**Final Report**

SCEC Award: 14165

# INTEGRATED STATIC AND DYNAMIC STRESS MODELING FOR INVESTIGATING TREMOR SOURCE REGIONS

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## Abstract

Under this project, we investigated the stress and frictional conditions of the SAF where tectonic tremor are dynamically triggered (by seismic waves) using numerical models of stresses. We studied the local static stress, and the dynamic stresses caused by passing triggering seismic waves from remote earthquakes. Dynamic stresses are modeled directly from recorded seismic signals, and static stress were obtained and modeled from existing SCEC Community Stress Model (CSM) contributions. We also investigate whether tremor signal characteristics (e.g. amplitude, duration, and frequency) can be used as a proxy to the local stress conditions where these are generated. Seismograms from more than 200 global earthquakes, with magnitudes equal or greater than 7, and occurred since 2000 to the present, were collected and visually inspected for triggered tremor. New cases of triggered tremor have been detected and triggering seismic waves have been modeled. Our preliminary results suggest that the average coefficient of friction at triggered tremor's source regions is $\mu$=1.9±0.5 in Northern California, $\mu$=1.4±0.4 for Central California, and $\mu$=2.1±0.6 for Southern California. Products resulting from this grant include 2 papers (one of which is progress) and 4 meeting presentation.


## Report

The main objective of this project was to investigate the frictional and stress condition of the regions along the SAF where tremor are triggered by seismic waves. We used existing numerical models of the static stress [*Smith-Konter and Sandwell*, 2009; *Luttrell et al.,* 2011], and models of the stress caused by the passing of triggering seismic waves to investigate tectonic tremor source regions. Dynamic stresses are modeled directly from seismograms [e.g., *Chao et al.,* 2013, *Aiken et al.,* 2016].

The first step in this project was to obtain seismograms to identify triggered tectonic tremor. We obtained seismograms from the Incorporated Research Institute for Seismology (IRIS) Data Management Center (DMC) for any event M ≥ 7 occurred from 2000 to the present. Seismograms were initially requested for periods of 5 hours before and after the mainshocks origin time. We request broadband and low-period high-gain (BH?, HH? And EH?) three components seismograms using the IRIS' BreqFast tool (http://ds.iris.edu/SeismiQuery/breq_fast.phtml) and/or the University of South Carolina's Standing Order for Data, SOD (http://www.seis.sc.edu/SOD/tools/index.html) software. Seismograms for more than 200 events were obtained. Seismograms were high-passed using different filter corners (2Hz, 4Hz, 5Hz) and inspected visually and using automatic tremor detectors.

In searching for triggered tremor special attention was given to mainshocks of magnitude large enough, and occurred at distances from the SAF small enough, to trigger seismicity, this according to the following criteria. In the most general approach, the dynamic stress caused by the passing of the surface waves is represented as the Peak Dynamic Stress (PDS), which is equal to the Peak Ground Velocity (PGV), the maximum amplitude recorded in velocity seismograms, multiplying by μ/β, where μ is the shear modulus and β is shear-wave velocity. Thus, in general, a PGV of 0.1cm/s corresponds to a PDS of ~10 kPa [e.g. Hill *et al*., 1993; Pankow *et al*., 2004; Velasco *et al.,* 2004]. In particular, surface waves with predominant periods of ~20 sec (see *e.g.* Hill, 2012a) and causing PDS > 10 kPa seem to be the most efficient in triggering seismicity [e.g. Chao *et al.,* 2013; Linville *et al*., 2014]. In order to define what events are the most likely triggers based on the observations above, we estimate the mainshock magnitude as function of distance needed to cause PDS > 10 kPa by surface waves of period 20 sec. This was done by calculating the ground particle velocity as function of mainshock distance and magnitude, and converting to PDS following Chao *et al.* [2013]. Also, we estimated the maximum distance of influence of the static stress as 5 times the mainshock rupture length. *Helmstetter et al.* [2005] suggest that aftershock regions are mostly limited by an average distance of about one mainshock rupture length. The rupture length $L$ of an earthquake of magnitude $M$ is estimated as $L \approx 0.01x10^{M/2}\ km$. Figure 1.a shows the areas of influence of the static stress and dynamic stress capable to trigger seismicity based on these calculations. Events falling in the dark-gray area are the most likely to dynamically trigger seismicity and thus are the ones we investigated more carefully. New potential cases of dynamically triggered tremor were identified; these findings are described in detail in *Gonzalez-Huizar et al.,* [2017], which will be summited to *Geophysical Research Letters*. Figure 1.b shows examples of these new cases of detections of tremor dynamically triggered along the SAF.

