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Evidence of earthquake triggering by the solid earth tides

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ABSTRACT

Clear evidence for earthquake triggering by the earth tides has remained elusive for more than a century. Using the largest global earthquake catalog available (the NEIC catalog with 442412 events), we observe a clear correlation (with ~99% confidence) between the phase of the solid Earth tide and the timing of seismic events: earthquakes occur slightly more often at the time of ground uplift by the Earth tide, i.e. when normal stresses are reduced within the lithosphere. We observe that this phase distribution anomaly is larger for smaller and shallower earthquakes. Although earthquakes in regions with dominantly normal and strike-slip faulting seem to exhibit more tidal triggering than regions dominated by thrust faulting, there is no statistically significant evidence for a focal mechanism-dependence on earthquake triggering. Finally, we show here that it is highly probable that the observed triggering is caused by the solid Earth tide, rather than by loading from the ocean or atmospheric tides. Although an additional impact due to loading from ocean tides is possible and probable, we cannot detect it here because the earthquake database is not sufficiently complete and homogeneous (more small magnitude earthquakes in oceanic areas are needed). Our results are consistent with the idea of a damped sensitivity of earthquake initiation to stress change—an event is slightly more probable (~0.5 to 1.0%) when the tidal displacement is maximum, particularly for small and shallow events.

1. Introduction

Earthquakes occur when fault stresses build to levels that exceed a critical threshold for fault rupture (Scholz, 1990). Thus, applying additional stress to a fault system that is near failure may initiate the rupture process that produces an earthquake (Emter, 1997). The triggering stress may be tectonic in origin, but it may also be the result of a smaller, non-tectonic stresses applied for a limited time. In fact, increased seismicity has been attributed to stresses changes associated with water reservoir-emplacement (Gupta, 2002), recent nearby earthquakes (Hardebeck et al., 1998; Stein, 1999), and deglaciation-induced deloading (Sauber and Molnia, 2004). Tidal attractions, exerted by the Moon and Sun, also induce elastic deformation of the solid Earth, and therefore also exert additional stresses, with magnitudes less than $\sim 4\times10^3$ Pa (compared to earthquake stress drops of $\sim 10^5$–10^7 Pa) (Vidale et al., 1998) that vary on an hourly basis. Consequently, Earth's tides might also trigger earthquakes, producing excess seismicity near the Earth tide maximum, when dilatational tidal stresses tend to diminish the normal stresses that hold faults together. Indeed, tidal deformations within the lithosphere are mostly radial and are larger close to the surface. This means that both tidal pressure and tidal shear stress variations within the lithosphere coincide with tidal surface displacement (e.g., Smith, 1974; Wahr, 1981a,b), but the pressure variations are significantly larger than the shear stress variations (Fig. 1).

Although the concept of tidal triggering is more than 110 years old (Schuster, 1897; Emter, 1997), increased seismicity near the tidal maxima on the Earth has not yet been clearly demonstrated on a global scale and for all earthquake mechanisms. By contrast, it is today well accepted that "moonquakes" that occur deep beneath the surface of Earth's moon are linked to tidal stress variations primarily induced by perturbations to the Moon's orbit (Lammlein, 1977; Lognonné, 2005). On the Earth, several studies have reported no correlation between the Earth tide and earthquake occurrence (Schuster, 1897; Morgan et al., 1961; Heaton, 1982; Vidale et al., 1998). Other studies have reported small positive correlations (Tanaka et al., 2002; Cochran et al., 2004), but typically only for a particular geographic region (Souriau et al., 1982; Wilcock, 2001; Tolstoy et al., 2002; Kasahara, 2002), type of focal mechanism (Tsuruoka et al., 1995; Cochran et al., 2004), or earthquake magnitude range (Wilcock, 2001; Tanaka et al., 2002; Kasahara, 2002). In addition, some studies investigate tidal stress variations due to solid tides (Heaton, 1982; Ding et al., 1983), while others investigate those due to all tidal effects on Earth, including loading induced by ocean tides (Tsuruoka et al., 1995; Wilcock, 2001; Cochran et al., 2004). Moreover, all previous studies

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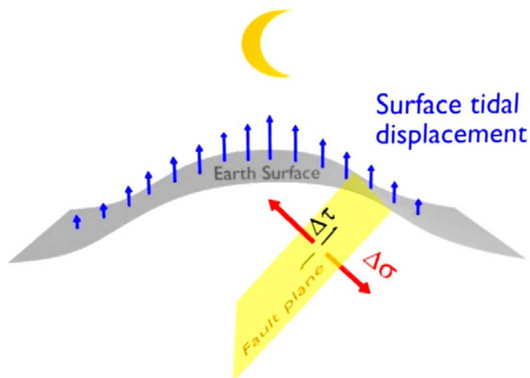

Fig. 1. Solid tide stress variations within the Earth. The attraction of the Moon (or the Sun) induces periodic displacements of the Earth's solid surface that are mostly vertical (because their very long wavelengths) and typically about a few tens of centimeters. Such deformation induces stress variations within the lithosphere that are dominated by pressure decrease at the time of ground uplift (tidal pressure variations are more than 10 times larger than tidal deviatoric stress variations at 20 km depth). On a fault plane, tidal stress variations normal to the fault ($\Delta\sigma$) are consequently larger than tidal shear stresses on the fault ($\Delta\tau$), and are thus more likely to induce failure. Note that since pressure variations are isotropic by definition and strongly dominate, total stress variations on the fault plane depend only slightly on the fault orientation.

