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Stress transfer process in doublet events studied by numerical TREMOL simulations: Study case Ometepec 1982 Doublet.

Josep de la Puente
Marisol Monterrubio-Velasco,
Quetzalcóatl Rodríguez-Pérez
F. Ramón Zúñiga
Otilio Rojas.

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- Our motivation is to study the stress transfer process in a Doublet earthquake scenario.

- In particular, we developed an alternative stochastic earthquake rupture model TREMOL to approach this problem

- TREMOL has shown the capability of obtaining similar statistical patterns than those observed in real earthquakes. TREMOL parameters are aggregate abstractions of physical parameters that simulate properties such as friction, radiated energy, or rock hardness.

- Earthquake doublets are a characteristic rupture style defined as successive events within a short window in space, and time, with a similar magnitude. This rupture mode is observed in different region worldwide, such as the Solomon Islands, the Middle American Trench at Guerrero, the Iranian plateau and the Southern Iceland Seismic Zone.

- The research on seismic doublets is of great importance since it can contribute to a better understanding of earthquake triggering mechanisms. This current study applies to regional subduction processes.

- Previous studies found that a relatively homogeneous distribution of similar-size asperities may be responsible for the frequent occurrence of doublets. In particular, the Ometepec area at the Mexican subduction zone.

- Asperities are defined as areas with larger slip or slip velocity, as well as patches of higher strength and stress concentration, relative to the average values on the fault plane.

- Asperities and Barriers: Both terms refer to strong patches of the fault plane that are resistive to breaking. However, they are used with different modeling roles of strong patches in the process of earthquake faulting.

- ➢ To study the general TREMOL parameters that produce a doublet type behavior. In particular, we use the 1982 Ometepec doublet to calibrate the model using their asperities area and their magnitudes, as reference.

- ➢ To analyze the model conditions that produce “barrier” or “asperity” type behavior.

- TREMOL (as an acronym of stochasTic Rupture Earthquake MOdeL) algorithm is based on the Fiber Bundle Model (FBM). FBM is a discrete stochastic model developed to study the rupture process of different heterogeneous materials.

- The FBM analyzes the earthquake dynamics from the point of view of material properties of deformable materials that break under critical stress.

- TREMOL applies the FBM to study the rupture processes of individual asperities.
- In essence, TREMOL captures the seismic statistical patterns without having any seismic assumption constraining the model.

model equations

1. Hazard-rate → $\kappa(\sigma) = \sigma^{\rho}.$

2. Time interval computed at each k-step, where $\boldsymbol{\sigma}_i$ is the load in the i-th cell, N is the total number of unbroken cells. Hence, the cumulative time is computed as the sum from 0 to k of $\boldsymbol{\delta}_k$ → $\delta_k = \frac{1}{\sum_{i=1}^{N} \sigma_i^{\rho}(t)},$

3. Rupture probability computed per each cell and at each k-step → $P_i = \delta_k \sigma_i^{\rho}(t).$

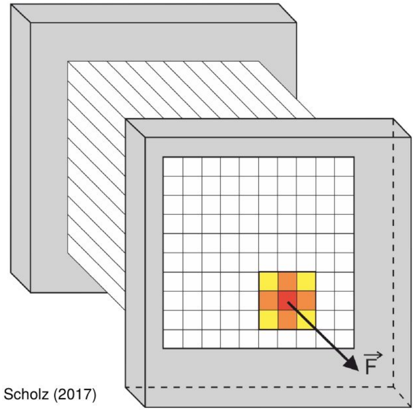
4. Mean load computed at each discrete k-step → $< \sigma >= \frac{\sum_{i=1}^{N} \sigma_i}{N}.$

5. The inter-velocity → $\Delta\nu_i = \frac{\Delta r_i}{\Delta \tau_i},$

where $\Delta r_i = \sqrt[2]{[x_i - x_{i-1}]^2 + [y_i - y_{i-1}]^2}$, and $\Delta \tau_i = T_i - T_{i-1},$

The basic components necessary to construct an FBM are :

