Assessing crustal stability via fault stress perturbation analysis

Davide Zaccagnino[†,@], Luciano Telesca[*], Carlo Doglioni[†,§]

[†] Department of Earth Sciences, Sapienza University, Rome, Italy;
[*] Centro Nazionale delle Ricerche (CNR-IMAA), Tito, Italy;
[§] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy.
[@] *davide.zaccagnino@uniroma1.it, PhD student (11/2021-ongoing)*

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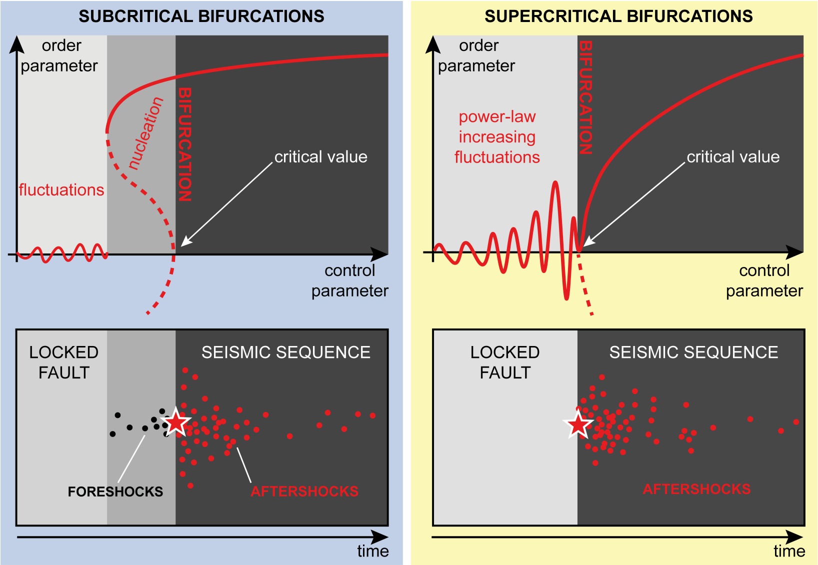
How do large-scale catastrophic patterns arise from progressive cooperative processes?

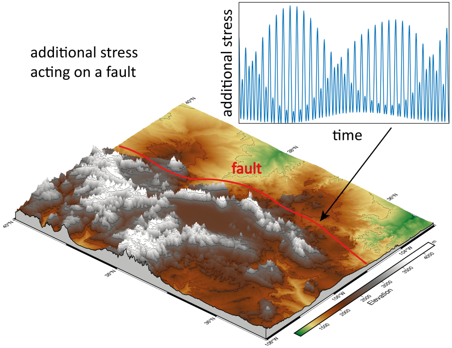


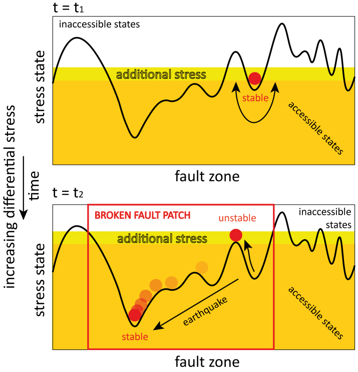
The problem and key idea

Assessing the stability state of faults is a crucial task not only for seismic hazard, but also for understanding how the earthquake machine works.

$\Longrightarrow$

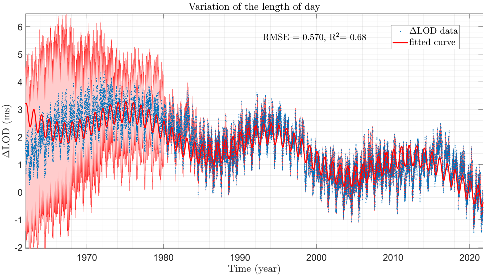
A possible approach consists in perturbing faults and studying how seismicity changes as additional stress is applied: if the initial energy state is stable, the system will oscillate around it; otherwise, the background seismic rate will be modified.