investigated a limited set of seismic events (typically 10 to 10 000), yet recent laboratory studies (Lockner and Beeler, 1999; Beeler and Lockner, 2003) showed that a larger number of events (which depends non-linearly on normal effective stress within the lithosphere) is generally necessary to detect a significant tidal correlation with earthquake occurrence. These studies concluded that any Earth tide impact on triggering will only be detectible at a statistically significant level if at least 13 000 seismic events are used. They also showed that shallow seismic events should be more susceptible to tidal triggering (see also Dieterich, 1987) because the confining pressure is smaller and tidal stresses relatively more important. Vidale et al. (1998) illustrated the Beeler and Lockner (2003) conclusions by studying a set of Californian earthquakes containing almost 13 000 events. They showed that the rate of earthquake occurrence appears to be ~2% higher during times in which tidal stresses favors rupture, but that this anomaly is not statistically significant at the 95% confidence level. Finally, recent works have demonstrated correlations between tidal phenomena and non-volcanic tremor induced by "slow earthquakes" at subduction zones (e.g., Obara et al., 2004; Ide et al., 2007; Rubinstein et al., 2008; Nakata et al., 2008).

In the present study, we looked for a tidal correlation in the timing of 442 412 globally distributed earthquakes (from the NEIC world seismic catalogue, available via the U.S. Geological Survey), which occurred between 1973 and 2007, with magnitudes from 2.5 to 9. The NEIC catalogue is actually a compendium of several network catalogues with different properties. For example, it combines global catalogues with detection levels of about magnitude 5, and results from North American and European local networks with magnitude cutoffs of about 2.5. The NEIC earthquake database is consequently not homogeneous or complete in terms of magnitude (Fig. 1), but it is the most complete