1) Spatial **discretization** in regular grid domain (2D or 3D). In our case the study area is represented as a discrete set of cells ("fibers") organized on a Two-dimensional and regular lattice.
2) **A failure law that is a** probability distribution function for the rupture of the individual elements.
3) **A load transfer rule** that dictates how the load is shared from the ruptured cell to its neighbors (local or global range)

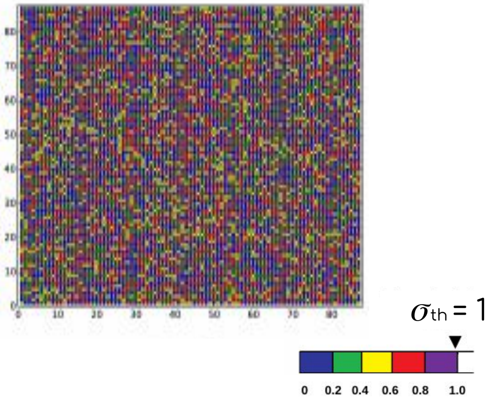


Scholz (2017)

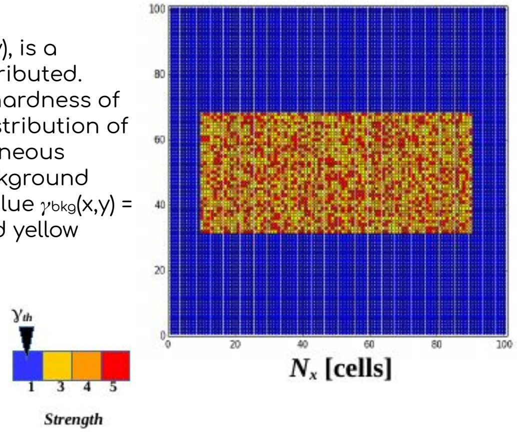
Hansen, A., Hemmer, P. C., & Pradhan, S. (2015). *The fiber bundle model: modeling failure in materials.* John Wiley & Sons.

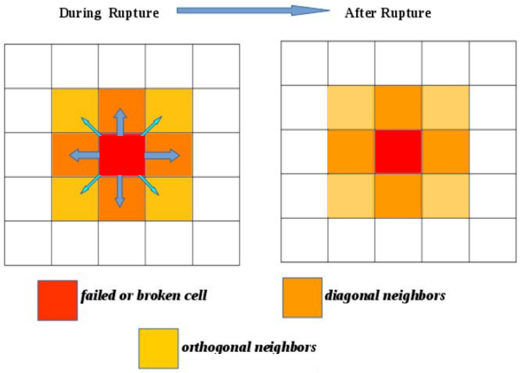
TREMOL initial conditions.

(I) The **load $\sigma_k(x,y)$ for each cell, $x=1, \ldots, Nx$ and $y = 1, \ldots, Ny$**, is initialized ($k=0$) from an random uniform distribution function, U(0,1]. It is a variable that will evolve during an FBM realization for the successive discrete k-steps, $k=0,\ldots,N_{stps}$.



(II) A **strength parameter** $\gamma(x,y)$, is a discrete value randomly distributed. This quantity simulates the hardness of the material. The random distribution of the values model a heterogeneous medium. The cells in the background region have the minimum value $\gamma_{bkg}(x,y) = 1$ and cells in red, orange and yellow have a strength $\gamma_{asp}(x,y) > 1$

