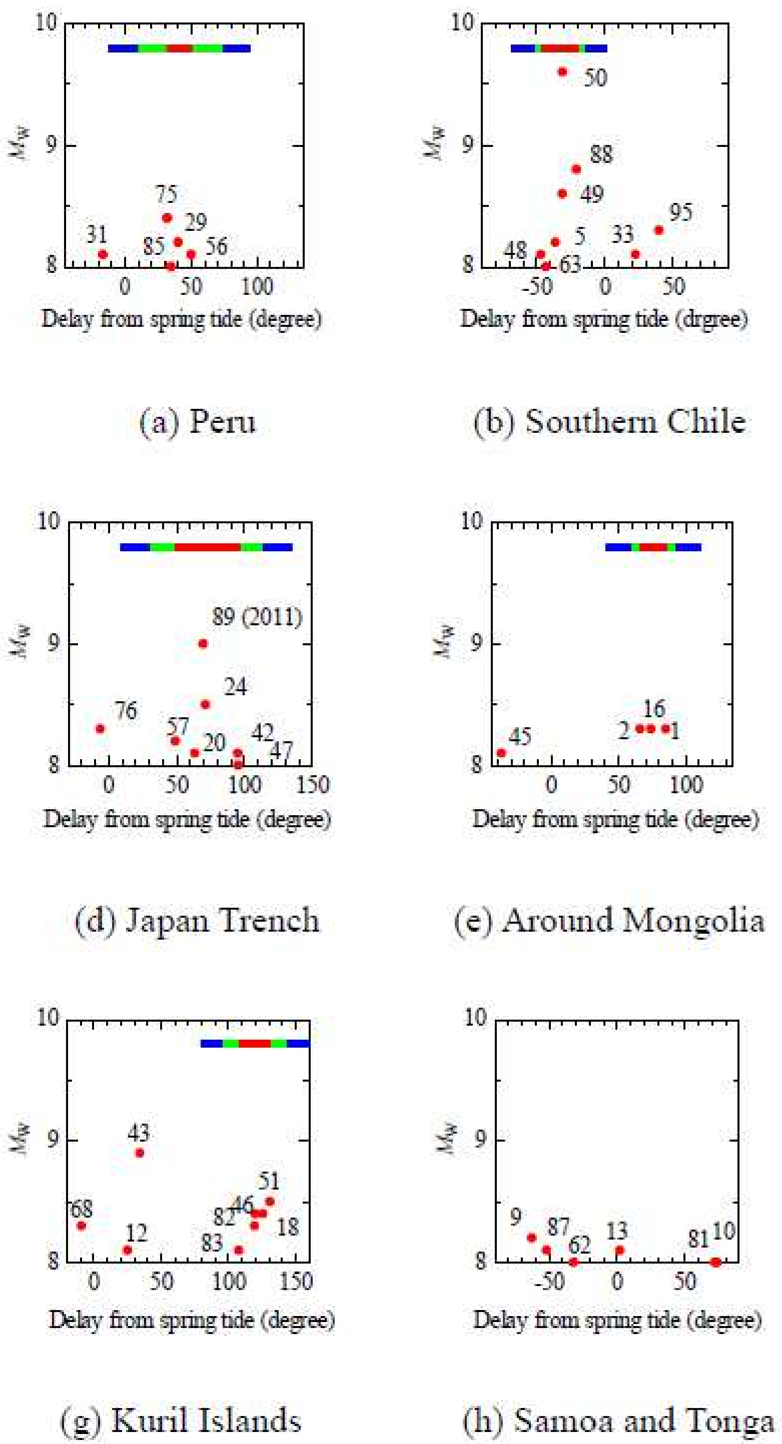


Figure 3

Lunar phase of giant earthquakes delayed from the spring tide. The red, green and blue bars denote the specific lunar phase and the lunar phase for the next giant earthquake with p = 0.01 and p = 0.05, respectively.