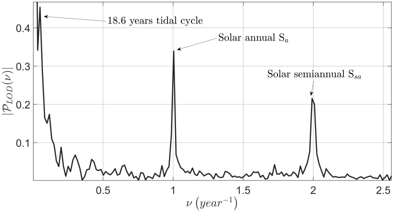


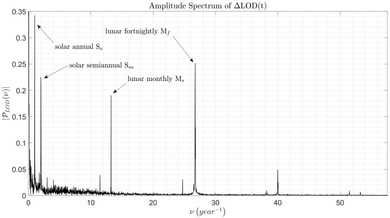


Stress sources

Tides provide natural stress sources featured by wide ranges of frequencies and amplitudes, which make them a suitable candidate for our investigation.







Methods

Tidal stress calculation

1) Given the tidal potential W(r,θ,ϕ), the components of **displacement** are

$$u_r = \frac{h_2(r)}{g(r)} W(r,\theta,\phi),\; u_\theta = \frac{l_2(r)}{g(r)} \frac{\partial W(r,\theta,\phi)}{\partial \theta},\; u_\phi = \frac{l_2(r)}{g(r)\sin\theta} \frac{\partial W(r,\theta,\phi)}{\partial \phi}$$

2) Strain is obtained by spatial derivation of displacement;
3) Tidal stress components, according to Hooke's law, for isotropic materials are

$$\sigma_{ij}(r) = \lambda(r)\varepsilon_{kk}(r)\delta_{ij} + 2\mu(r)\varepsilon_{ij}(r)$$

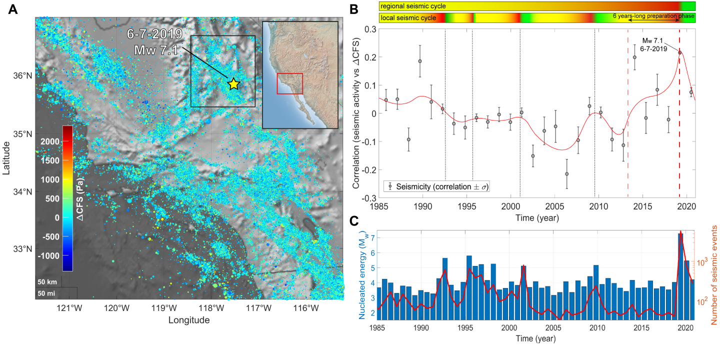
4) Fault orientation is taken into account in order to calculate shear, τ, and normal stress, σ_n (focal mechanisms + geological data);
5) Ocean loading is evaluated using NAO.99b if needed;
6) The variation of tidal Coulomb failure stress can be estimated $\Delta CFS = \tau + \mu\sigma_n$;
7) Correlation between seismic rates and tidal stress is calculated

$$\rho(t) = \frac{\sum_{i=1}\left(M_{w\,i} - \overline{M_w}\right)\left(\Delta CFS_i - \overline{\Delta CFS}\right)}{\sqrt{\sum_{i=1}\left(M_{w\,i} - \overline{M_w}\right)^2 \sum_{k=1}\left(\Delta CFS_k - \overline{\Delta CFS}\right)^2}}$$

8) Uncertainties are calculated considering magnitude and hypocentral errors;

9) Correlation **time series** are realized using different time steps (data availability).

Southern California: the case of Ridgecrest (M_w 7.1, 2019)



A: ΔCFS map for seismicity in Southern California, SCEDC Catalogue, 1985−2021, $M_L \geq 1.0$. Seismicity occurs, on average, at slightly positive ΔCFS values.
B: Correlation ρ between ΔCFS and seismicity in the Ridgecrest District, California. The scatter plot is realized by taking into account earthquakes happened in the black contour square at a depth of -2−20 km. **C**: Histogram of cumulative energy (M_w) nucleated by earthquakes (blue bars) and plot of the number of recorded seismic events (red line).

