

Constraining families of dynamic models using geological, geodetic and strong ground motion data

Elisa Tinti, Emanuele Casarotti, Thomas Ulrich, Taufiqurrahman, Duo Li, Alice Agnes Gabriel



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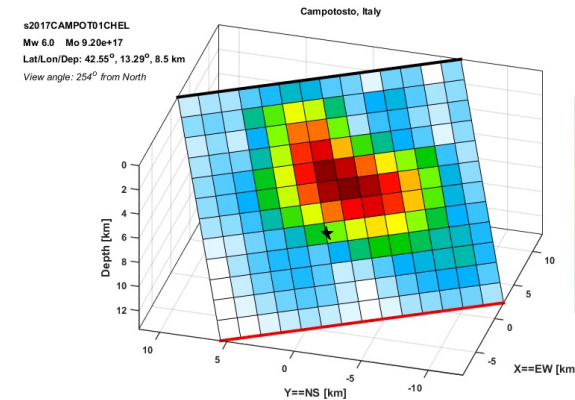
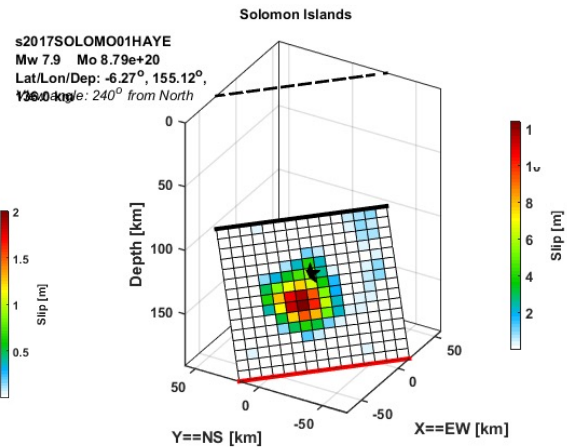
