Tidal Triggering of Earthquakes: Response to Fault Compliance?

E.S. Cochran[1]

[1]*Institute of Geophysics and Planetary Physics, Scripps, La Jolla, CA 92093, USA*

Corresponding Author: E. S. Cochran, ecochran@ucsd.edu

Abstract: *Clear tidal forcing of earthquakes has recently observed by several local and global studies. Using tidal amplitudes in addition to tidal phase the stress level required for tidal forcing is determined. Cochran et al. (2004) find that natural faults are highly responsive to relatively small stress changes and faults behave more weakly than would be expected from laboratory rate and state friction and stress corrosion measurements. Stress changes on the order of a tenth of a bar can cause modulation of the timing of earthquakes, similar to that measured for aftershock sequences. In addition, recent geodetic and seismologic studies suggest that faults are not simple planes of slip, but zones of highly damaged, sheared rock. These damage zones are highly compliant and may result in higher stress concentration in the fault than in the surrounding intact rock. Thus, fault zone compliance may reduce the stress loads required for rupture.*

1. Introduction

Seismological data is often mined to determine the amplitude of stress perturbation, whether natural or induced, required to trigger an earthquake. One application of standard statistics to a basic seismological question is the question of whether Earth tides affect the timing of earthquakes. For a century or longer, studies have been conducted to determine whether Earth tides modulate the timing of earthquakes. Each of these studies depends on the accuracy of tidal calculations and the statistical tests applied to the data. In addition, an additional step is taken to match recent seismologic and geodetic observations of fault zone properties with the notion that relatively low amplitude stresses trigger earthquakes.

Tidal modulation of the timing of earthquakes is based on the assumption that faults are more likely to rupture when stress levels encourage failure. Computing tidal stresses is not trivial and includes the direct solid Earth tide, caused by the gravitational pull of the Sun and the Moon, and the indirect Earth tide due to ocean loading. An accurate accounting for the tides is an imperative first step in a global study of tidal triggering (e.g. *Tanaka et al.*, 2002; *Cochran et al.,* 2004) Local studies have had greater success at showing a tidal correlation as tidal stress can more easily be inferred from local tidal gauge measurements (e.g. *Tolstoy et al.,* 2002).

Comparing tidal triggering rates with the laboratory-derived measurements of triggering by stress loads suggests that natural faults are more responsive to low amplitude stress changes. Therefore, a mechanism is needed to explain failure of faults due to relatively low applied stress. The answer may lie in recent seismological and geodetic measurements that suggest faults are significantly more compliant than the surrounding country rock. Seismological measurements include observations of velocity reduction within a 100 – 200 m fault core by fault zone trapped waves (e.g. *Li et al.*, 2003; *Li et al.*, 2004; *Rubinstein and Beroza*, 2004). Shear wave splitting measurement indicate a highly sheared material with a width that corresponds to the low-velocity trapping structure (*Cochran et al.*, 2005; *Boness and Zoback*, 2004). InSAR provides further clues of a highly compliant fault zone that experiences larger strains that the surrounding intact rock (*Fialko et al.*, 2002). We infer a link between the responsiveness of faults to low amplitude tidal stresses with the observed fault zone compliance.

2. Observations of Tidal Triggering

Cochran et al. (2004) determined the amplitude of stress required to trigger shallow, thrust earthquakes by Earth tides. The two statistical tests used to determine significance levels are: Schuster's test and a binomial test. Two independent tests were used to compare the resulting significance levels.

The Schuster test is used to test for periodicity in a sequence and is used to determine if the timing of the earthquakes is modulated by the periodic fluctuation in the tidal stress. Not only do we find a clear periodicity to the timing of events, but we also see a clear peak of events at the tidal phase (θ) defined to encourage failure. The vector sum over the tidal phase angles is:

$$D^2 = \left(\sum_{i=1}^{N} \cos\theta_i\right)^2 + \left(\sum_{i=1}^{N} \sin\theta_i\right)^2 \quad , \tag{1}$$

The resulting p-value gives a measure of how random (p ~ 1) or non-random (p ~ 0) the distribution is:

$$p = \exp\left(-\frac{D^2}{N}\right) \quad , \tag{2}$$

Schuster's Test indicates a greater than 99% probability that the events are non-randomly distributed. In addition, the peak of events is show to be at nearly 0° tidal phase, the phase expected to promote failure.

To confirm the results of the Schuster test, *Cochran et al.* (2004) also employ a binomial test. This simple statistic tests whether the earthquakes are divided equally across the tidal phase. The tidal phase is divided into two tidal phase bins, each covering 90 degrees. One bin contains tidal phases expected to most promote failure (-90 < θ < 90) and the other bin