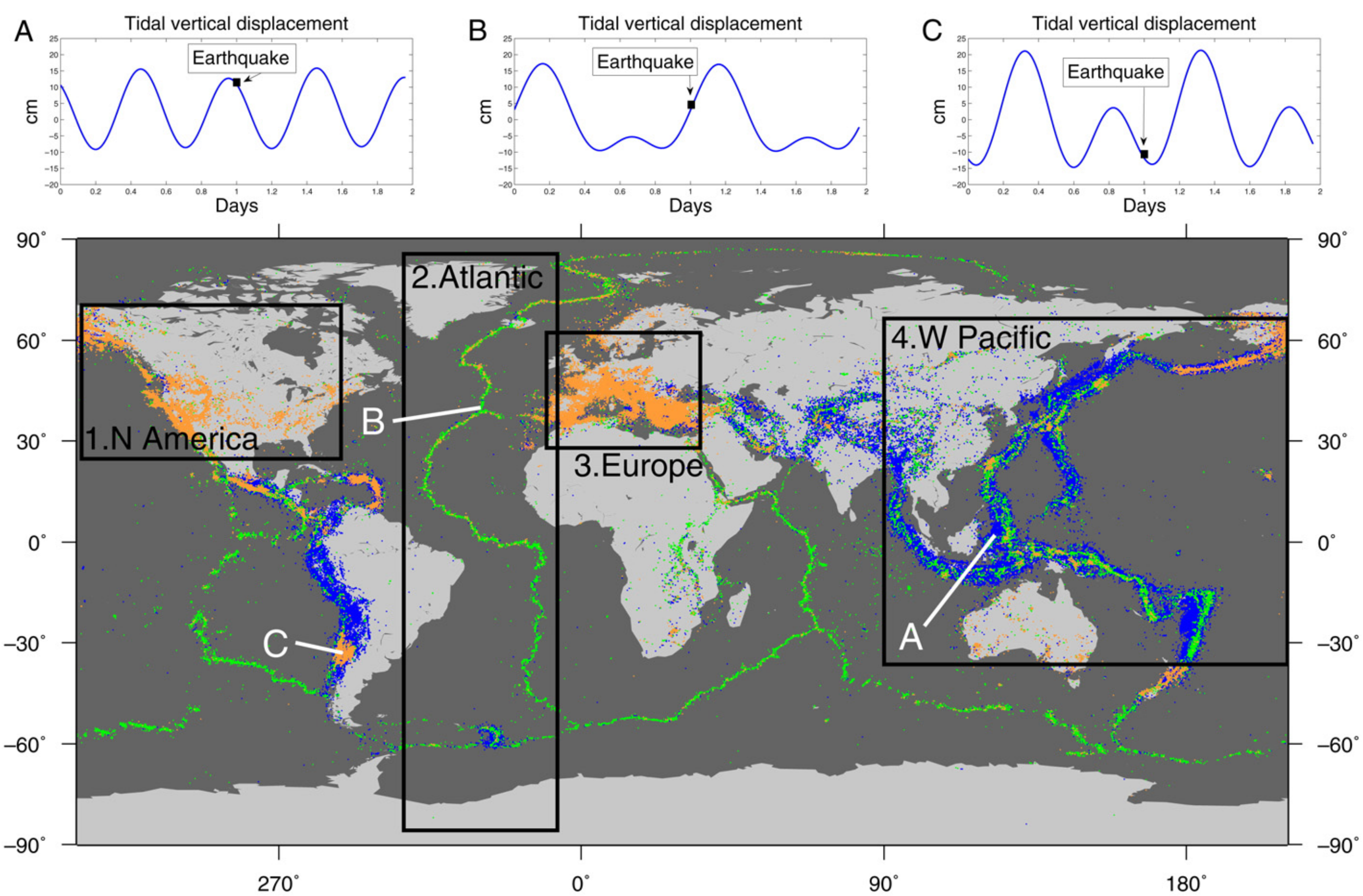

Fig. 2. Locations of earthquake hypocenters. In orange, small and shallow earthquakes (magnitudes less than or equal to 4, and depths shallower than 20 km); in green, shallow earthquakes with larger magnitude; in blue, events deeper than 20 km (note that some are hidden by green and orange dots). A, B, and C show examples of ground tide vertical displacements that were occurring at the time of three given earthquakes. One can see that the tidal signals present mostly semi-diurnal and diurnal periodities (mainly semi-diurnal in graph A, mainly diurnal in graph B, and partly semi-diurnal/diurnal in graph C). In these examples, the earthquakes occurred at tidal phases: A: 39°/−144°, B: −115°/−58°, C: 115°/−125° for semi-diurnal/diurnal components respectively. Boxes, noted 1–4, show different regions that we studied in greater detail (Table 1). Boxes 1 and 3 contain most of the small and shallow earthquakes, box 2 contains mostly Mid-Atlantic ridge earthquakes (normal and strike-slip faults), and box 4 contains mostly subduction zone earthquakes (reverse faults).

global catalog freely available. We used here the largest possible database to maximize our chances of detecting excess events in a particular tidal phase, and to allow us to subdivide the database to interrogate tidal triggering variations that would depend on earthquake magnitude, depth or location. Note that the NEIC catalogue includes aftershocks, so that the times of some earthquakes are not independently distributed. However, Jeffreys (1938) showed that while aftershocks need to be removed before testing for possible tidal triggering by long period tides (weeks or longer), non-independency of aftershocks should not affect correlations when one investigates tidal triggering on a daily basis (induced by semi-diurnal and diurnal tides), as in the present work. Because the time of an aftershock in a given day may be affected by tidal stresses maximum, we consequently kept aftershocks in the database for the purpose of this investigation.

2. Global correlation between the earthquake timing and tidal deformation

Tidally-induced seismicity is detected by looking for inhomogeneity in the number of earthquakes occurring within different phases of the tidal cycle. Classically, the phase of the earthquake was determined by interpolation between the nearest tidal maximum and minimum (Tsuruoka et al., 1995; Tanaka et al., 2002; Cochran et al., 2004). However, actual tidal signals present various periodicities (annual, monthly, diurnal, semi-diurnal, ter-diurnal, etc.; Fig. 2A–C), which means that tidal phases determined by interpolation do not have the same meaning for all the earthquakes. In order to avoid this problem, we decomposed the tidal signal into its basic periodic components. Over time scales of days to weeks, there are two main components to the tidal signal (Figs. 2A–1C): diurnal (~24 h periodicity) and semi-diurnal (~12 h periodicity) components. Using an Earth tide model based on the HW95 tidal potential catalogue (Hartmann and Wenzel, 1995), we determined the phase within the diurnal and semi-diurnal components of the surface tide vertical displacement at the time of each event. The HW95 catalogue contains 12 935 tidal components of various periodicities induced by the gravitation of the Moon, the Sun, and planets. For each earthquake, the diurnal and semi-diurnal phases of the tidal signal have been computed by summing all the tidal components with periods close to 24 h (diurnal, 2990 components) and 12 h (semi-diurnal, 2155 components) at the time and the location of the earthquake (on the Earth's surface, above the earthquake hypocenter). Note that the periods of diurnal and semi-diurnal tidal components are usually not exactly 12 h and 24 h. As demonstrated by synthetic tests (see below), these small departures can be neglected and will not affect our general results. We also investigated smaller tidal periodicities (ter-diurnal, quart-diurnal, etc.). However, these components are very small compared to semi-diurnal and diurnal components, and we observed no significant correlations to earthquake timing periodicities. We did not investigate long period tidal components (weekly, monthly,