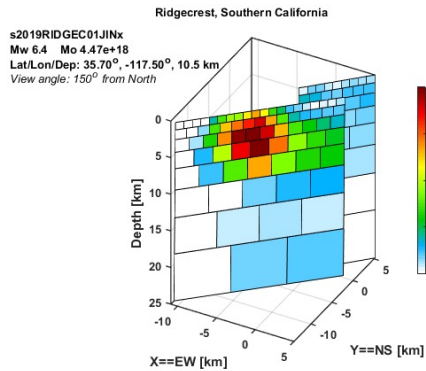
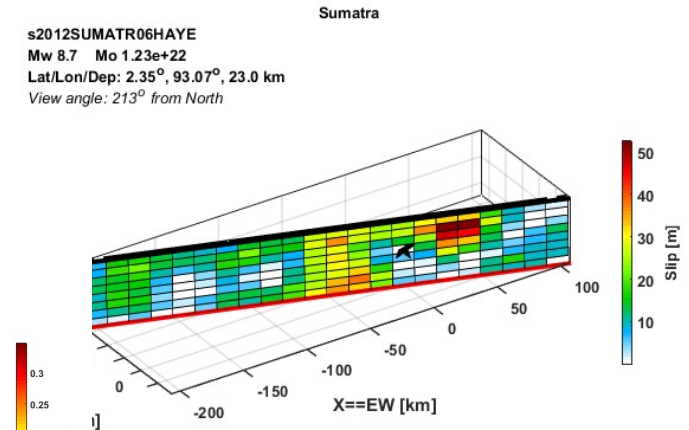
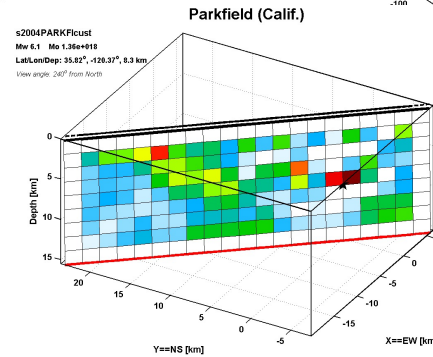
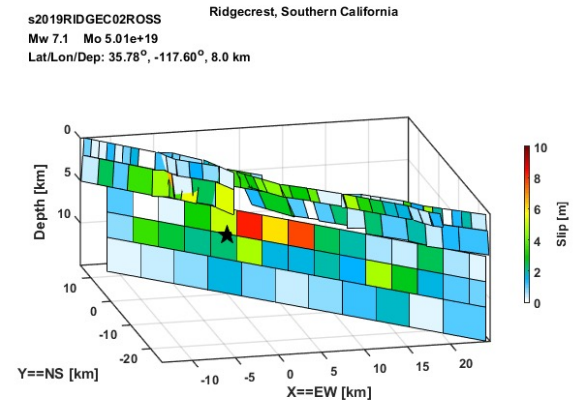
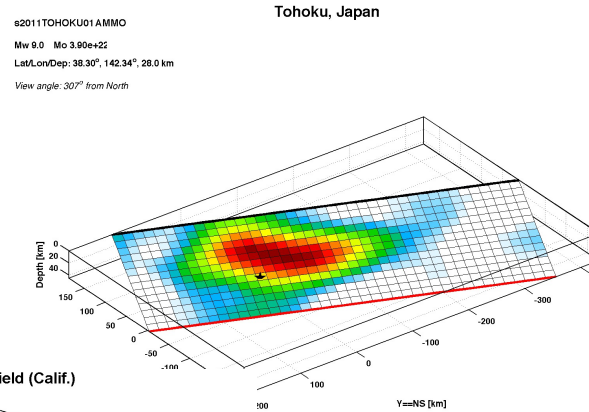
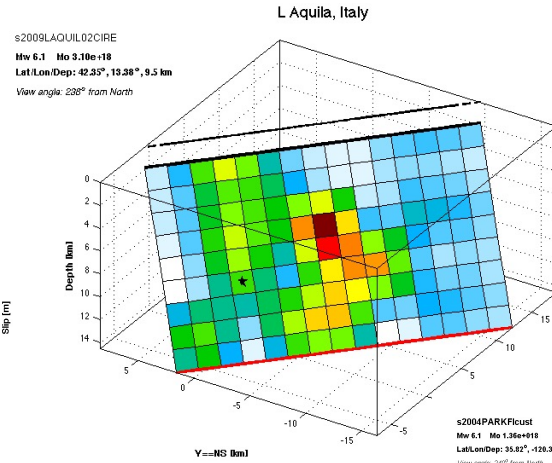
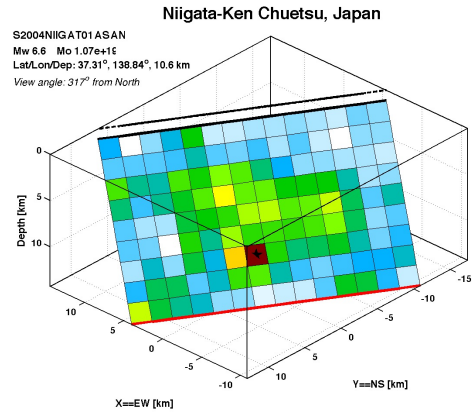
Describe the seismic source with...