Dynamics stresses are modeled based on the recorded seismograms and the equations of body and surface waves particle motion [*see e.g. Gonzalez-Huizar and Velasco,* 2011; *Hill* 2012*; Chao et al.,* 2013; *Aiken et al.,* 2016]. Figure 2 presents an example of the dynamic stress modeling caused along the SAF by the seismic waves from the 2011, M9.0 Tohoku-Oki, Japan earthquake, which triggered tremor in Central California [Gonzalez-Huizar et al., 2017].

Local static (tectonic) stresses in the source region of the triggered tremor were obtained from the SCEC Community Stress Model (CSM) contribution by *Smith-Konter and Sandwell* [2009]. Figure 3.b shows a transverse section along the SAF showing present-day earthquake cycle stress accumulation near locked fault segments, along with a list of large earthquakes that have been previously reported to trigger tremor along the SAF system used in this study. Listed also appear some of our new findings (in red-color) of tremor triggered by the surface waves from recent large-magnitude earthquakes (in Fig 1.b).

Based on the Coulomb failure criteria, the coefficient of friction $\mu$ can be calculated as the rate between the absolute shear ($\tau$) and normal ($\sigma$) stresses acting at the moment ($t_0$) when failure occurs. Then, it can be approximated as:

$$\mu = \frac{\tau_{static}(t_0) + \tau_{dynamic}(t_0)}{\sigma_{static}(t_0) + \sigma_{dynamic}(t_0)}$$

Our preliminary results present the following values for the average coefficient of friction at the source regions where tremor where dynamically triggered (Fig 3.c):

Northern California: $\mu$=1.9±0.5
Central California: $\mu$=1.4±0.4
Southern California: $\mu$=2.1±0.6

As more triggered seismic waves are modeled and their related dynamic stresses are calculated, we will be able to reduce the errors in these values. This task is still in progress and final results will be presented in *Gonzalez-Huizar et al.* [2017].

## Products from this grant

By the time of preparation of this report, 2 papers (one in preparation) and 4 meeting presentations resulted from this grant. We are preparing a manuscript [*Gonzalez-Huizar et al.,* 2017], tentatively to be summited in Summer 2017 to Geophysical Research Letters, where we will summarize our findings and results for the SAF triggered tremor. Moreover, the stress modeling for tremor triggered along the SAF have allowed to investigate tremor triggering in regions that hold certain tectonic similarities with the SAF, for example, we have recently published in *Earth and Planetary Science Letters* an study where we model the dynamic stress that triggered tremor in the plate-boundary defined by the Enriquillo-Plantain Garden Fault in Haiti, a large strike-slip fault related to the 2010 Mw7.0 Haiti earthquake. Finally, results from the SAF triggered tremor have been presented in 4 international meetings, which are listed below:

**Gonzalez-Huizar, H**., S. Hardy, B. Smith-Konter (2017- in preparation), Integrated Static and Dynamics Stress Models for Investigating Tremor Sources, to be submitted to *Geophysical Research Letters*

Aiken, C., K. Chao, **H. Gonzalez-Huizar**, R. Douilly, Z. Peng, A. Deschamps, E. Calais, J. Haase (2016), Exploration of Remote Triggering: A Survey of Mutiple Faults Structures in Haiti, *Earth and Planetary Science Letters*, 10.1016/j.epsl.2016.09.023.

**Gonzalez-Huizar,** H., S. Hardy, B. Konter (2016), Investigating tremor sources along the San Andreas Fault using integrated static and dynamic stress models, *SCEC Annual Meeting 2016*, abstract.

Hardy, S., **H. Gonzalez-Huizar,** B. Konter (2016), Integrated Static and Dynamic Stress Modeling for Investigating Tremor Source Regions in the San Andreas Fault, *IASPEI Regional Assembly*, Costa Rica.

