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The San Andreas Fault in fine detail: seismology and rock physics

Discussion

Eun-Sun Chong (ASU)
John D. West (ASU)
Arizona State University
EarthScope Seminar Class

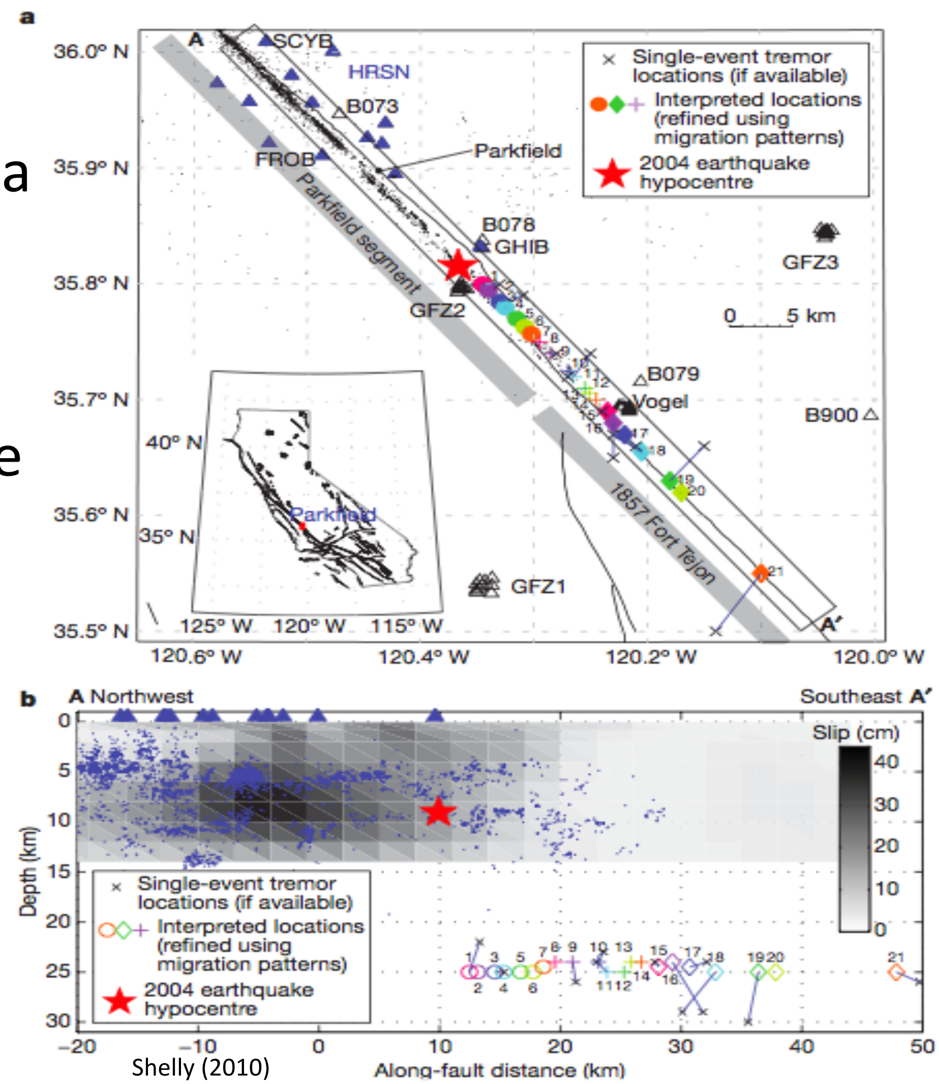
Figures and information referenced from various sources.

1. Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas Fault

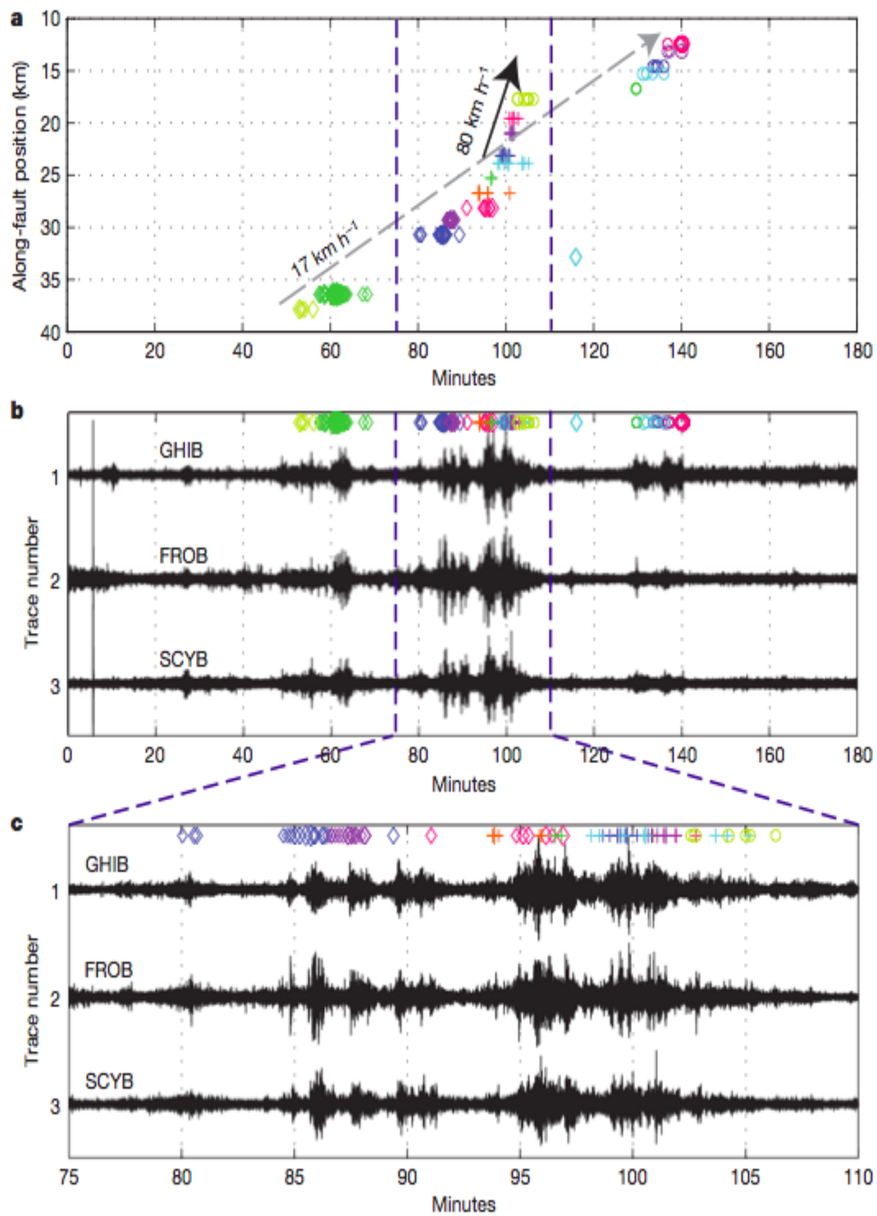
David R. Shelly Nature (2010) Vol. 463 (7281) pp. 648 - 653

<u>Data:</u> Continuous seismic data from mid-2001 to 2008.

<u>Result:</u> Evidence supports deep fault shear failure as the basic mechanism of tremor. Physical condition that controls the spatial distribution of such tremors remain in question. Fluid pressure in the fault zone at depth is suggested.



Shelly (2010)



This figure is said to represent tremor migration.

a)Extended tremor migration episode, approximately 25km along fault strike for over 90 minutes. 17 km represents average propagation rate in a given episode.