Kinematic modeling ↔ Dynamic modeling

are these models always consistent?

Main motivations

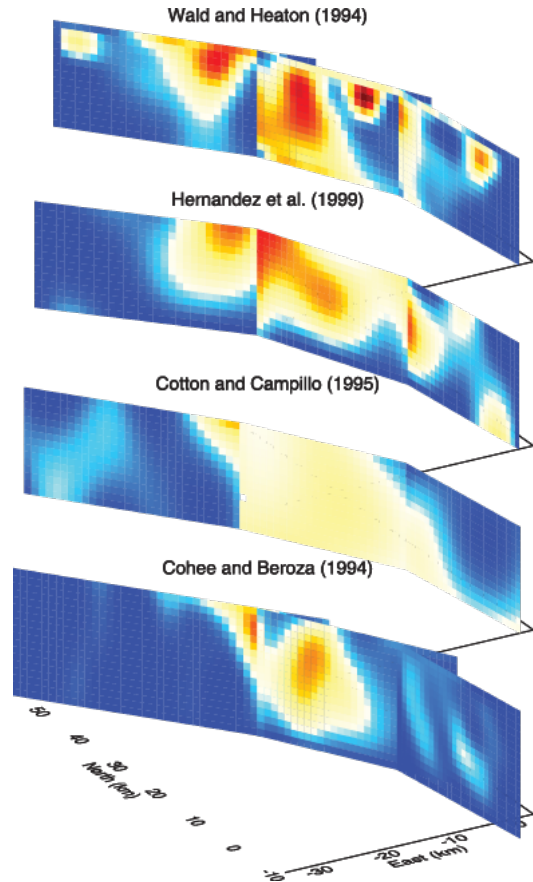
Kinematic inversion models



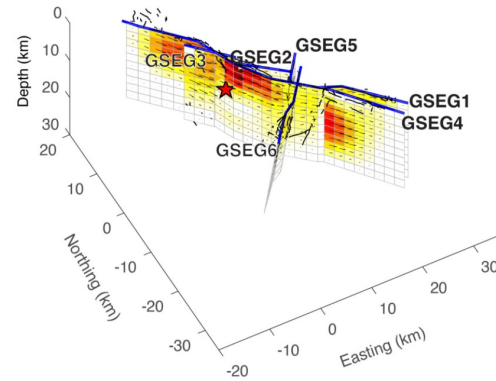
Main motivations

Kinematic inversion models

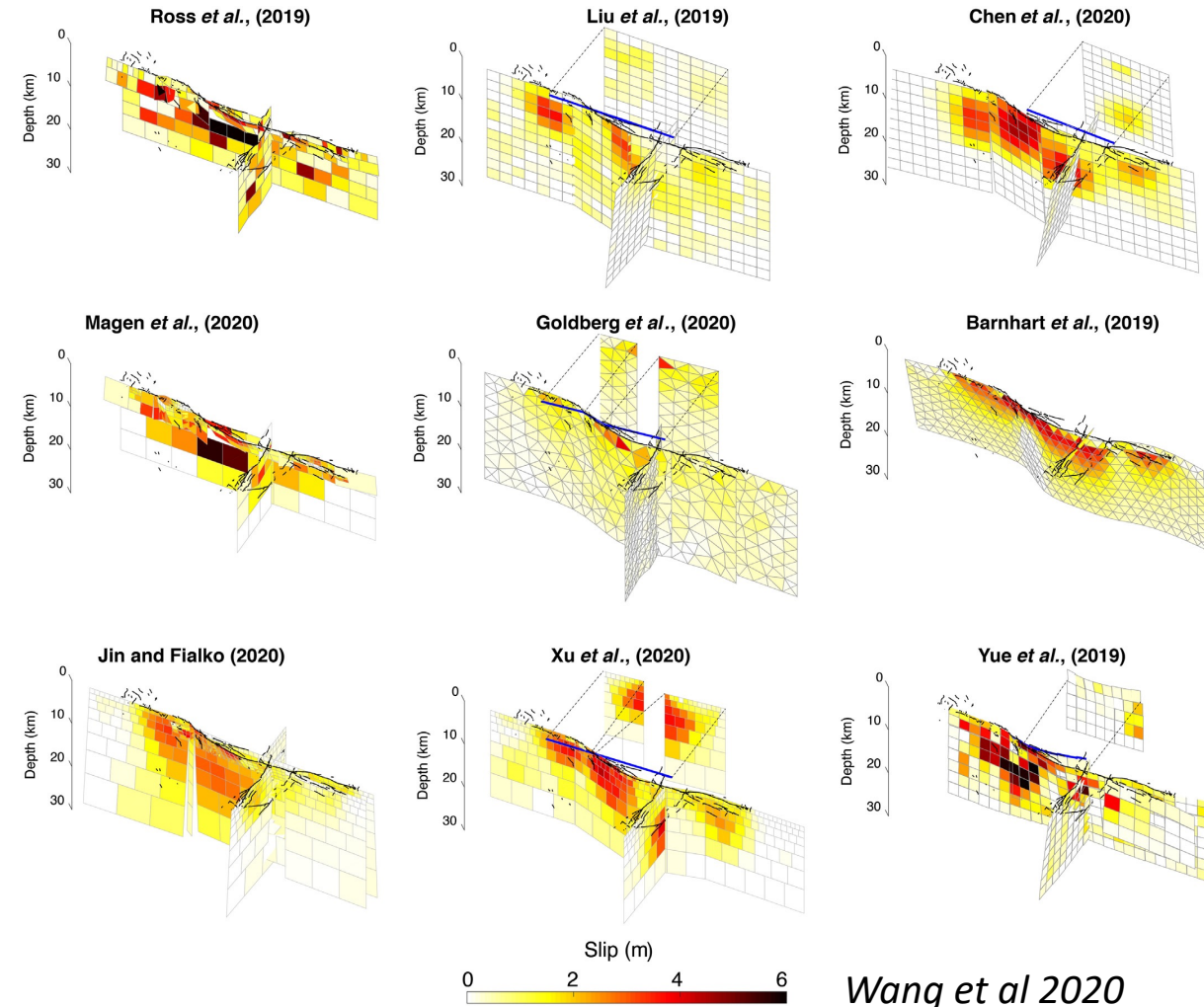
For the same seismic event sometimes the solutions are so awkwardly different even if some of them are retrieved by using the same data set.