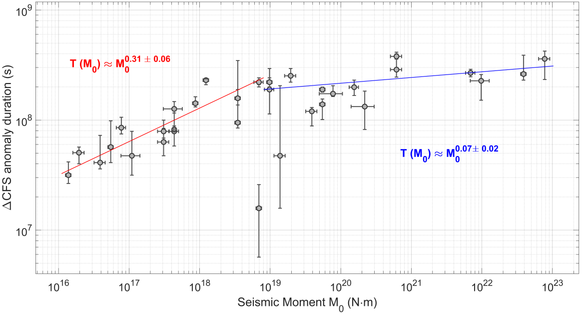
Scaling laws for crustal destabilization

$T \propto M_0^{0.31 \pm 0.06}$

$M_0 \leq 10^{19} N \cdot m$,
$R^2 = 0.94$

$T \propto M_0^{0.07 \pm 0.02}$

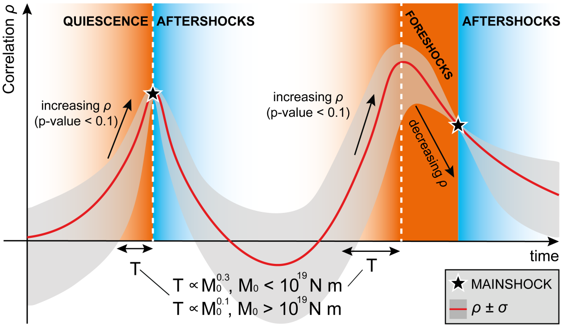
$M_0 \geq 10^{19} N \cdot m$,
$R^2 = 0.83$



Comments

- In mean-field regime, the critical dynamics of the order parameter is $m \sim H^{1/\delta}$, $\delta = 3$, where H is the intensity of the perturbing field $\rightarrow T \sim M_0^{1/\delta}$.
- $\delta \sim 3$ also characterizes seismic nucleation scaling of single earthquakes $\Rightarrow$ Are observed trends related to coalescent nucleation phases in the crust?
- The latter exponent, $\delta \sim 0.1$, may stem from cascade triggering.

Take-home messages



Stress perturbation analysis may highlight mounting instability in the brittle lithosphere

Even though it is unlikely that our results may ever be of practical use for seismic hazard, analogous procedures could illuminate slow hidden processes of destabilization taking place in the upper crust.

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Different Fault Response to Stress during the Seismic Cycle

Davide Zaccagnino [1,*], Luciano Telesca [2] and Carlo Doglioni [3,4]

1 Department of Physics, Sapienza University of Rome, 00185 Rome, Italy
2 Istituto di Metodologie per l' Analisi Ambientale (CNR-IMAA), 85050 Tito Scalo, Italy; luciano.telesca@imaa.cnr.it
3 Department of Earth Science, Sapienza University of Rome, 00185 Rome, Italy; carlo.doglioni@uniroma1.it
4 Istituto Nazionale di Geofisica e Vulcanologia (INGV), 00143 Rome, Italy
* Correspondence: zaccagnino.1748720@studenti.uniroma1.it

Featured Application: This article introduces a method to establish the state of mechanical stability of a fault system by analyzing modulations of seismic activity as a function of known perturbations, i.e., tidal stress. In addition to providing useful information about the physics of fault systems, our method can be applied to evaluate how unstable faults are with respect to additional stress, and therefore forecast their future slip. *Mutatis mutandis*, our approach can also be adopted in other fields where it is of paramount interest to assess the loading state of a physical system alternating stability to sudden breaking.

Abstract: Seismic prediction was considered impossible, however, there are no reasons in theoretical physics that explicitly prevent this possibility. Therefore, it is quite likely that prediction is made stubbornly complicated by practical difficulties such as the quality of catalogs and data analysis. Earthquakes are sometimes forewarned by precursors, and other times they come unexpectedly; moreover, since no unique mechanism for nucleation was proven to exist, it is unlikely that single classical precursors (e.g., increasing seismicity, geochemical anomalies, geoelectric potentials) may ever be effective in predicting impending earthquakes. For this reason, understanding the physics driving the evolution of fault systems is a crucial task to fine-tune seismic prediction methods and for the mitigation of seismic risk. In this work, an innovative idea is inspected to establish the proximity to the critical breaking point. It is based on the mechanical response of faults to tidal perturbations, which is observed to change during the "seismic cycle". This technique allows to identify different seismic patterns marking the fingerprints of progressive crustal weakening. Destabilization seems to arise from two different possible mechanisms compatible with the so called *preslip patch*, *cascade* models and with seismic quiescence. The first is featured by a decreasing susceptibility to stress perturbation, anomalous geodetic deformation, and seismic activity, while on the other hand, the second shows seismic quiescence and increasing responsiveness. The novelty of this article consists in highlighting not only the variations in responsiveness of faults to stress while reaching the critical point, but also how seismic occurrence changes over time as a function of instability. Temporal swings of correlation between tides and nucleated seismic energy reveal a complex mechanism for modulation of energy dissipation driven by stress variations, above all in the upper brittle crust. Some case studies taken from recent Greek seismicity are investigated.