Hardy, S., **H. Gonzalez-Huizar** and B. Smith-Konter (2015), Integrated Static and Dynamic Stress Modeling for Investigating Tremor Source Regions in the San Andreas Fault, *AGU Fall meeting abstract*.

**Gonzalez-Huizar, H**., S. Hardy and B. Smith-Konter (2015), Integrated Static and Dynamics Stress Models for Inverstigating Tremor Sources, *SCEC Annual Meeting*, abstract.

## Broader impacts

Dr. Gonzalez-Huizar is a Hispanic Junior Investigator, and this project supported his effort during summer months. We are also training a UTEP doctoral student Sandra Hardy who is working in the analysis and modeling of the seismic data. UTEP is a major Hispanic Serving Institute (HIS), thus, the research and educational material resulting from this project directly influence traditionally underrepresented minorities.

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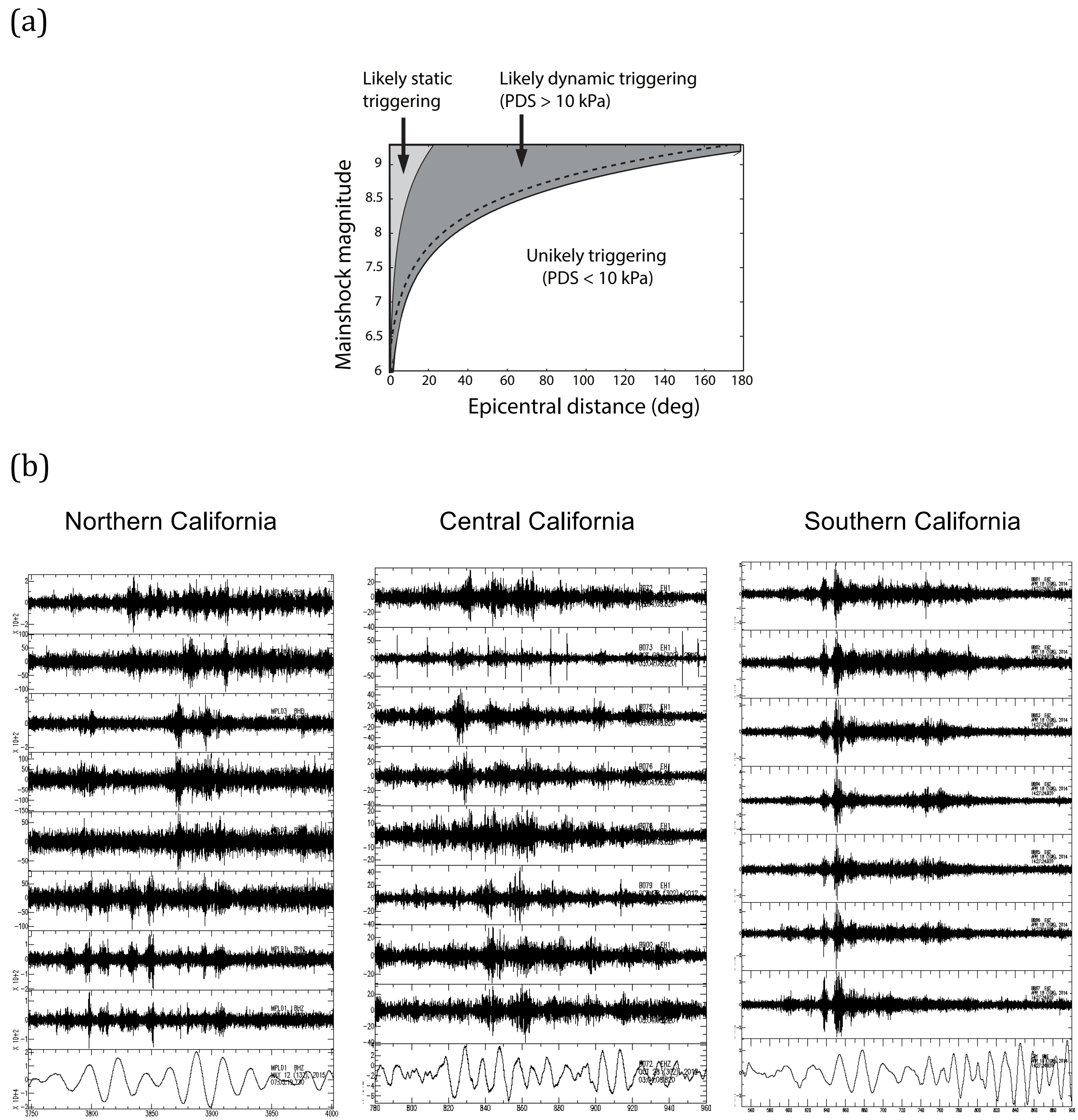