4 models of the Mw 7.3, 1992 Landers earthquake



10 models of the Mw 7.1, 2019 Ridgecrest earthquake



Main motivations

Dynamic inversion models




JGR Solid Earth

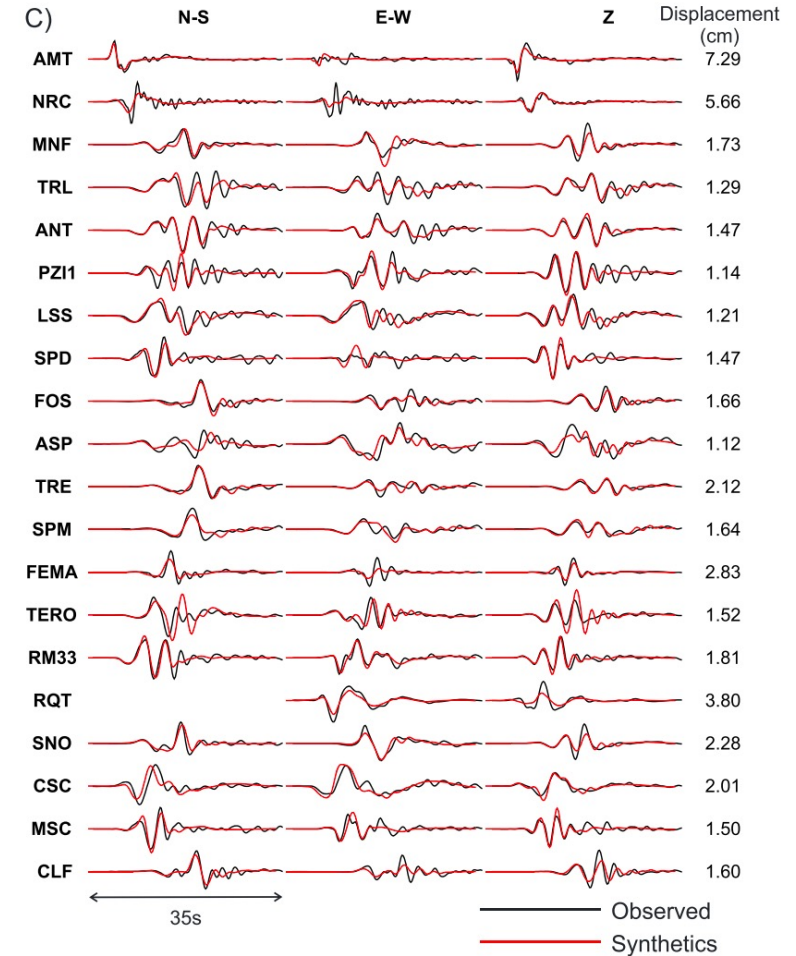
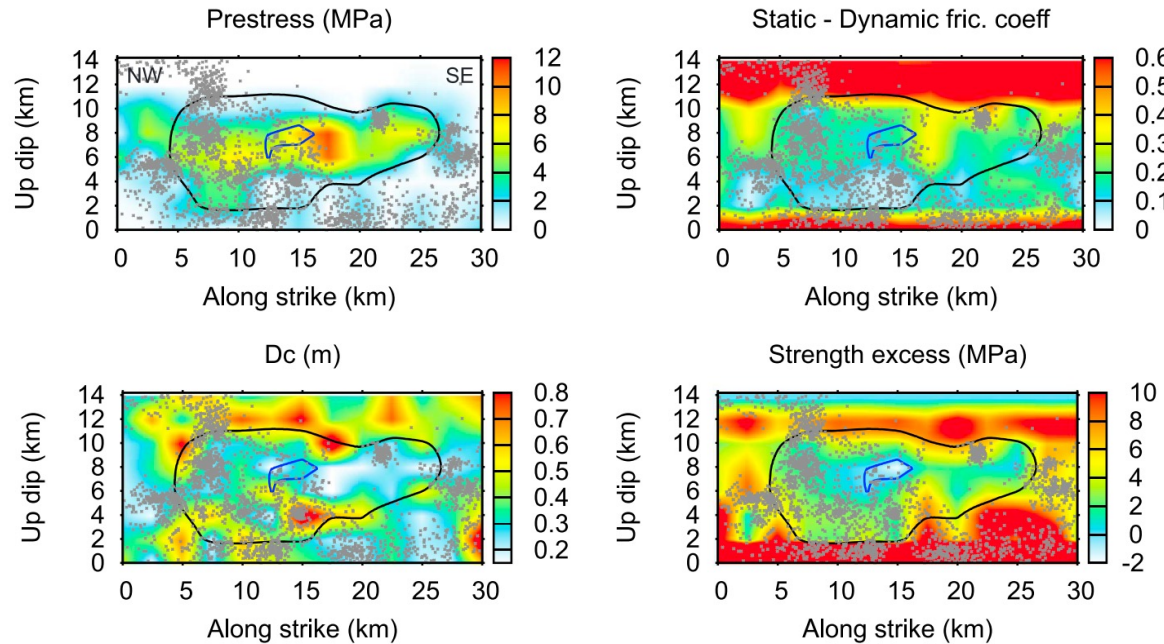
RESEARCH ARTICLE

