Scaling Organization of Fracture Tectonics (S.O.F.T.)

Strike-slip Fault Network Formation & Evolution

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Summary

• Introduction to a non-linear geophysics:
  ● dynamo mechanism in the Earth’s outer core.
  ● small scale roughness at the core-mantle boundary.
  ● seismicity along an isolated fault segment.

• The fracturing process at a regional scale through a multiple scale dynamical system.

• Different phases of evolution of networks of strike-slip faults.

• Conclusions & Perspectives.
Philosophy of our approach

It is necessary to develop techniques that deal with the geocomplexity.
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- Construct dynamical systems that reproduce Earth-like behaviours.
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It is necessary to develop techniques that deal with the geocomplexity.

- Construct dynamical systems that reproduce Earth-like behaviours.
- Extract from these models control parameters and characteristic scenarios.
- Extrapolate the results to real geophysical systems.
**Fondamental concepts**

Large scale phenomena come from organization at all small scales
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The complexity of geophysical systems does not come from the details of the physical processes
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**Hierarchical organization**

**Stochastic processes**
Hierarchical organization

Different levels represent the state of the system at different scales

- Rules of evolution.
- Transfers of physical parameters (cascades).
Time dependent stochastic process

The heterogeneities of the system are taken into account without pre-determination.

State 1 → State 2

Probability per unit of time

Physical laws
Domains of application

Dynamo mechanism in the Earth’s outer core.

Narteau et al. (2000a)
Domains of application

Small scale roughness at the core-mantle boundary.

Narteau et al. (2001)
Domains of application

seismicity of an isolated fault segment.

Narteau et al. (2000b)
Seismicity along an isolated fault segment

- Seismic cycle
- Foreshocks and aftershocks.
- Gutenberg-Richter and Omori laws.
- Swarms of earthquakes.
- Seismic noise.
- Seismicity of a creeping segment.

An adimensional control parameter
Characteristic scenarios of seismicity
Seismicity along an isolated fault segment

Statistical behaviors

Relationship between the density of microfractures and the stress stored into the fault zone.

*Weakening process*

Relationship between the seismic properties and the tectonic loading.

*Threshold of activity*
What do we study?
What do we study?
What do we study?
What do we study?
What do we study?
What do we study?
What do we study?
Strike-slip fault network

(a)

North

σ₁

σ₃

K Scale

(b)

K

K+K-3

K+K-2

K+K-1

K+K
Overview of the model

- A fault segment becomes active as a result of the micro-fracturing process; a fault segment may become stable as a result of the evolution of the regional tectonic setting.
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- the new fault segment $f$ is included in a fault $F$ of length $l_F$ which now interacts with the whole fault network until a characteristic length $L_F$. 
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- a fault segment \( f \) become active as a result of the micro-fracturing process; a fault segment may become stable as a result of the evolution of the regional tectonic setting.

- the new fault segment \( f \) is included in a fault \( F \) of length \( l_F \) which now interacts with the whole fault network until a characteristic length \( L_F \).

- in the neighborhood of a new fault, \( F \), the perturbation of the stress rate takes place within a zone proportional to \( l_F \), with an amplitude defined by \( L_F \), \( l_F \) and the tectonic loading.
The dynamical system at scale \( K \)

At the fault segment scale, the dynamical system consists of the interrelated evolution of

THE STATE

active or stable

&

THE STRESS ACCUMULATION RATE
quantifies the stress due to tectonic loading
dissipated at this point in space
The $K$ scale transitions

stable $\rightarrow$ active

$$\alpha_a = \begin{cases} 
0 & \text{for } \Delta E(x, y) \leq \Delta E_c \\
\kappa_a \left( \frac{\Delta E(x, y) - \Delta E_c}{\Delta E_c} \right) & \text{for } \Delta E(x, y) > \Delta E_c
\end{cases}$$
The $K$ scale transitions

stable $\rightarrow$ active

$$\alpha_a = \begin{cases} 0 & \text{for } \Delta E(x, y) \leq \Delta E_c \\ k_a \left( \frac{\Delta E(x, y) - \Delta E_c}{\Delta E_c} \right) & \text{for } \Delta E(x, y) > \Delta E_c \end{cases}$$

active $\rightarrow$ stable

$$\alpha_b = \gamma$$
The fault

A fault-orientation neighborhood rule:
The fault

A fault-orientation neighborhood rule:

Same segment

Pull apart or bend

Parallel faulting or push-up

Branching

Branching
The fault interactions

(a) cooperative configurations
(b) orientation
(c) minimal activating configurations

(d) scale k
(e) scale k+1

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The fault interactions
The stress rate redistribution

- it is located in the neighborhood of the fault
  \[ \sim r^{-2} \]
- its intensity is determined by fault interactions
  \[ \sim \sqrt{L_F} \]
- its shape depends of the geometry of the fault at all scales.

\[ \begin{align*}
\mathbf{e}_1 &= \begin{pmatrix} 5 & 1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \\
\mathbf{e}_2 &= \begin{pmatrix} 4 & 2 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \\
\mathbf{e}_3 &= \begin{pmatrix} 1 & 3 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \\
\mathbf{e}_4 &= \begin{pmatrix} 1 & 1 \\ 2 & 4 \\ 0 & 0 \end{pmatrix} \\
\mathbf{e}_5 &= \begin{pmatrix} 1 & 1 \\ 0 & 5 \\ 0 & 0 \end{pmatrix}
\end{align*} \]
The stress rate redistribution

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Fault network formation & evolution

The top figures represent the distribution of the stress rate for the fault networks presented on the bottom figures.

Any black cell is a vertical dextral strike slip fault zone oriented at 30° from the north.

The bottom figures represent the distribution of the active fault segments.

1. A low tectonic loading.
2. A high tectonic loading.
The growth phase

(a) Position along the fault

(b) Position along the fault

(c) Position along the fault

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The interaction phase

Diagram showing two phases: T and T+ ΔT. Points a and b are marked in both phases.
The interaction phase
The localization process
The homomogeneization along faults

(a) Stress rate on the fault

(b) Normalized total stress rate on the fault

(c) Time (years)
The cumulated stress dissipation
The cumulated stress dissipation
The structural regularization

![Graph showing structural regularization](image)

- **Time (years)**
- **$\langle n_F / I_F \rangle$**

I, II, III indicate different stages or phases of the process.
The stress rate per unit of fault length

![Graph showing normalized stress rate against fault length](image-url)
Conclusions

- We model the evolution of a population of faults and isolate different phases of evolution.
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**Conclusions**

- We model the evolution of a population of faults and isolate different phases of evolution.
- These phases are associated with a general process of localization.
- For the whole network and along each fault we can analyse the variations of the state of stress (homogeneization, ...).
- This model determines at any point in time the boundary conditions of the fault segments where we can apply the model of seismicity.

Synthetic catalogs from a multidomain S.O.F.T. model