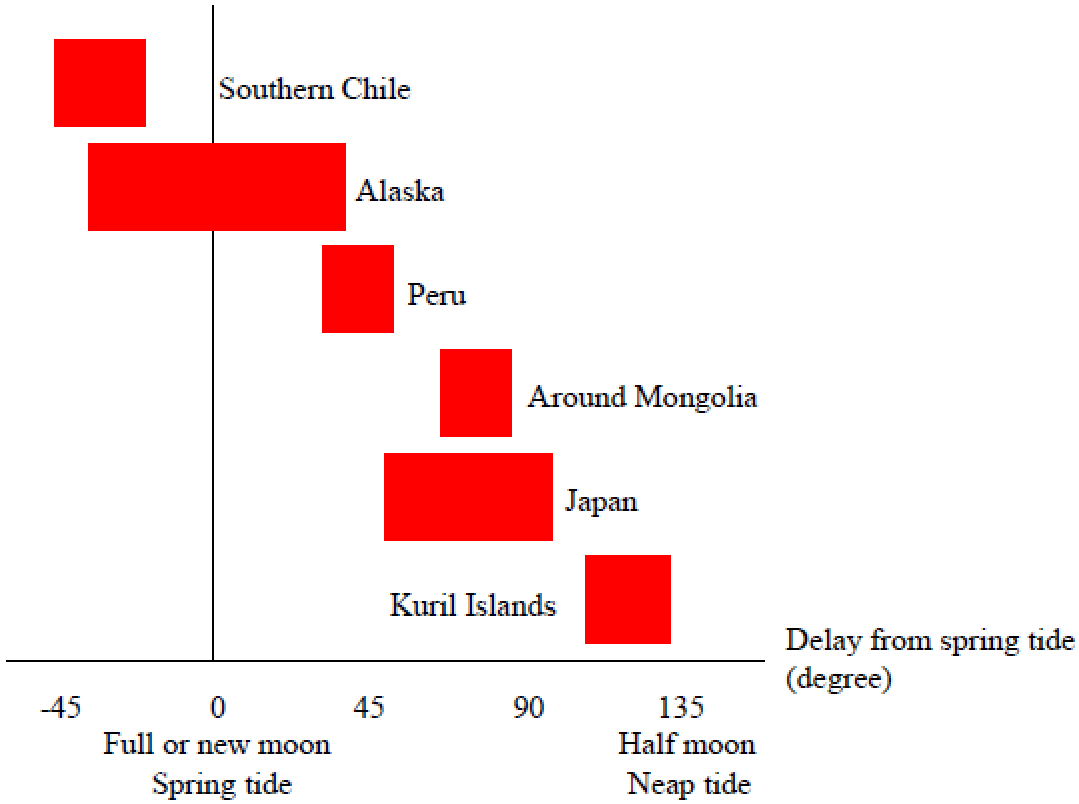
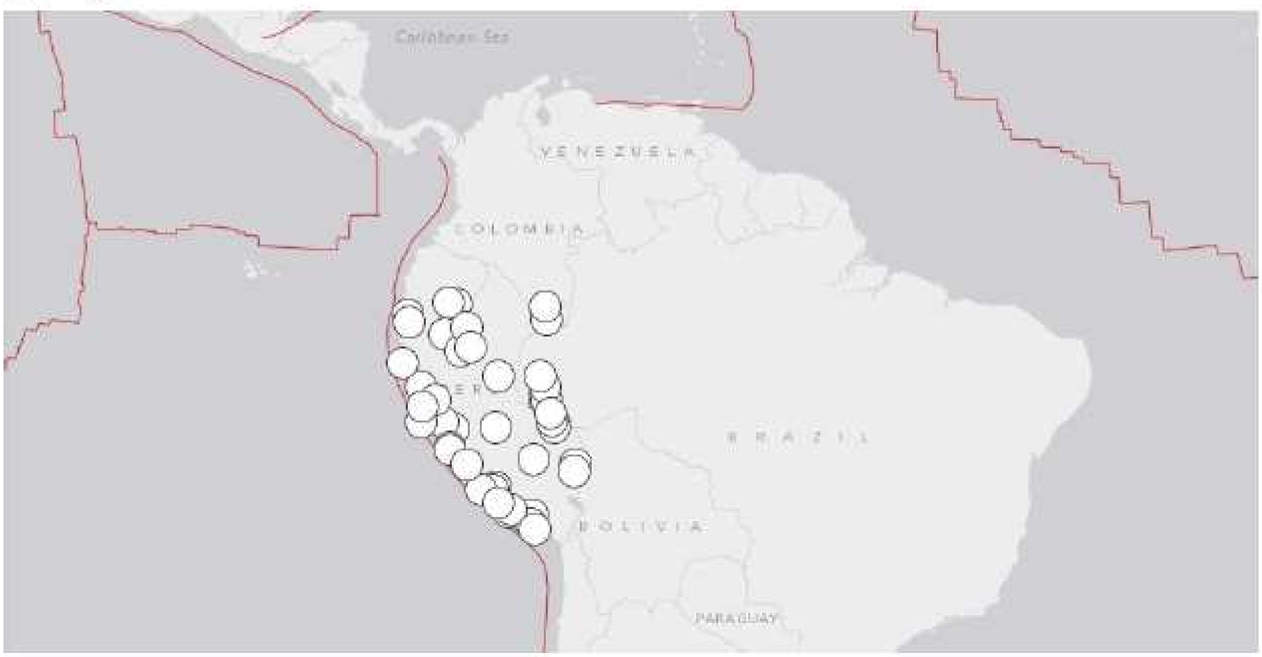


Figure 4

Specific lunar phases in delay from the spring tide for each subduction zone and around Mongolia.