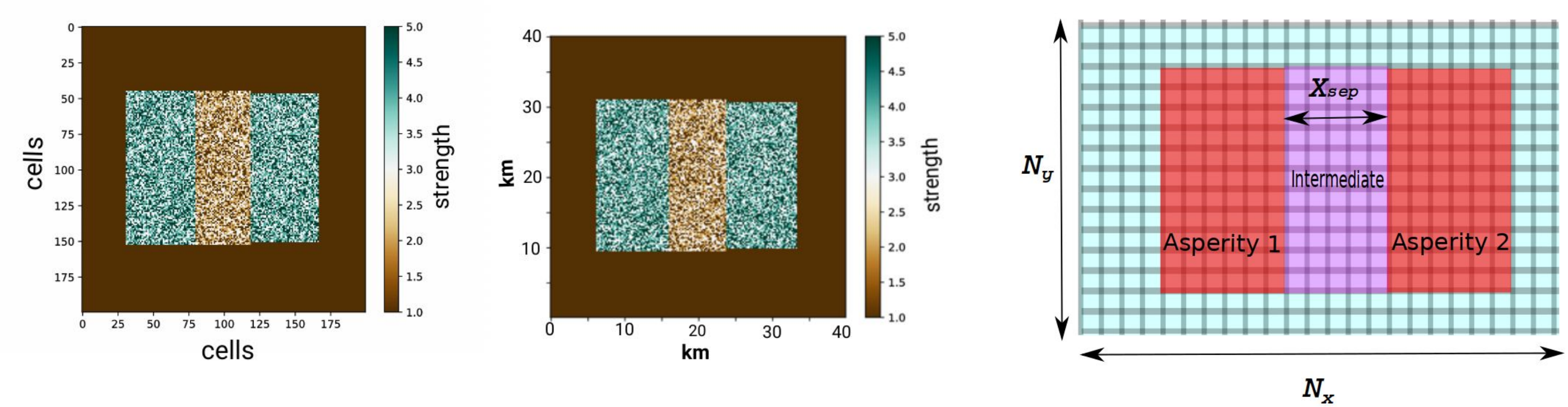




(III) When a cell failures, it distributes its load, in a Local sharing rule, to its eight neighbors. The percentage of shared load in each rupture is given by the **conservation parameter $\pi(x,y)$** that simulates dissipative effects. The model considers open **boundary** conditions.

(IV) To distinguish between an asperity and the background region, the model considers different values for $\pi(x,y)$ and for $\gamma(x,y)$, $\pi_{asp}(x,y)$ $\pi_{bkg}(x,y)$, $\gamma_{asp}(x,y)$, $\gamma_{bkg}(x,y)$ respectively. Those values try to capture the asperity/barrier behavior, i.e. larger slip and greater strength compared to the average values on the fault plane. In our model, the slip is represented by the rupture area that depends on $\pi(x,y)$, and on the strength by the $\gamma(x,y)$ parameter.

Doublet case: Study parameters



X_{sep} separation length between both asperities in the discrete domain

π_{int} percentage of transferred load for cells within the intermediate area

γ_{int} strength of the cells within the intermediate area

Input parameters	
$A_{eff(a1)}$, $A_{eff(a2)}$	fault rupture area computed for asperity one and two, respectively.
S_{a1}, S_{a2}	the ratio of the asperity size for both asperities

Output parameters	
$n_{synEQ(Int)}$	number of synthetic earthquakes generated at the intermediate region
n_{synEQ}	number of synthetic earthquakes generated at the whole domain
N	array storing the rupture area (in cells units) of each simulated earthquake
$<\sigma(t)>$	mean load time-series (dimensionless)
$\Delta v(t)$	inter-event time series (dimensionless)

Post-process: Scale-area relations

The link between the rupture area simulated in TREMOL and the seismic magnitude is given by scale-area relations.

For example, four scale-magnitudes:

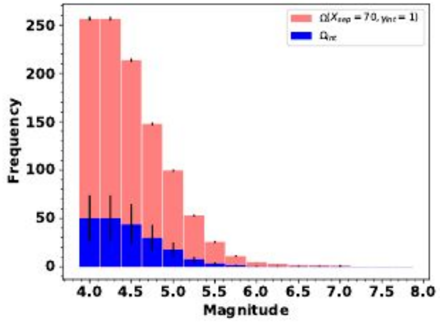
$M_w = (\log_{10} A_a + 4.393)/0.991$ (Somerville, 1999)

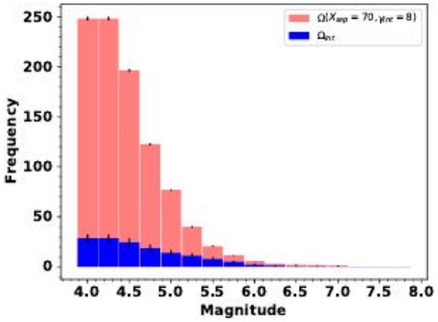
$M_w = (\log_{10} A_a + 5.518)/1.137$ (Mai et al., 2005)

$M_w = (\log_{10} A_a + 6.013)/1.146$ (Mai et al., 2005)

$M_w = ⅔ * (\log_{10} A_a/(7.78*1.0e^{-9})^{(1/0.55)}) - 6.07$ (Ramirez, 2014)

where A_a is the asperity area (real or synthetic).