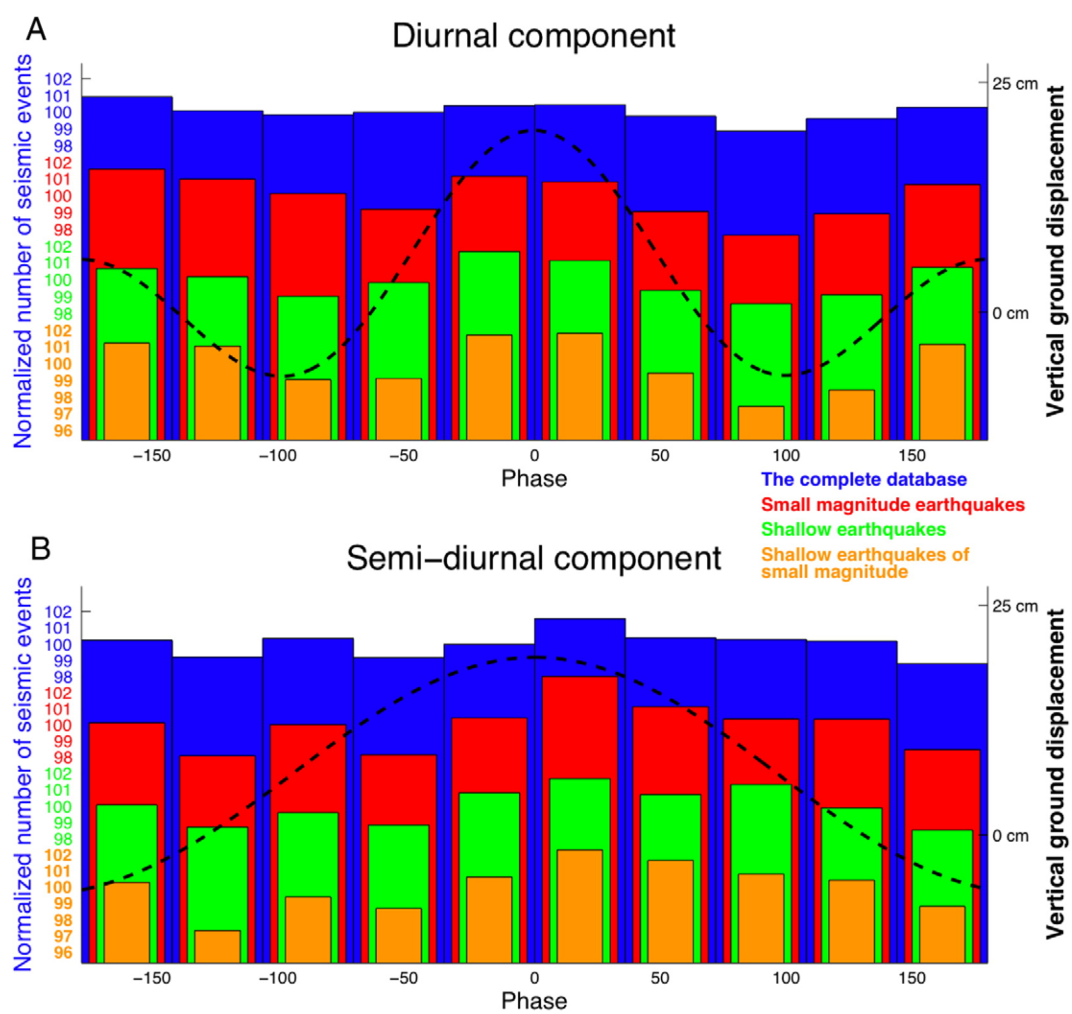

Fig. 3. Earthquake distribution within the tidal phase. The histograms show the phase of the diurnal (A) and semi-diurnal (B) tide at the time and the place of the seismic events (normalized to 1000 events, so the average bin has 100 events). The four histograms show all seismic events (blue), small events (magnitudes less than 4.0, red), shallow events (less than 20 km depth, green), and shallow events of small magnitude (orange). The mean vertical ground displacement (for all events) is superimposed (dashed black curves) and correlates with the phase distribution.

annual, etc.) because these tidal components are smaller than the semi-diurnal and diurnal components; and also because, as mentioned above, the NEIC earthquake database contains aftershocks, which may introduce artificial periodicities on the time distribution of earthquakes over weeks and months (Jeffreys, 1938).

Separating the signal into different periodic components is not always physically meaningful because the extrema of the periodic components are not necessarily extrema of the actual total tide signal, which is a combination of the different periodic components. Here we focus on the two predominant components of tides, which happen to be correlated due to astronomical configurations. In fact, the extrema of the semi-diurnal and diurnal tides usually occur approximately at the same time; consequently the maximum of the diurnal and semi-diurnal tides is also a maximum of the total tide signal. This point can be seen quite well on Fig. 3A, where the black dashed line, which shows a mean tidal displacement signal (with all the periodicities), is primarily a semi-diurnal signal with small variations of its maximum magnitude (induced by the diurnal component of tides).

If tides do not affect earthquake triggering, then we can expect earthquakes to be uniformly distributed within each tidal phase. Histograms of seismic distribution as a function of phase, however, show an obvious departure from uniform for both diurnal (Fig. 3A) and semi-diurnal (Fig. 3B) tides. The statistical significance of this departure can be tested using various different statistical tests. Because we are investigating tidal phase data, which can be expressed over a circle, we use a statistical test that is particularly suited to circular data, the Kuiper's test, which is an extension of the Kolmogorov–Smirnov statistical test (Kuiper, 1962; Fisher, 1993). The main idea of this test is to quantify the difference between a given cumulative distribution constructed from observed tidal phases and the cumulative distribution constructed from a uniform tidal phase distribution (the null hypothesis). To implement this test, one determines the Kuiper statistic $R=\left(\sqrt{N}+0.155+0.24/\sqrt{N}\right)(D^{+}-D^{-})$, where D^{+} and D^{-} are respectively the maximum and the minimum separation between these two cumulative distributions, and N the number of events. Note that R is always positive because D^{-} is null or negative. The R value quantifies the departure of a given distribution from a uniform distribution, and also allows us to quantify the significance of this departure (Kuiper, 1962). Generally, the level of statistical significance over which one can exclude the null hypothesis (that the observed phase distribution is statistically similar to a uniform phase distribution) is chosen to be 0.95 (or 95%). Statistical significance at this level means that there is only a 5% of chance that purely random fluctuations would generate a R value this large or larger.