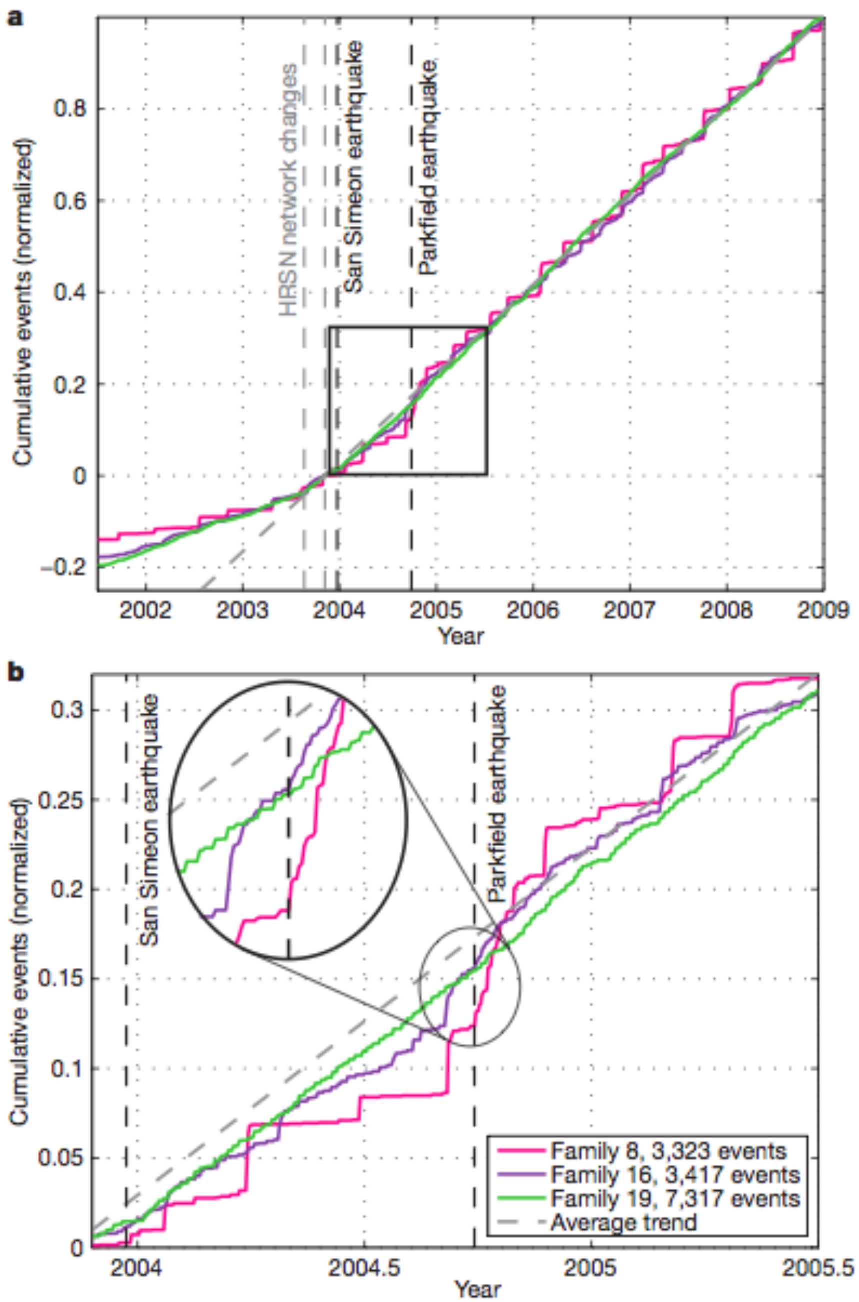
b)Three HRSN borehole stations, waveforms and event family matches during the same period.

c)Zoomed view of the highest-amplitude and fastest-migrating portion of the sequence.

A lot seems to be said through display of this figure but very uncertain on how such information was derived.

Event Families?

Shelly (2010) *Lack of legend makes this figure difficult to comprehend.



Shelly (2010)

Questions:

1. What does it mean when cumulative events are “normalized”?

2. What do the numbers on that particular axis represent?

3. What is the purpose of this figure?

Shelly (2010)