On the 7th of June 1982, an earthquake doublet consisting of two events of Mw = 6.9 occurred within five hours of each Ometepec area (Guerrero State, México).

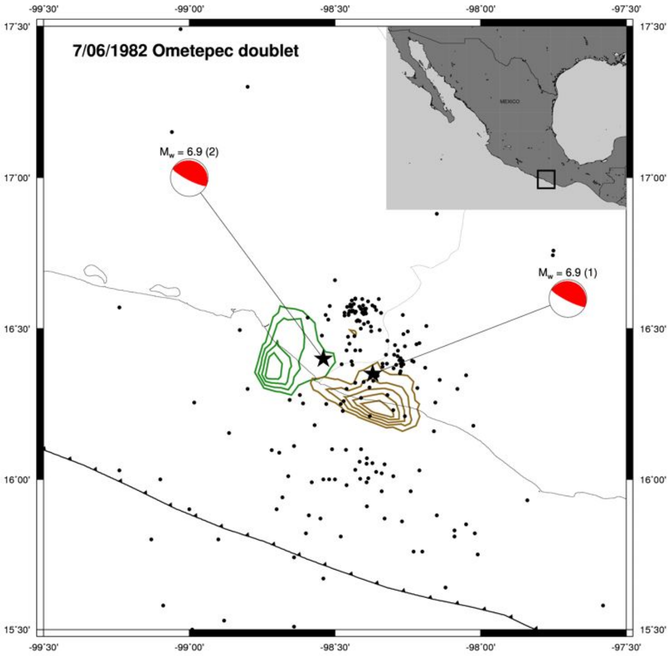


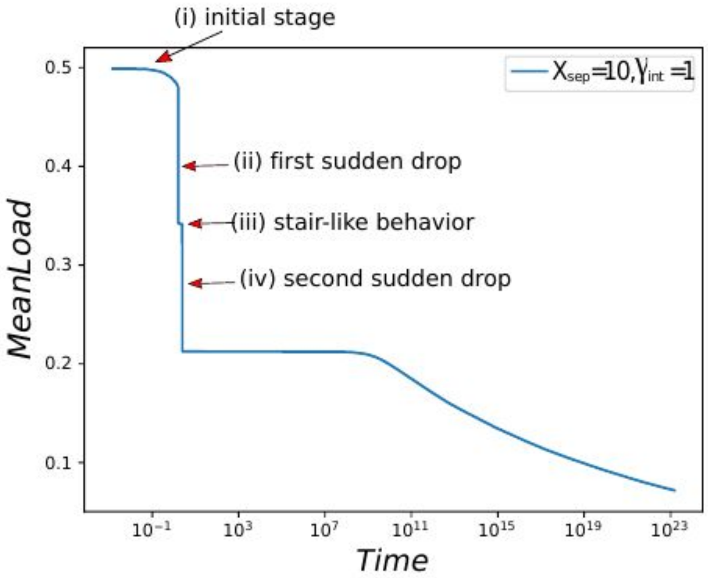
Table 1. Studied events. Depth and magnitude of the epicenter from Yamamoto et al., (2002). The focal mechanism from Beroza et al. (1984).