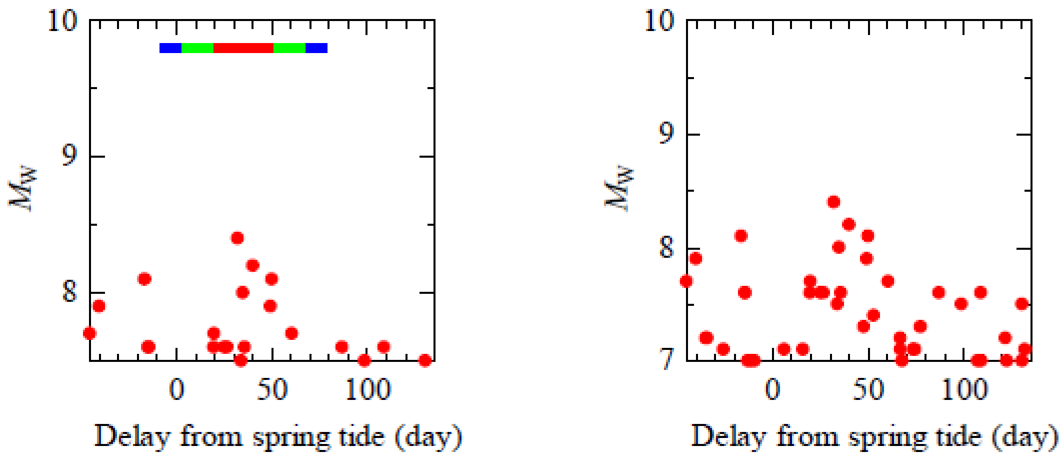
(a) $M_W \geq 7.5$



(b) $M_W \geq 7.0$

Figure 5

Earthquakes in Peru from 1900 to November 15, 2016 using the Search Earthquake Archives at the USGS Website.



(a) $M_W \geq 7.5$ ($p = 0.00067$)

(b) $M_W \geq 7.0$

Figure 6

The lunar phase of earthquakes in Peru from 1900 to November 15, 2016 (source: the Search Earthquake Archives at the USGS Website).

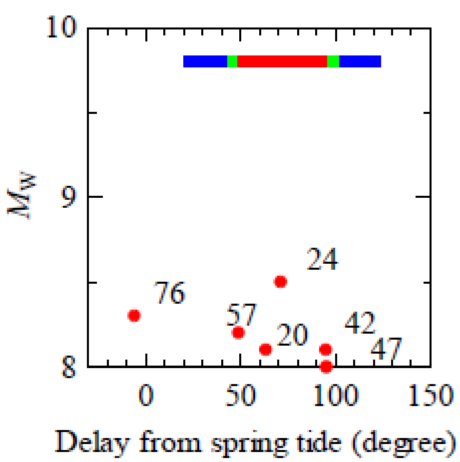


Figure 7

The lunar phase of giant earthquakes delayed from the spring tide for earthquakes in the Japan Trench from 1900 to just before the Tohoku 2011 earthquake. The red bar indicates the specific lunar phase before Tohoku 2011 (p = 0.018). The green or blue bar indicates the lunar phase for the next giant earthquake (p = 0.01 or p = 0.05).

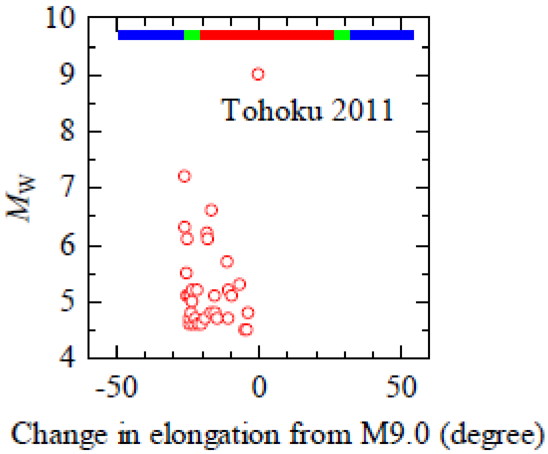


Figure 8

Foreshocks and mainshock of the Tohoku 2011 event (source: Database on Seismic Intensity of the Japan Meteorological Agency (JMA) Website). The red bar denotes the specific lunar phase before Tohoku 2011. The green or blue bar denotes the lunar phase for the next giant earthquake (p = 0.01 or 0.05).

Supplementary Files

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- FujiiTable2.pdf
- GraphicalAbstract.pdf