In the present study, we find that the departure from a uniform distribution of phases is significant at the 99.87% level for the semi-diurnal component and at the 94.37% level for the diurnal component (Table 1). Because the anomaly is relatively small, the observed departures from a uniform distribution are caused by only 0.2–0.3% of the events for the complete database in Fig. 3. By superimposing the mean vertical ground displacement on the seismicity histograms (Fig. 3, black dashed curves), we can see that the number of earthquakes is larger near the maximum positive vertical displacements.

We also investigated the possible correlation between earthquake triggering and tides following the approach of Tsuruoka et al. (1995) (also Tanaka et al., 2002; Cochran et al., 2004) in which the phase of the earthquake is determined by interpolation between the nearest tidal maximum and minimum. Following this approach, we obtained results for tidal phase correlations with seismicity that are very similar to the above correlations for the semi-diurnal phase, and with a similar significance (98.2% of significance). Both methods are consequently relatively equivalent, except that, in our approach, results for diurnal tides give a second viewpoint on the link between seismicity and tides. Moreover, we investigate here an earthquake database that is 10 to 1000 times larger than databases investigated in the previous studies.

Note that, with such a large number of events, a small systematic error in the phase determination could create artificial variations in the phase distribution. In order to “validate” our method, we performed two tests on synthetic sets of randomly-distributed earthquakes containing the same number of events as the true catalogue. In the first test we investigated a set of earthquakes randomly-distributed in time and space. However, we know that earthquakes are not homogeneously located over the Earth, but are instead localized regionally by plate tectonics. For this reason we used the NEIC database in the second test, but randomly exchanged the dates of earthquakes. We obtained values of the Kuiper' statistic that are consistent with no anomaly in the phase distribution in both tests. The level of significance of the second test (for the semi-diurnal component) is presented on the Table 1, under the “random” heading. Consequently, we are confident that the observed correlations between seismicity and tidal phase are not associated with any systematic bias in our method for determining the tidal phase.

Table 1
The statistical significance of the earthquake phase distributions

Probability	All depths (D)	$D\leq20$ (km)	$D>20$ (km)
All magnitudes (M)	Diurnal: 0.9439 S-Diurnal: **0.9987** Random: 0.1661 (100%)	Diurnal: 0.8985 S-Diurnal: **0.9996** Random: 0.5540 (41%)	Diurnal: 0.3131 S-Diurnal: 0.4584 Random: 0.3171 (39%)
$M\leq4$	Diurnal: **0.9998** S-Diurnal: **1.0000** Random: 0.2079 (46%)	Diurnal: **0.9938** S-Diurnal: **1.0000** Random: 0.2711 (29%)	Diurnal: **0.9728** S-Diurnal: 0.9275 Random: 0.2919 (13%)
$M>4$	Diurnal: 0.6077 S-Diurnal: 0.3790 Random: 0.3720 (54%)	Diurnal: 0.7665 S-Diurnal: 0.8461 Random: 0.7959 (12%)	Diurnal: 0.1921 S-Diurnal: 0.0590 Random: 0.3748 (26%)

Probability (semi-diurnal)	Region 1 N. America	Region 2 Atlantic	Region 3 Europe	Region 4 W. Pacific
All seismic events	0.9484 (0.14%)	0.8072 (4%)	**1.0000** (20%)	0.1926 (43%)
$M\leq4$ and $D\leq20$ km	**0.9669** (9%)	**0.9928** (2%)	**0.9999** (15%)	0.6652 (2%)
$M>4$ or $D>20$ km	0.2296 (5%)	0.3071 (2%)	**0.9986** (5%)	0.1948 (41%)

The probability of a statistically significant correlation between tidal phase and earthquake distribution is computed from the Kuiper's test (Kuiper, 1962) of the tidal phase distributions for different subsets of seismic events. A probability of 0.9998 means that there is a 0.02% chance that a phase anomaly of the size we obtained (measured by the R estimator), could be obtained with no signal at all (i.e. the true distribution is uniform but our sample happens to mimic a non-uniform distribution). A bold value indicates that the significance is superior to the 95%-level. The number in parentheses indicates the fraction of seismic events within that subset compared to the complete database (note that 20% of the events have no estimated depth, which is why the depth-separated columns do not add up to 100%). The different regions (1 to 4) are presented in the map (Fig. 2).