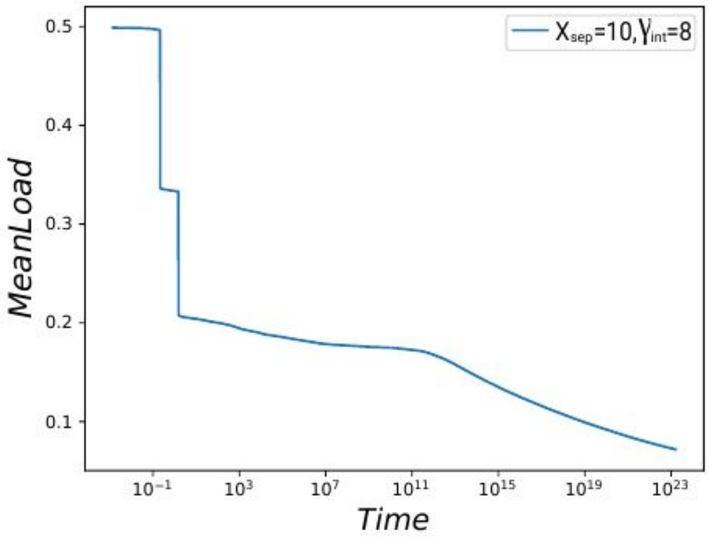
Date	Origin Time	Latitude	Longitude	Depth	Ms	Focal Mechanism (stk,dip,rake)
7 June 1982 (1)	06:52:33.7	16.35	-98.37	25.0 km	6.9	292,10,85
7 June 1982 (2)	10:59:40.1	16.40	-98.54	8.0 km	7.0	292,11,85

Table 2. Finite-fault parameters obtained by Rodríguez-Per ́ez et al. (2018). Asperity definition based on (Somerville et al. 1999); L_{eff}, W_{eff}, and A_{eff} are the effective length, width and rupture area based on (Mai & Beroza 2000); A_a is the asperity area.

Date	L_{eff} [km]	W_{eff} [km]	A_{eff} [km²]	$Sa = A_a/A_{eff}$
7 June 1982 (1)	34.47	17.81	613.83	0.23
7 June 1982 (2)	22.59	25.86	584.00	0.25

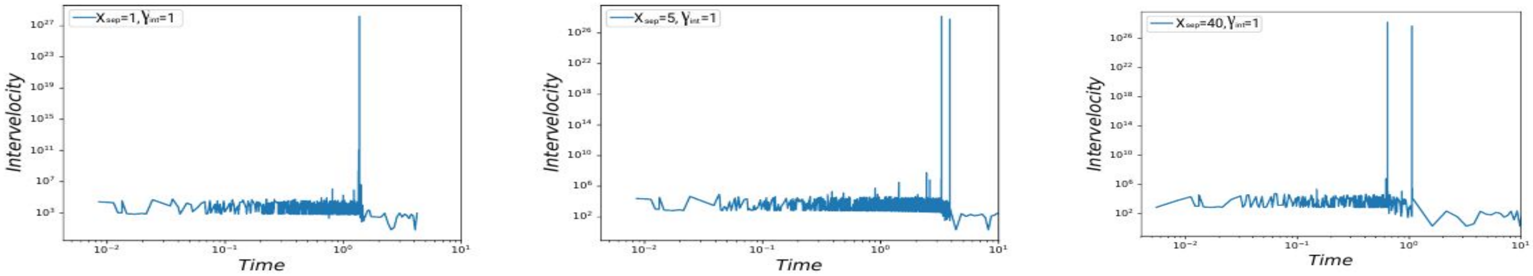
Mean load evolution



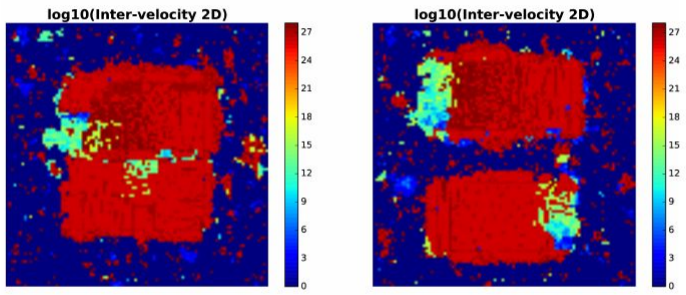


These two figures show the mean load evolution four different X_{sep} and γ_{int}. Left figure shows four different stages. Each sudden drop is related to an asperity rupture. Right figure shows a larger time for the stair-like behavior after the second drop occurs. This larger time is related to the intermediate strength value γ_{in} = 8.