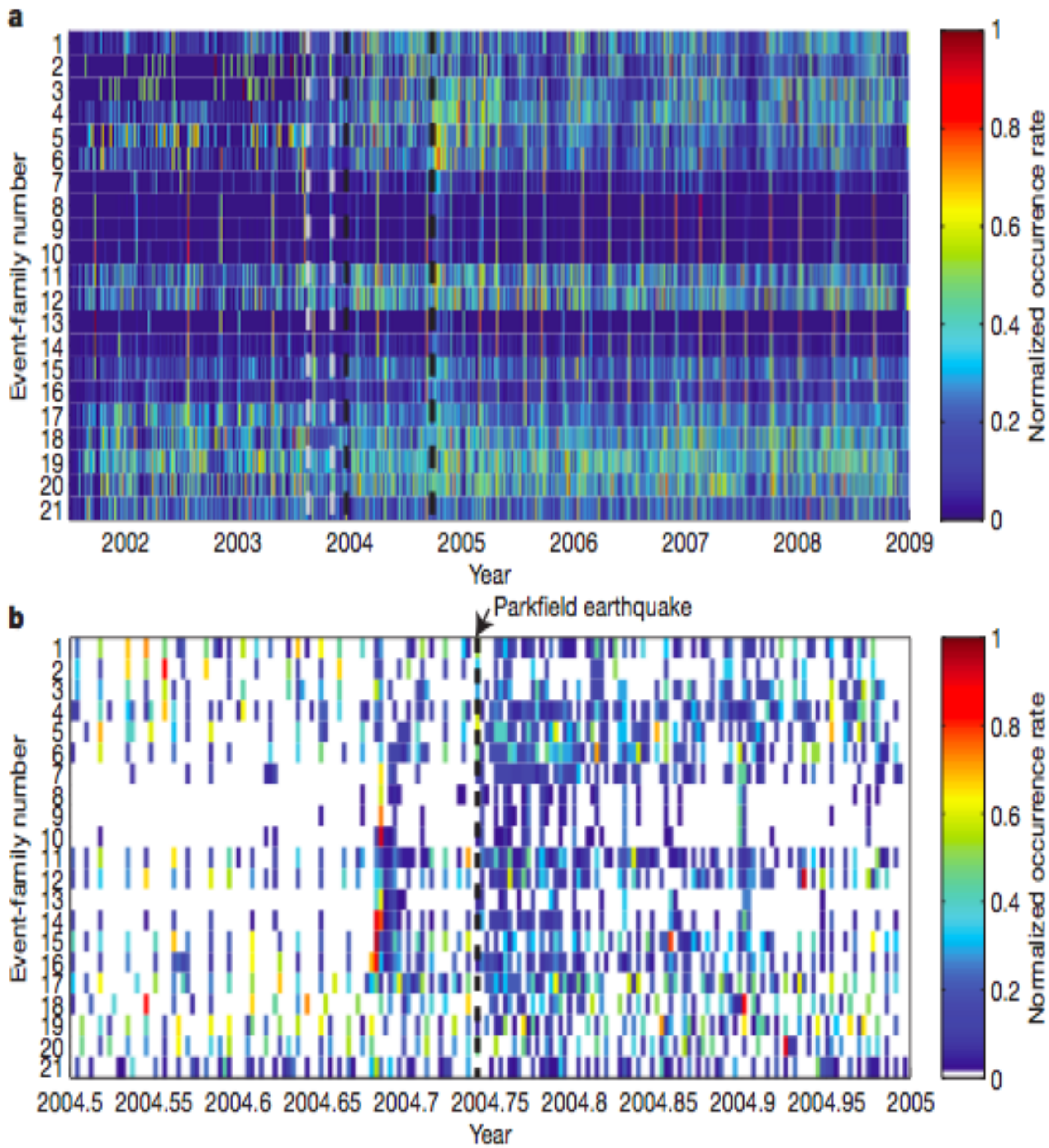


Figure 4. Recurrence patterns for 21 event families.

a) Mid 2001 to 2008. Black dash lines indicate San Simeon and Parkfield earthquakes. Gray dash lines indicate when HRSN stations experienced operational changes.

b) Basically a zoomed in version of (a) with different time scale.

Methods

Cross-correlation in a multi-channel matched filter.

1. Selection of waveform templates.
   a. Selection of relatively strong and isolated events as templates.
   b. Used the template that appeared to have the highest signal-to-noise ratio.
2. Template event location.
   a) An absolute location for each template event based upon P and S wave arrival times of a low frequency earthquake with a good signal-to-noise ratio at permanent and temporary stations.
   b) A grid search for location of hypocenters with a Vp/Vs ratio of 1.78.
3. Event detection.
   a) 20 samples/second, bandpass filtered at 2-8 Hz.
   b) Cross-correlation at lag increments of one sample. Measure similarity by correlation sum across all channels and stations of the network.
   c) Fixed correlation sum threshold of 4.0 for the 25 selected channels, with a maximum of one event every 4 seconds.
4. Stations and components used for consistent detection.
   a) 10 sets of stations and channels used to compare tremor rates over time.
5. Stations used for template event locations.
   a) Additional stations to constrain the data.
   b) Four temporary arrays of ten stations each.
   c) Six individual three-component stations from the PBO and HRSN.
   d) Two additional stations from the Southern California Seismic Network to help locate southernmost event family.

Key Points

- Tremor has been identified beneath the strike slip San Andreas fault near Parkfield, California.
  - Tremor locations aligned with fault strike and triggering by tidally induced right lateral shear stress strongly suggest that San Andreas fault tremor is generated by tectonically driven slip on the deep fault.
  - Similar to subduction zone tremor.
  - Dominant frequency content of 2-8 Hz.

- Several advantages over amplitude-based analysis of tremor.
  - Ability to identify short duration tremor and low amplitude tremor.
  - Shape and timing of waveforms. Analysis on much shorter spatial and temporal scales, differentiating activity on many small patches of the deep fault.
  - Differentiates between tremor and other seismic signals (aftershocks, cultural noise).
  - No need to exclude the times immediately following significant earthquakes.