3. Impact of magnitude, epicenter depth, and focal mechanism

In order to determine which earthquakes are most prone to tidal triggering, we divided our database into sub-categories. We found that small magnitude (less than magnitude 4.0) and shallow (less than 20 km depth) earthquakes are more easily triggered by tides, with the departure from a uniform distribution caused by 0.6–0.7% of the events (Fig. 3). Shallow or small events by themselves generally show larger correlations and thus a greater probability that the observed triggering is not random (Table 1). We also subdivided the dataset based on event location, looking at 4 tectonically-distinct regions in particular (Fig. 2). In doing so, we consider the dominant tectonic environment in each region as a proxy for the average focal mechanism. The tidal correlation in the mid-Atlantic zone (Region 2, dominantly normal fault and strike-slip focal mechanisms) seems to be globally more significant than the tidal correlation in subduction zones (Region 4, dominantly reverse fault focal mechanisms), which may suggest that earthquakes on normal and strike-slip faults are more easily triggered than earthquakes on reverse faults. However, when all earthquakes in the regions are considered, the significance of these correlations falls below the 95%-significance level, which makes

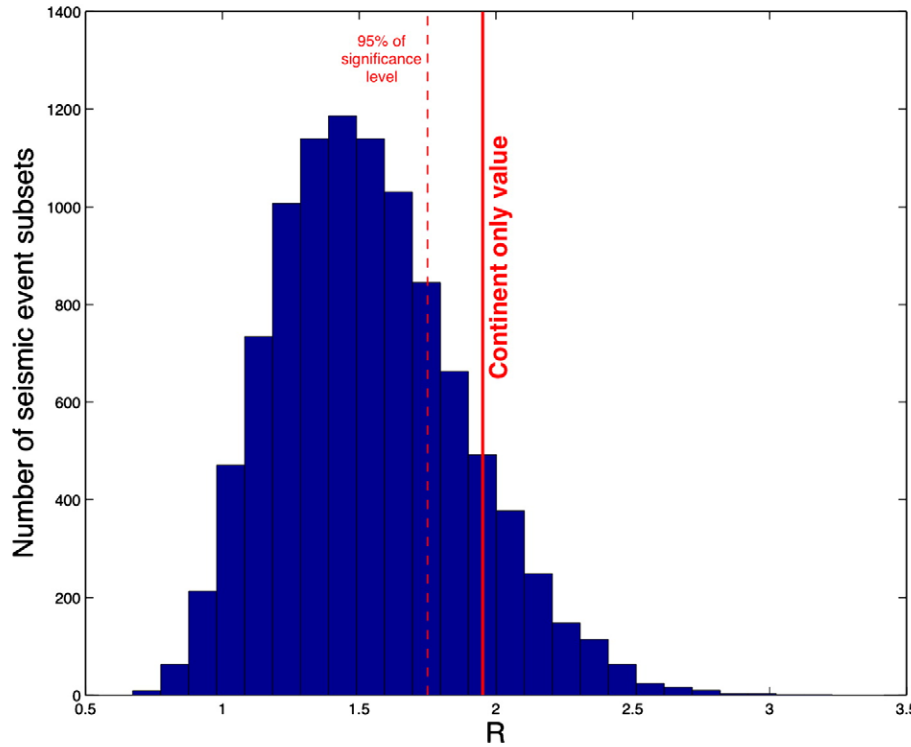

Fig. 4. Triggering anomaly for continents compared to other subsets. In red: The value of Kuiper' statistic R (Kuiper, 1962) for the semi-diurnal phase distribution of the subset containing only continental seismic events (more than ~200 km from the coasts). This departure from a uniform distribution of phase (R=0) is significant at the 98.9% level. In blue: histogram of R values of 10 000 subsets containing the same number of seismic events as the continent-only subset (175 495 events), in which seismic events have been randomly selected from the complete database. The R value of the continent only subset is larger than the mean value of the distribution, which suggests that the observed correlation between tides and seismicity is mostly due to solid earth tides.

the comparison meaningless. Only for the set of small and shallow earthquakes in the Atlantic region do we find a significant tidal correlation. This may suggest that small shallow earthquakes are more likely to be triggered in extensional or strike-slip environments, but primarily this finding emphasizes our previous results that magnitude and depth are key parameters that control tidal triggering. We thus conclude that we detect no clear (or significant) evidence for a focal mechanism-dependence on earthquake triggering. Finally, most of the recorded shallow and small events are clustered in North America (Region 1) and Europe (Region 3) because of their proximity to large densities of seismometers. Of these, the triggering anomaly is slightly more significant, and consequently larger, in Europe than in North America. This could be due to differences in the lithospheric properties (e.g., thickness, strength).

4. Solid earth tides versus oceanic tidal loading

Several studies have suggested that tidal-triggering is more likely to be caused by a combination of solid and ocean tides rather than solid earth tides only (Tsuruoka et al., 1995; Wilcock, 2001; Cochran et al., 2004) because stress changes associated with ocean tide loading can be locally larger than stress changes associated with the solid Earth tide, at least within oceanic lithosphere. Note that laboratory studies (Rydelek et al., 1992; Lockner and Beeler, 1999; Beeler and Lockner, 2003) showed that the link between tidal stress magnitude and a possible correlation with earthquake triggering is complex and non-linear.