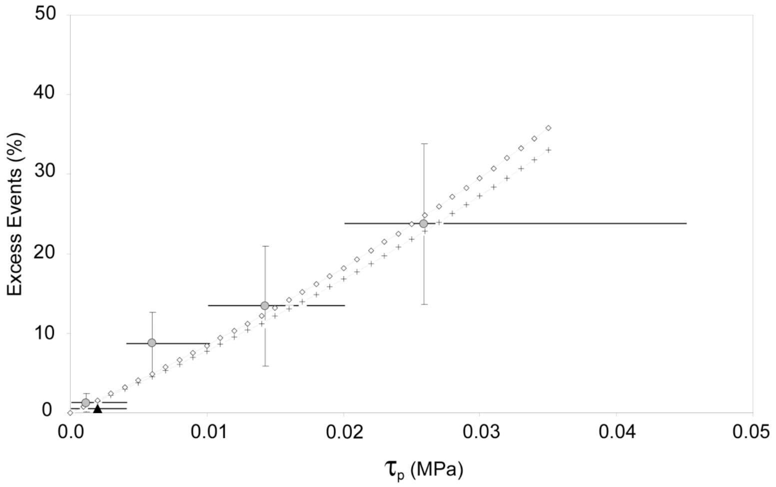

Figure 1 *Percentage of excess events versus the peak tidal stress. Points are located at the mean peak tidal stress and solid horizontal lines indicate the range. Grey circles are global thrust data; solid triangle denotes California strike-slip data. Crosses and diamonds show the least squares fit to rate- and state- dependent friction and stress corrosion, respectively. From Cochran et al., (2004).*

contains the remaining tidal phases. A probability of >99.99% that earthquakes correlate with the tides is found for large tidal stresses (> 0.01MPa).

The amplitude of tidal stress required to trigger an earthquake is determined by dividing the data into four bins based on amplitude of the background peak tidal stress. A clear trend of increasing triggering of events with the increasing peak tidal stress amplitude is observed (figure 1). Laboratory experiments have been conducted to determine the relationship between the number of events triggered and the applied load. The data are fit to rate and state friction and stress corrosion. To fit both laboratory-derived trends we have to assume parameters for the fault viscosity or material properties that suggest natural faults are more responsive to stress loads than those measured in the lab.

3. Fault Zone Compliance

The responsive nature of faults to relatively small stress loads is suggestive of a dependence on a more complex fault structure than a simple slip plane. Several seismology and geodetic studies have found evidence for a complex zone of deformation near the main slip plane. These studies may explain the relative weakness of fault to applied stresses whether tidal, seismic, or any number of man-induced stress changes. I will briefly outline recent studies that indicate that faults have reduced shear moduli reflecting a highly damaged zone with a strong shear fabric.

Seismologic studies have been conducted near numerous active faults and a few common features have been observed. Clear indications of reduced P and S velocities have been observed in addition to waves trapped in the low velocity fault core. The shear velocities in the San Andreas Fault are reduced by 30 – 40 % compared to the nearby intact rock (*Li et al.*, 2004). The velocity reduction has been shown to vary across the seismic cycle and may account for some of the variation in measured velocities.

In addition, shear wave splitting studies conducted near active faults suggest faults have a shear fabric that reflects the highly damaged nature of the fault zone (*Boness and Zoback*, 2004; *Cochran et al.*, 2005). Shear wave splitting is used to determine the anisotropic field near a fault and can be used to look for variation near a fault plane. *Peng and Ben-Zion* (2004) found a large spatial variation in splitting measurements that were dependent on whether the wave traveled through the main fault core. A recent study by *Cochran et al.*, (2005) of shear wave splitting along the Parkfield segment of the San Andreas fault shows a clear spatial variation in splitting measurements. Fast directions preferentially oriented parallel to the fault within 100 m of the main fault plane correspond to the location of the main trapping structure detailed by *Li et al.* (2004) and discussed above.

InSAR studies clearly highlight the compliance of faults. *Fialko et al.* (2002) showed a clear coseismic concentration of strain on faults near the M7.1 Hector Mine earthquake. The strain is concentrated on a zone that is approximately 1 km wide with an inferred reduction in shear moduli of 50%. This compliant zone extends to at least 5 km depth (*Fialko et al.*, 2002). While the width of the compliant zone observed with InSAR is wider than that seen with the seismologic data, the overall implications are the same. Likely the two data sets are sampling different aspects of the same structure with the damage grading from a highly sheared fault core out to intact rock (figure 2).

4. Discussion

Clear evidence for tidal triggering has been observed in several recent studies suggesting are more highly responsive to applied stress loads than expected from laboratory results.

Seismic and geodetic data suggest faults are highly compliant and localize strain in the highly damaged fault core. The triggering of faults by relatively small stress loads (> 0.01 MPa) may be attributed to the physical structure of the fault itself.

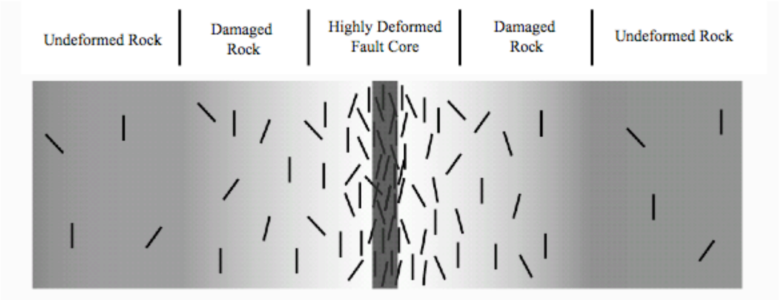

Figure 2 *Schematic cross-section of an active fault zone depicting a gradient in damage across the fault. The fault core is a zone of highly deformed rock that contains the main slip planes. Oustide of the main fault core the cracks are mostly mode 1 opening fractures that decrease in density away from the fault (after Chester et al., 2003).*

5. Acknowledgement

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