10.1029/2019JB017512

This article is a companion to Gallovič et al. (2019), <http://doi.org/>

Bayesian Dynamic Finite-Fault Inversion: 2. Application to the 2016 M_w 6.2 Amatrice, Italy, Earthquake

F. Gallovič¹ , L. Valentová¹, J.-P. Ampuero² , and A.-A. Gabriel³ 



To reduce the number of parameters, dynamic friction is often assumed constant. “Dc” results the more heterogeneous and less constrained parameter.

Main motivations

Dynamic scenarios consistent with rocks properties

JGR Solid Earth

Research Article | [Open Access](#)

A Geology and Geodesy Based Model of Dynamic Earthquake Rupture on the Rodgers Creek-Hayward-Calaveras Fault System, California

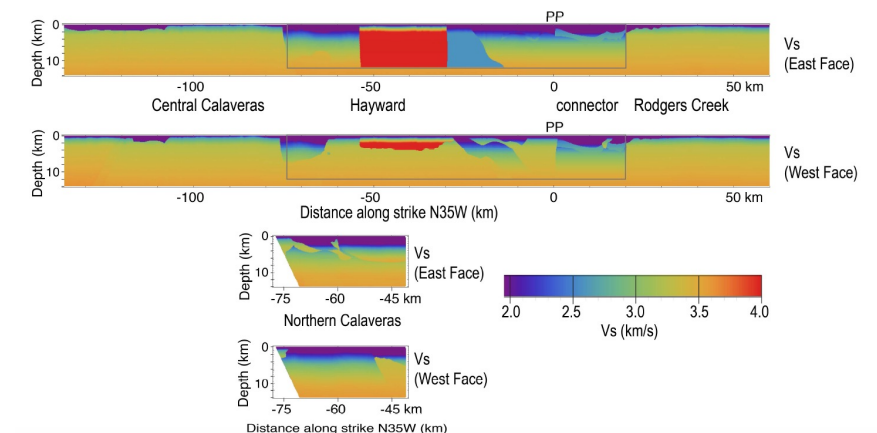
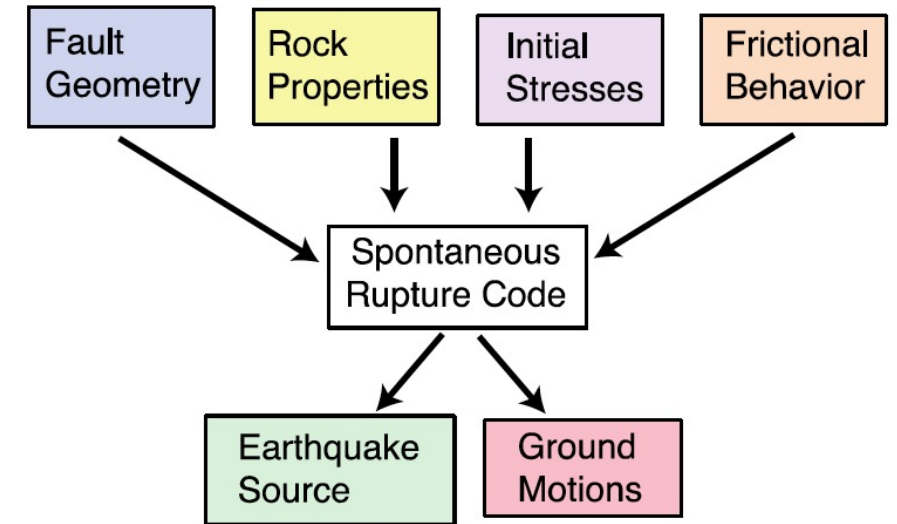
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First published: 17 January 2021 | <https://doi.org/10.1029/2020JB020577>