In the present work, we detected a correlation between earthquake occurrence and Earth's solid tides. However, because the ocean and earth tides are also correlated, we cannot eliminate the possibility that the oceanic tide is indirectly the main cause of the observed correlation. To determine whether ocean and/or solid tides play a major role in earthquake triggering, we examined only earthquakes occurring in continental areas (more than ~200 km from any coast), and computed the R value of the semi-diurnal phase distribution of these 175 495 events. We then randomly selected 10 000 samples of the same size from the total set, and computed the R value of each subset. The continent-only subset has an R value superior to the 95%-confidence limit (Fig. 4). Indeed, the phase anomaly that we observed, which is similar to the one observed in Fig. 3, is quite large (98.6% of significance).

The significance of the anomaly obtained in the continent only subset demonstrates that the solid tides do affect the earthquake triggering. As mentioned before, the phase anomaly is mostly associated with events of small magnitude, which are, in the NEIC database, almost only observed in continental area (North America and Europe). The lack of data in oceanic area, and the phase coincidence between ocean and solid earth tides, prevent us to test any effect of ocean tides. The absence of significance in ocean regions does not mean that there is no effect, but barely that our dataset does not allow us to test for such an effect. Our results, nevertheless, evidence a very significant impact of Earth solid tide on the earthquake triggering, at least for shallow events of small magnitude. This effect might be modified, amplified or even canceled in ocean area by the oceanic tide, but such an effect cannot be tested using the dataset we have.

5. Conclusions

The detection of tidally-triggered events suggests that tidal stresses, which are typically smaller than 0.1–1% of tectonic stress magnitudes, are sufficient to trigger up to about 0.2–0.3% of all the earthquakes of the NEIC database. However as mentioned above, this global earthquake catalogue is not complete for small magnitude events (less than 4.0) that we have shown to be more easily triggered by tides. In fact, we find that the tidal phase anomaly for small and shallow earthquakes is caused by 0.6–0.7% of the events. Because earthquake frequency varies inversely with magnitude following a power law, we can conclude that this last ratio of tidally triggered earthquakes is probably closer to the appropriate ratio for all earthquakes (of magnitude superior to 2.5). This result is in agreement with the laboratory results of Beeler and Lockner (2003) who concluded that at most 1% of earthquakes should be triggered by tidal phenomena. Such a small number of tidally-triggered earthquakes suggests that earthquake initiation has a damped sensitivity to stress change (Knopoff, 1964; Scholz, 1990; Rydelek et al., 1992; Lockner and Beeler, 1999; Beeler and Lockner, 2003). We showed that these earthquakes are likely triggered by the solid earth tides, but we cannot eliminate loading from ocean tides as a source because most small earthquakes in our database are located in continental areas (North America and Europe) and not beneath the oceans.

Shallow earthquakes are more easily triggered, which could be explained by the fact that tidal dilations become relatively smaller with depth compared to the increasing confining stresses on faults, and are thus less likely to trigger deeper earthquakes (Dieterich, 1987; Scholz, 1990; Lockner and Beeler, 1999; Beeler and Lockner, 2003). The greater triggering rate for smaller earthquakes is more difficult to explain, but may result from differences in earthquake-producing faults, which are more likely to be longer and older for larger earthquakes. Alternatively, tidal triggering is more likely if the time-scale of stress accumulation is closer to the tidal timescale. While large earthquakes typically relieve tectonic stresses that build over centuries, smaller earthquakes are more likely to be triggered by short-time-scale stress changes associated with recent seismicity (e.g., aftershocks) (Hardebeck et al., 1998; Stein, 1999) or surface loading (Sauber and Molnia, 2004), and thus may be more prone to tidal triggering. Finally, if differences between the rupture initiation mechanisms of large and small earthquakes exist (Ellsworth and Beroza, 1995), then the increased triggering rate for small earthquakes may indicate a sensitivity of tidal triggering to these differences. If this is the case, then greater understanding of tidal triggering may provide important insight into the earthquake nucleation process. Further study of very large earthquake databases will be necessary to gain such insight.

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References

Beeler, N.M., Lockner, D.A., 2003. Why earthquakes correlate weakly with the solid Earth tides: effects of periodic stress on the rate and probability of earthquake occurrence. J. Geophys. Res. 108 (B8), 2391. doi:10.1029/2001JB001518.

Cochran, E.S., Vidale, J.E., Tanaka, S., 2004. Earth tides can trigger shallow thrust fault earthquakes. Science 306, 1164–1166.

Dieterich, J.H., 1987. Nucleation and triggering of earthquake slip: effect of periodic stresses. Tectonophysics 144, 127–139.

Ding, Z., Jia, J., Wang, R., 1983. Seismic triggering effect of tidal stress. Tectonophysics 93, 319–335.

Ellsworth, W.L., Beroza, G.C., 1995. Seismic evidence for an earthquake nucleation phase. Science 268, 851–855.

Emter, C., 1997. Tidal triggering of earthquakes and volcanic events. In: Wilhem, H., Zürn, W., Wenzel, H.-G. (Eds.), Tidal Phenomena, vol. 66 of Lecture Notes in Earth Sciences. Springer-Verlag, Berlin, pp. 293–310.