- Suggestion of fluid pressure in the fault zone.
  - Possible sources of fluid:
    1. A fossil slab
    2. Subducted sediments proposed to exist near the tremor zone by Trehu et al. (1987)
    3. Serpentinite or fluid-saturated schist on basis of receiver function study by Ozacar et al. (2009)

2. Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas Fault

Thomas et al. Nature (2009) vol. 462 (7276) pp. 1048-1051

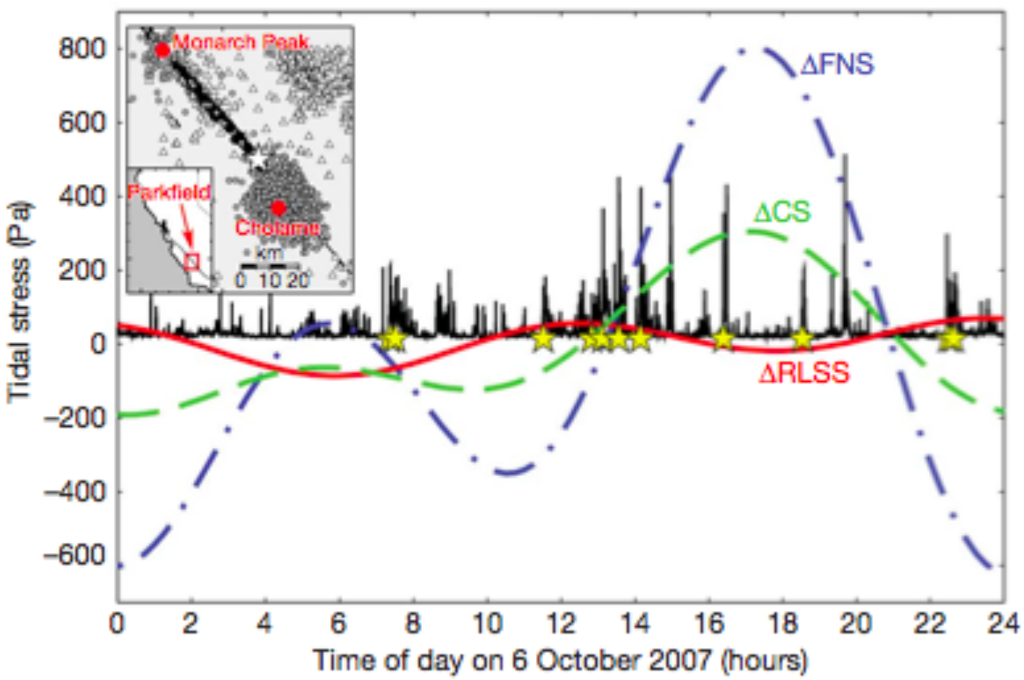


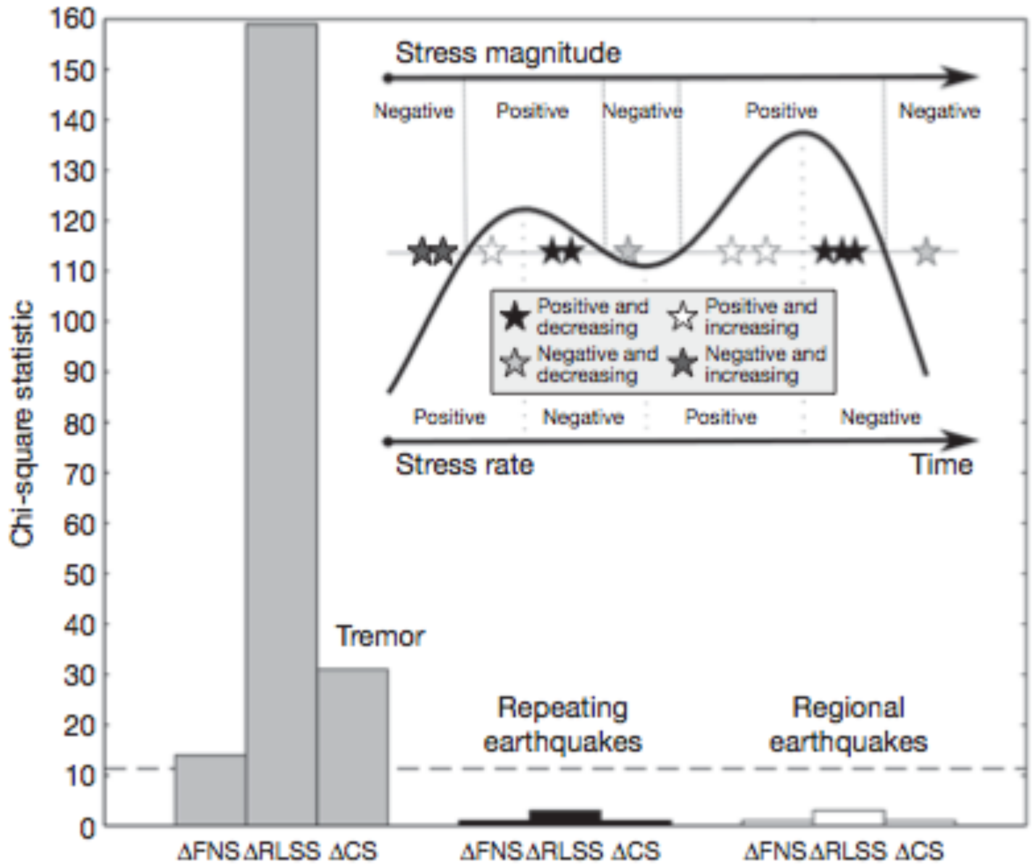
Figure 1. Example one-day tremor time series with superimposed tidal stresses.