Keywords: tidal triggering of earthquakes; seismic cycle; coulomb failure stress; preparatory phase; seismic prediction

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Correlation between seismic activity and tidal stress perturbations highlights growing instability within the brittle crust

Davide Zaccagnino[1✉], Luciano Telesca[2] & Carlo Doglioni[1,3]

Faults become more and more responsive to stress perturbations as instability mounts. We utilize this property in order to identify the different phases of the seismic cycle. Our analysis provides new insights about the features of impending mainshocks, which are proposed to emerge from a large-scale crustal-weakening preparation process whose duration depends on their seismic moments, according to the power-law $T \propto M_0^{1/3}$ for $M_0 \leq 10^{19}$ N m. Moreover, further studies are performed about the impact of tidal stress perturbation on seismicity; in particular, the relationship between frequency-magnitude scaling and perturbations is discussed, showing that the sensitivity of earthquakes to solid Earth tides decreases as their magnitudes increase.

Several research works prove a significant responsiveness of seismicity to additional stress sources (e.g.,[1]). A nonlinear dependence of the time to failure on stress variations has been known since the Eighties[2]. It does not only mean that seismic rate is a direct effect of loading, but also implies that small additional stress can result in highly unpredictable states of crustal instability. Observations suggest that seismicity rates can be influenced by both static and dynamic perturbations, although in different ways[3]. Tides are ubiquitous periodical stress perturbation sources featured by harmonics with a wide spectrum of periods ranging from a few hours to decades. This is the reason why tidal stress loading can be a key for highlighting different stages of the seismic cycle, i.e., interseismic, pre-seismic, post-seismic phases. Unfortunately, from a statistical viewpoint, earthquake catalogs are often insufficient to detect significant modulations of seismic activity over time with respect to stress modulations. Tides are tiny perturbations of the gravitational field (usually ~0.1–10 kPa) with respect to typical earthquake stress drops (1–50 MPa), so that usually a few thousand events are required to observe a statistically significant correlation between tidal phase and earthquakes occurrence. However, the actual impact on the stability of rock volumes largely depends on the tectonic setting, the spatial orientation of the fault, the depth and the epicentral latitude; finally, also the magnitude of the impending event modifies the response of the system to the tidal perturbation (compare with our results in section "Discussion"). At last, seismic response to tidal loading is strongly affected by the duration of earthquake nucleation[4]. Therefore, it is not surprising that a wide range of results was found in different geographical areas. Beyond the aforementioned issues, well-established scientific evidence exists about tidal synchronization in seismic catalogs[5] as well as the correlation of seismicity with solid Earth tides has been now well documented (e.g.,[6,7]). Both global and regional seismic time series show tidal[8], climatic and seasonal patterns[9]. The effect of tidal stress can clearly be distinguished into its vertical and horizontal components; in particular, the last has been suggested to provide the energetic tectonic source that is retained by the crustal volume as an hysteresis of the tidal wave passage[10], whereas the vertical component appears mainly as a transient oscillation of the gravitational load, which acts as the seismic trigger when the threshold of the critical stress is reached also acting in different ways according to the tectonic settings. It has been shown that thrust-related earthquakes are more frequent during the high tide[11], whereas normal fault related earthquakes occur more often during the low tide[12]. This is mechanically coherent respectively with a decrease of g and consequently of the lithostatic load given by dgz, where d is the crustal density, g is the gravity of Earth and z represents the depth of the hypocenter, in contractional tectonic settings (σ_3), favouring fault activation, and opposingly by an increase of g and the lithostatic load (σ_1) in extensional tectonic settings[13]. In this work, we perform an analysis of the correlation time series of seismic activity and tidal stress perturbations resolved