**Figure 1.** (a) Areas for which static and dynamic stresses are expected to trigger seismicity, as function of mainshock's magnitude and epicentral distance. Line limiting the white and dark-gray area is the PDS for Love waves and the doted line is the PDS for the Rayleigh waves. (b) Examples of detected triggered tremor in the SAF by the surface waves from recent large magnitude earthquakes. ***Left panel*** shows the surface waves from the 2015, M7.3 Nepal earthquake recorded by station GS.MPL01 (bottom trace), and triggered tremor recorded by nearby stations (high-pass filtered at 5 Hz). ***Central panel*** shows the surface waves from the 2012, M7.8 Queen Charlotte Island earthquake recorded by station PB.B072 (bottom trace), and triggered tremor recorded by nearby stations (high-pass filtered at 5 Hz). ***Right panel*** shows the surface waves from the 2014, M7.2 Guerrero, Mexico earthquake recorded by station AZ.CRY (bottom trace), and triggered tremor recorded by nearby stations (high-pass filtered at 5 Hz).

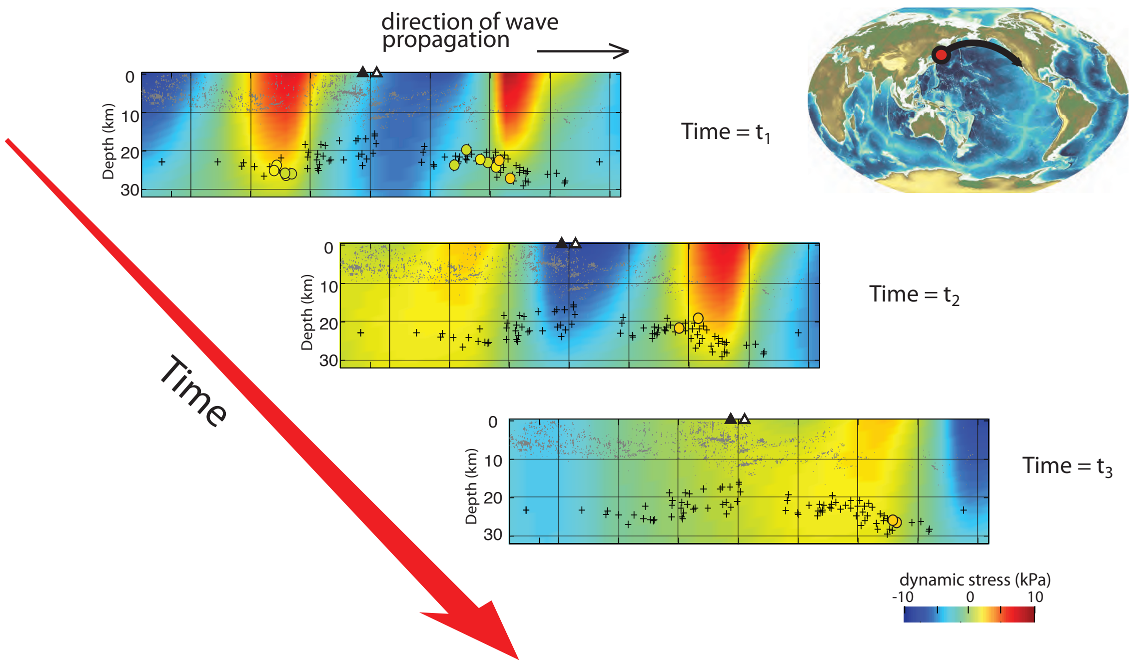


**Figure 2.** Modeling of the dynamic Coulomb stress caused by the surface waves from the Tohoku-Oki event, and is correlation to triggered tremor. Tremor were identified and located by Hill et al. [2013]. Yellow circles represent families of trigged tremor and plus (+) signs represent ambient tremor families identified by Shelly and Hardebeck [2010]. Small dots are the ambient seismicity [Waldhauser and Schaff, 2008].