Thomas et al. (2009)

<u>Data:</u> Catalogue of 1,777 non-volcanic tremors detected over an eight year period. Regional catalogue of earthquakes within 0.5° of Cholame. Another catalogue of characteristically repeating micro-earthquakes located along the creeping segment of the San Andreas fault (NW of Cholame)

<u>Results:</u> Tremor occurs preferentially when subjected to tidal shear stresses that promote right lateral failure along San Andreas fault. Low stress perturbations from solid-Earth tides are responsible for significant tremor rate increases and effective normal stress in the trmor source region is required to explain apparent tidal triggering. Capable of producing seismic radiation. Lithostatic pore fluids are present in the tremor source region.

Thomas et al. (2009)



<u>Figure 2. Results of Chi-square significance tests.</u>

•Results correlate the tremor, regional and repeating earthquake catalogues with tidally induced ΔFNS, ΔRLSS, ΔCS.

•Tremor start times were separated into four "quadrants" based on magnitude and rate of change of the stresses.

•Dashed line shows 99% confidence level. Larger values indicate that the hypothesis of random event occurrence can be rejected.

Thomas et al. (2009)

Most compelling correlation

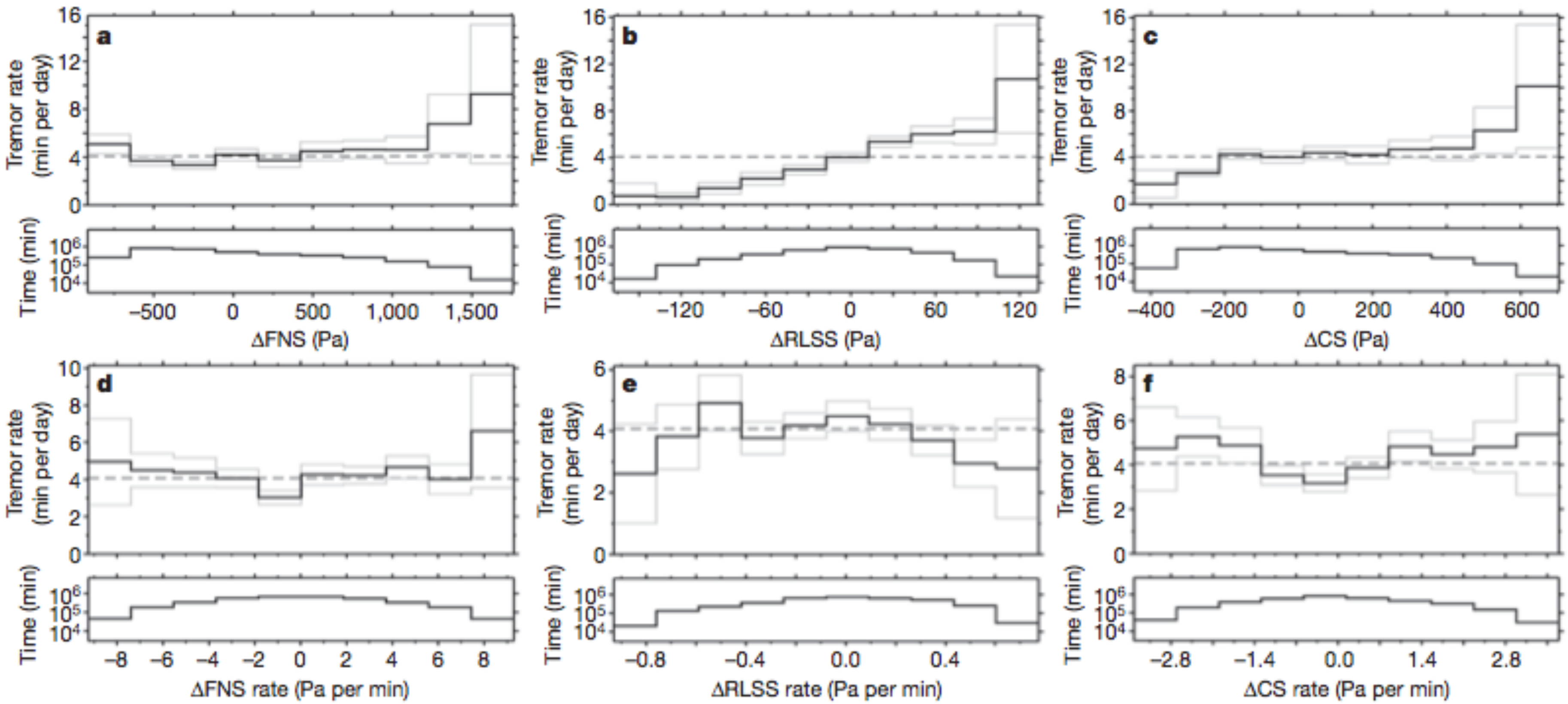


Figure 3. Tidal stress magnitude and rate distributions.

Most compelling correlation because distinct increases in tremor activity that correspond to positive right lateral shear stresses parallel to the San Andreas fault and equally apparent decreases when values are negative.

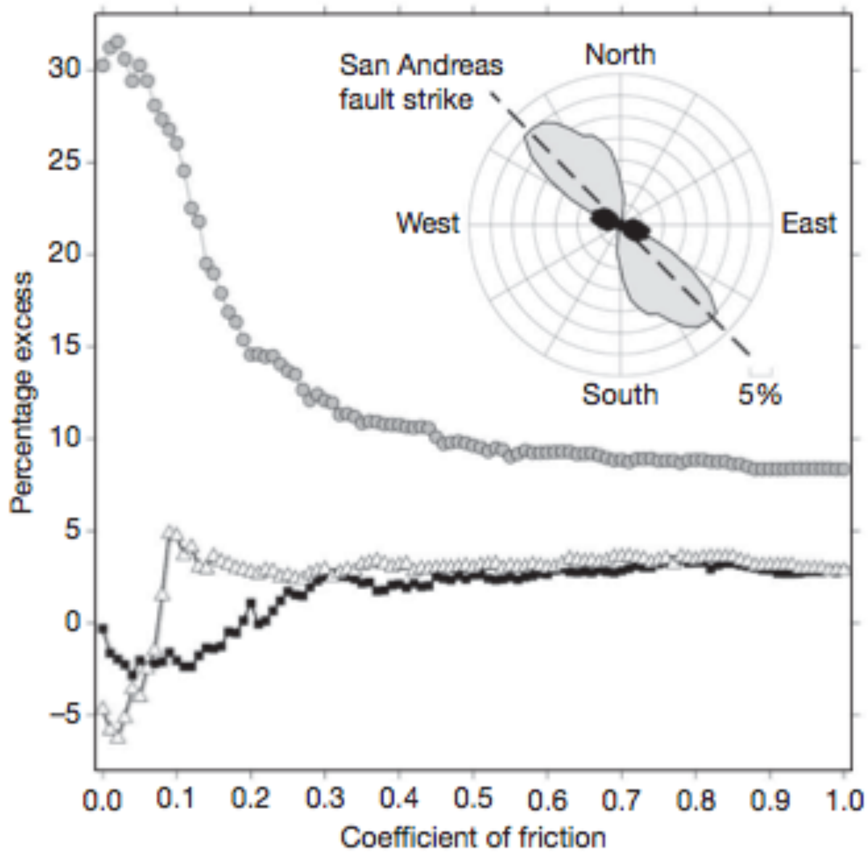


Figure 4. Percentage of excess events versus friction coefficient.