3D dynamic earthquake rupture simulations including 3D geology and 3D geometry to investigate physics-based scenarios of large earthquakes on the Rodgers Creek, Hayward, Calaveras, and Northern Calaveras faults.

- rock properties affect the locations and amount of slip produced in simulated large earthquakes
- rupture behavior is controlled by nucleation locations and fault geometry

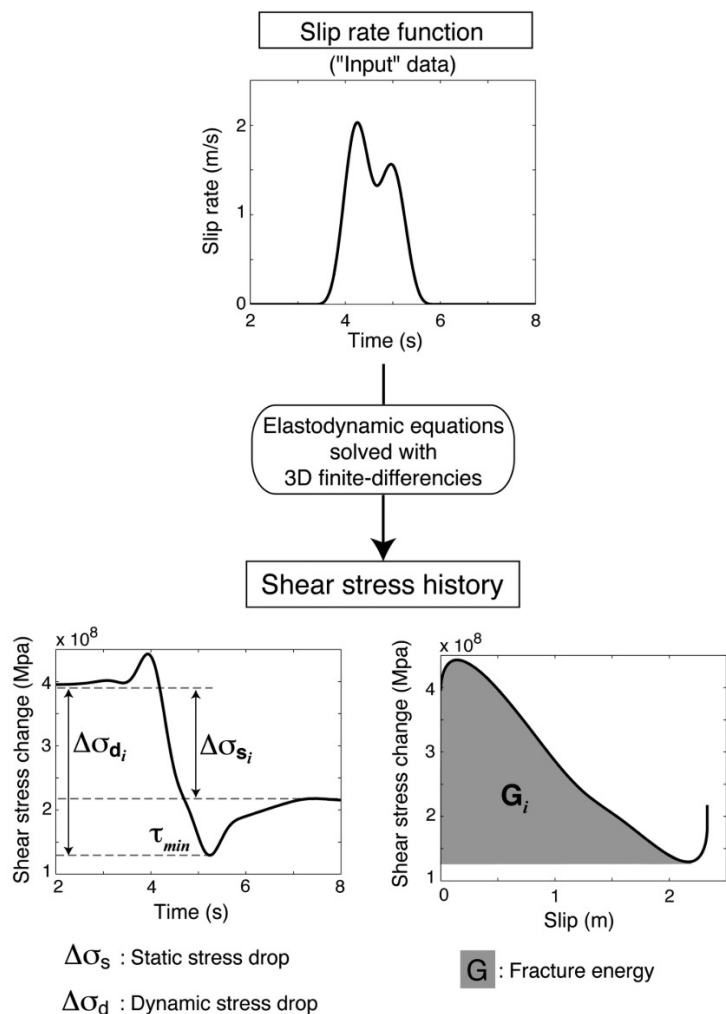
Spontaneous Earthquake Rupture Simulation