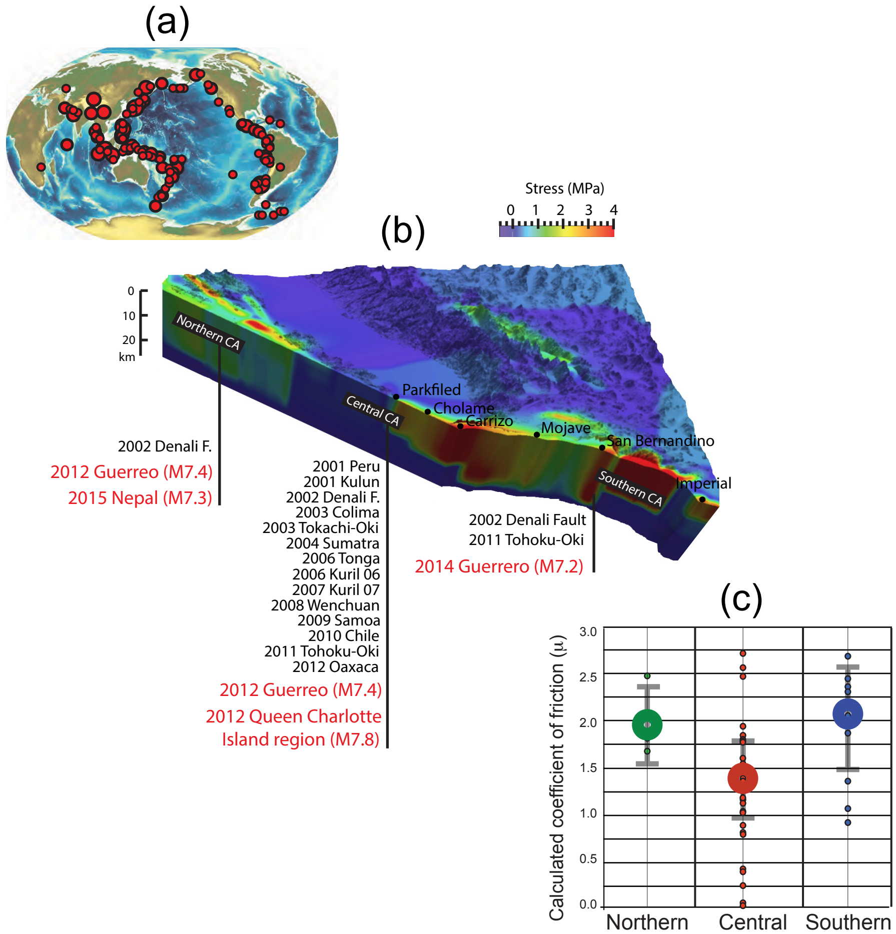


**Figure 3.** (a) Earthquakes M≥7.0 occurred since 2000 to present (about 200 mainshocks) investigated as potential triggers of tremor in the SAF. (b) Present-day earthquake cycle stress accumulation near locked fault segments in the SAF caused by the interseismic stress accumulation, coseismic stress drop, and postseismic stress relaxation over the last 1500 years on the SAF [Smith-Konter and Sandwell, 2009]. Listed are recent large earthquakes that have been reported to trigger tremor along the SAF system. In red-color are listed some of our new findings of cases of dynamically triggered tremor by global earthquakes. (c) Average coefficient of friction estimated for three broad geographic regions. Coefficient of friction $\mu$ was calculated as the rate between the absolute shear ($\tau_{static}+\tau_{dynamic}$) and absolute normal ($\sigma_{static}+\sigma_{dynamic}$) stresses acting at the moment when failure (sliding) occurs. Each dot corresponds to the value calculated from an individual triggered tremor pulse. Large circles are the average calculated for each region. Errors bars represents the standard deviation.