Above long term average during times of positive ΔCS versus effective coefficient of friction.

$$\sigma = 2\tau/(aR_a)$$

σ = Effective normal stress = 0.035 to 0.009 MPa

τ = Shear stress = 177 Pa for maximum tidal induced shear stress

a = rate constitutive parameter = 0.005 to 0.02

$R_a = (R_{max} - R_{min})/R_{avg}$

Effective normal stress is found to be 0.035 to 0.009 Mpa. These values are orders of magnitude lower than the lithostatic overburden pressure at given depth, suggesting that lithostatic pore fluids are present in the tremor source region.

Methods

1. Event Catalogues
   - 1,777 events between July 2001 to May 2008 using detection methodology.
   - Tidal stress time series were computed for Cholame only.
   - Repeating earthquake catalogue constains 2,594 events between 1984 and 1999 on the creeping section of San Andreas fault.
   - Regional earthquake catalogue consists of all earthquakes from the Advanced National Seismic System catalogue between July 2001 to May 2008.
2. Tidal Stress Calculation
   - Tidally induced stresses in the lithosphere were computed using SPOTL code by Agnew.
   - Green's functions to compute azimuthal and vertical strains that can be converted to stress.
   - Tidal model predictions were compared with strainmeter records in Pinon Flat using perturbation matrix.
3. Statistical Methods
   - Pearson's Chi-square test is designed to test the similarity between two frequency distrubitions knowns as chi-squared statistic.

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

4. Uncertainty estimates from Fig 3.
   - Two-standard-deviation error estimates are determined using a bootstrap method.
   - Randomly selects an individual tremor from the original tremor catalogue. Repeated 1,777 times for random sample.
   - Above process repeated 50 times for 50 random versions of the original catalogue.
   - Tremor rate distributions as a function of the tidally induced stresses are then calculated for each of the 50 randomly sampled catalogues
   - Multiplied by 2.
   - Errors arise from variability in tremor detection sensitivity.

Key Points

1. The lack of correlation in the regional and repeating earthquake catalogues is not surprising given the size of the catalogues and results from previous efforts to establish a significant tidal triggering of earthquakes.

2. Couloumb stresses exhibit less correlation than the shear stress alone.

3. Assuming a frictional Coulomb failure process is an appropriate model for non-volcanic tremor, the optimal friction coefficient is the value that maximizes the number of events that occur during times of encouraged failure stress.

4. Tremor appears to be associated with the presence of fluids at near-lithostatic pressures, and given similar observations in variable tectonic environments, the same mechanism is probably responsible for non-volcanic tremor elsewhere.

3. Frictional behavior of materials in the 3D SAFOD volume

Carpenter et al. Geophysical Research Letters (2009) vol. 36 (5) pp. L05302

Purpose: To resolve following

1.Debate concerning the absolute strength of the San Andreas Fault.
2.Controls on the stability of frictional sliding.

Data:

Outcrop samples of lithologies thought to comprise and abut the fault zone at depth on the basis of:
1.Detailed geologic cross sections for the SAFOD sites.
2.Published geologic maps
3.Cuttings retrieved during SAFOD Phase I and II drilling.

Samples included:
1.Natural serpentinite from New Idria Mine
2.Granodiorite from Phase I
3.Arkosic metasandstone from Phase I
4.Siltstone from Phase II

Results:

1.Serpentinite exihibits low strength but is not weak enough to completely satisfy weak falut models.
2.All other samples are consistent with a strong fault and crust.
3.If the fault is weak (μ<0.2) due to the presence of serpentinite or talk, these minerals would likely need to constitute over 50% by weight of the shear zone.

Methods

1. Rock and core samples were crushed in a roll crusher in a shatter box to a grain size of <125μm.
2. Samples were sheared in layers 3 to 5 mm thick constructed by pouring and smoothing the experimental gouge onto grooved, steel forcing blocks.
3. Conducted shearing experiments in double direct shear in a true triaxial pressure vessel. Stresses are same and nominal contact area remains constant at $0.025m^2$.
4. Constant normal stress is applied and maintained by a hydraulic servo-control system.
5. Displacing the center block between the two stationary side blocks causes shear.
6. Forces are measured with strain gauge load cells to ±5 N, and vertical and horizontal displacements are measured by DCDTs to ±0.1μm.
7. Recorded data continuously at 10kHz and averaged to values ranging from 1 Hz to 1kHz depending on shearing velocity.
8. Stable shear fabric in the layer was established to attain steady-state friction. Used 5mm shear displacement 'run in' in the beginning of all experiments.
9. Coulomb failure envelope and friction constitutive properties under a variety of stresses using normal stress stepping procedure.