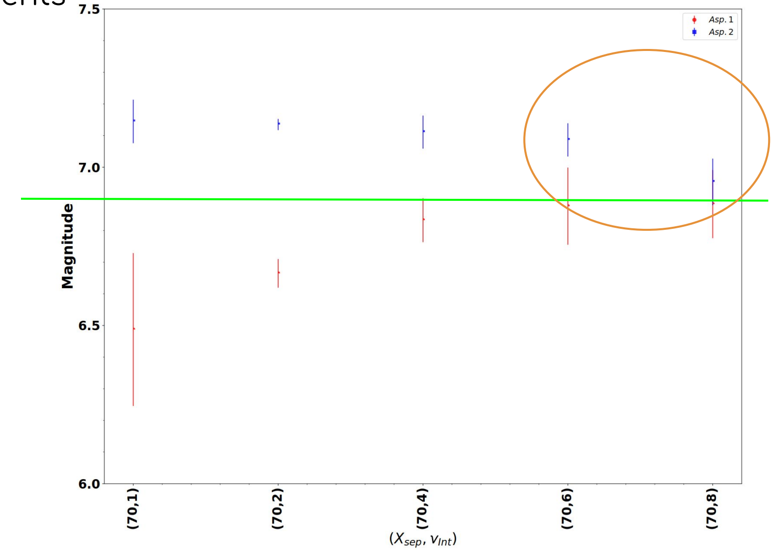
Inter-velocity, Δv_k.



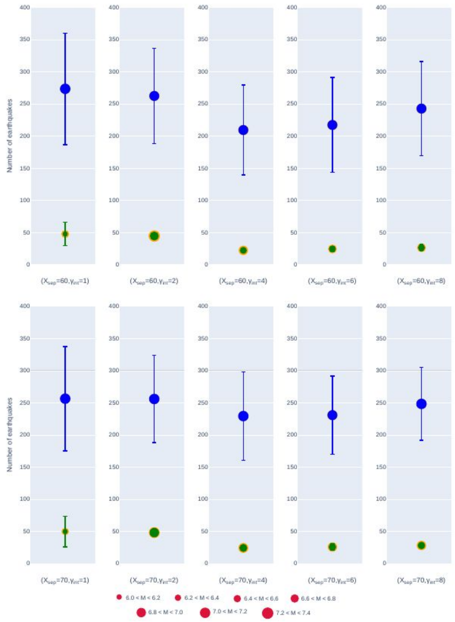
The inter-velocity, Δv_k, calculates the rate of occurrence of two consecutive earthquakes. Upper plots show Δv_k as a function of time. The pulse-like behavior of Δvk occurs during the asperity rupture (right figures). These figures show that as X_{sep} increases, the two asperities break up over different times, showing a doublet type behavior, where two events are closely, but clearly spaced in time.



Maximum magnitude and number of generated events



The median value and interquartile range (error bars) of maximum magnitude, M_{max}, calculated for asperity 1 (blue) and asperity 2 (red) as function of γ_{int} , and X_{sep}. We choose X_{sep}=70 cells because the Ometepec doublet epicentral coordinates agree to this distance.



Comparison between the mean of the number of earthquakes produced in Ω (blue circles), and Ω_{int} (green circles) for different γ_{int}, and X_{sep} = [60,70]. The equivalent maximum magnitude, M_{max}, of the γ_{int}, and X_{sep} represented by different circle sizes. Error bars introduce the standard deviation for the number of events from twenty realizations, and the orange circles indicate the standard deviation of the magnitude. A clear reduction in the number of events generated in the intermediate region is observed. These events decrease for stronger intermediate areas, $\gamma_{int} \geq 4$, similarly to barrier type behavior.

- TREMOL is well suited to study the faulting properties that lead to a doublet scenario. Two main parameters control a doublet behavior: the strength of the intermediate area γ_{int} and the separation between both asperities, X_{sep}.

- We can find optimal TREMOL parameters that allow simulated results approaching a real doublet, such as the Ometepec, 1982. In this case, $X_{sep} = 70$, $\gamma_{int} \geq 4$

- The behavior observed in seismic asperities and barriers can be modeled by using the strength of the intermediate area. As $\gamma_{int} \geq 4$, the intermediate areas act as barriers where the earthquake activity is decreased.

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Thank you

marisol.monterrubio@bsc.es

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