Fisher, N.I., 1993. Statistical Analysis of Circular Data. Cambridge University Press, New York.

Gupta, H.K., 2002. A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India. Earth-Sci. Rev. 58, 279–310.

Hardebeck, J.L., Nazareth, J.J., Hauksson, E., 1998. The static stress change triggering model: Constraints from two southern California aftershock sequences. J. Geophys. Res. 103, 24427–24437.

Hartmann, T., Wenzel, H.-G., 1995. The HW95 tidal potential catalogue. Geophys. Res. Lett. 22, 3553–3556.

Heaton, T.H., 1982. Tidal triggering of earthquakes. Bull. Seismol. Soc. Am. 72, 2180–2200.

Ide, S., Beroza, G.C., Shelly, D.R., Uchide, T., 2007. A scaling law for slow earthquakes. Nature 447, 76–79.

Jeffreys, H., 1938. Aftershocks and periodicity in earthquakes. Gerlands Beitr. Geophys. 53, 111–139.

Kasahara, J., 2002. Tides, earthquakes and volcanoes. Science 297, 348–349.

Knopoff, L., 1964. Earth tides as a triggering mechanism for earthquakes. Bull. Seismol. Soc. Am. 54, 1865–1870.

Kuiper, N.H., 1962. Tests concerning random points on a circle. Proc. K. Ned. Akad. Wet., Ser. A 63, 38–47.

Lammlein, D., 1977. Lunar seismicity and tectonics. Phys. Earth Planet. Inter. 14, 224–273.

Lockner, D.A., Beeler, N.M., 1999. Premonitory slip and tidal triggering of earthquakes. J. Geophys. Res. 104 (B9), 20133–20151.

Lognonné, P., 2005. Planetary seismology. Annu. Rev. Earth Planet. Sci. 33, 571–604. doi:10.1146/annurev.earth.33.092203.122604.

Morgan, W.J., Stoner, J.O., Dicke, R.H., 1961. Periodicity of earthquakes and the invariance of the gravitational constant. J. Geophys. Res. 66 (11), 3831–3843.

Nakata, R., Suda, N., Tsuruoka, H., 2008. Non-volcanic tremor resulting from the combined effect of Earth tides and slow slip events. Nature Geos. 1, 676–678.

Obara, K., Hirose, H., Yamamizu, F., Kasahara, K., 2004. Episodic slow slip events accompanied by non-volcanic tremors in southwest Japan subduction zone. Geophys. Res. Lett. 31. doi:10.1029/2004GL020848.

Rubinstein, J.L., Rocca, M.L., Vidale, J.E., Creager, K.C., Wech, A.G., 2008. Tidal modulation of nonvolcanic tremor. Science 319, 186–189.

Rydelek, P.A., Sacks, I.S., Scarpa, R., 1992. On tidal triggering of earthquakes at Camp Flegrei, Italy. Geophys. J. Int. 109, 125–1376.

Sauber, J.M., Molnia, B.F., 2004. Glacier ice mass fluctuations and fault instability in tectonically active Southern Alaska. Glob. Planet. Change 42, 279–293.

Scholz, C.H., 1990. The Mechanics of Earthquakes and Faulting. Cambridge Univ. Press, New York. 439 pp.

Schuster, A., 1897. On lunar and solar periodicities of earthquakes. Proc. R. Soc. Lond. 61, 455–465.

Smith, M.L., 1974. The scalar equations of infinitesimal elastic-gravitational motion for a rotating, slightly elliptical Earth. Geophys. J. R. Astron. Soc. 37, 491–526.

Souriau, M., Souriau, A., Gagnepain, J., 1982. Modeling and detecting interactions between Earth tides and earthquakes with application to an aftershock sequence in the Pyrenees. Bull. Seismol. Soc. Am. 72, 165–180.

Stein, R.S., 1999. The role of stress transfer in earthquake occurrence. Nature 402, 605–609.

Tanaka, S., Ohtake, M., Sato, H., 2002. Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data. J. Geophys. Res. 107 (B10), 2211. doi:10.1029/2001JB001577.

Tolstoy, M., Vernon, F.L., Orcutt, J.A., Wyatt, F.K., 2002. Breathing of the seafloor: tidal correlations of seismicity at Axial volcano. Geology 30, 503–506.

Tsuruoka, H., Ohtake, M., Sato, H., 1995. Statistical test of the tidal triggering of earthquakes: contribution of the ocean tide loading effect. Geophys. J. Int. 122, 183–194.

Vidale, J.E., Agnew, D.C., Johnston, M.J.S., Oppenheimer, D.H., 1998. Absence of earthquake correlation with Earth tides: an indication of high preseismic fault stress rate. J. Geophys. Res. 103, 24567–24572.

Wahr, J.M., 1981a. A normal mode expansion for the forced response of a rotating Earth. Geophys. J. R. Astron. Soc. 64, 651–675.

Wahr, J.M., 1981b. Body tides on an elliptical, rotating, elastic and oceanless Earth. Geophys. J. R. Astron. Soc. 64, 677–703.

Wilcock, W.S., 2001. Tidal triggering of microearthquakes on the Juan de Fuca Ridge. Geophys. Res. Lett. 28, 3999–4002.