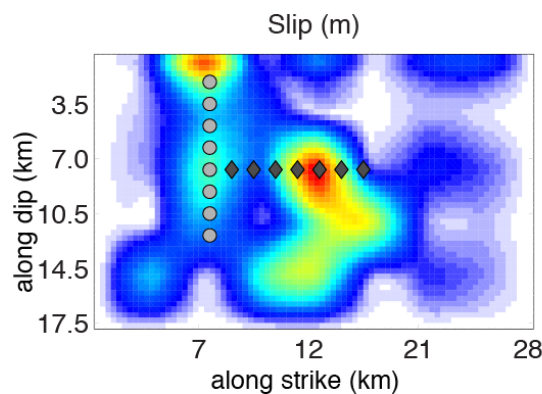
Main motivations

Dynamic parameters from kinematic models

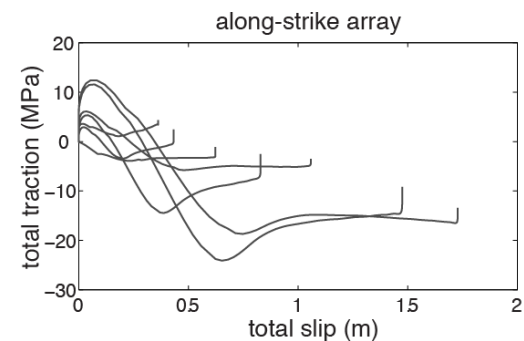
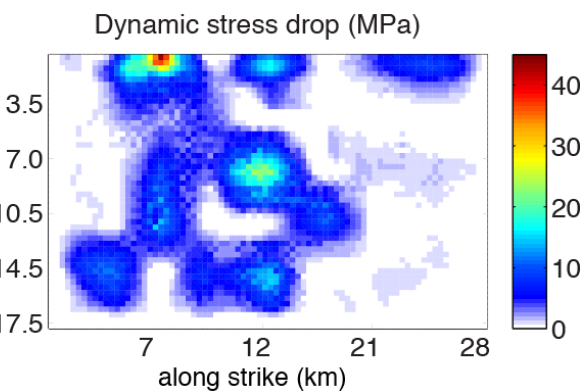
Computation of local dynamic parameters



INPUT



OUTPUT



These models retrieve the dynamic parameters of the slip weakening behavior without any assumption on the constitutive law.

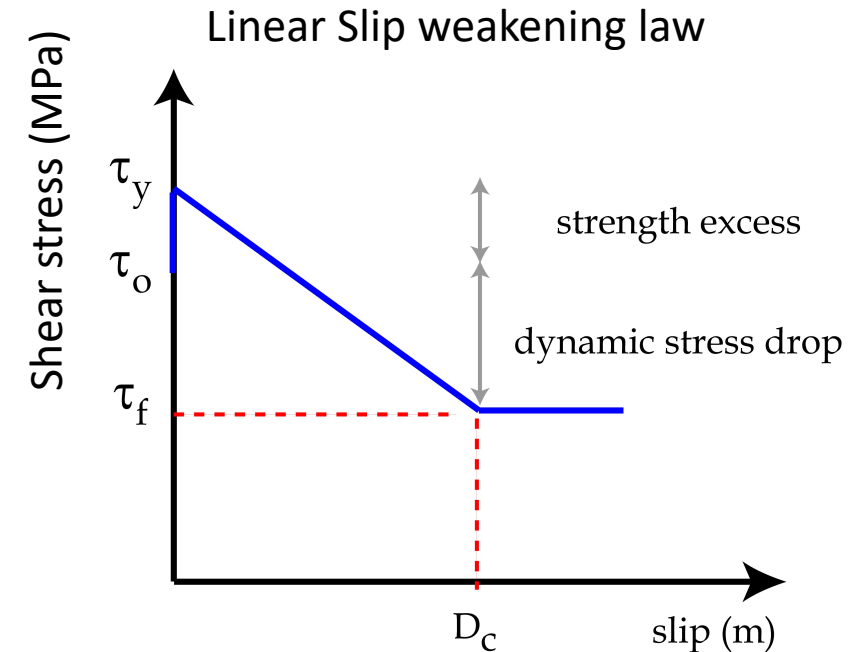
However, these results cannot tell us if the adopted kinematic parameters would allow the models to evolve in spontaneous dynamic ruptures.

Workflow

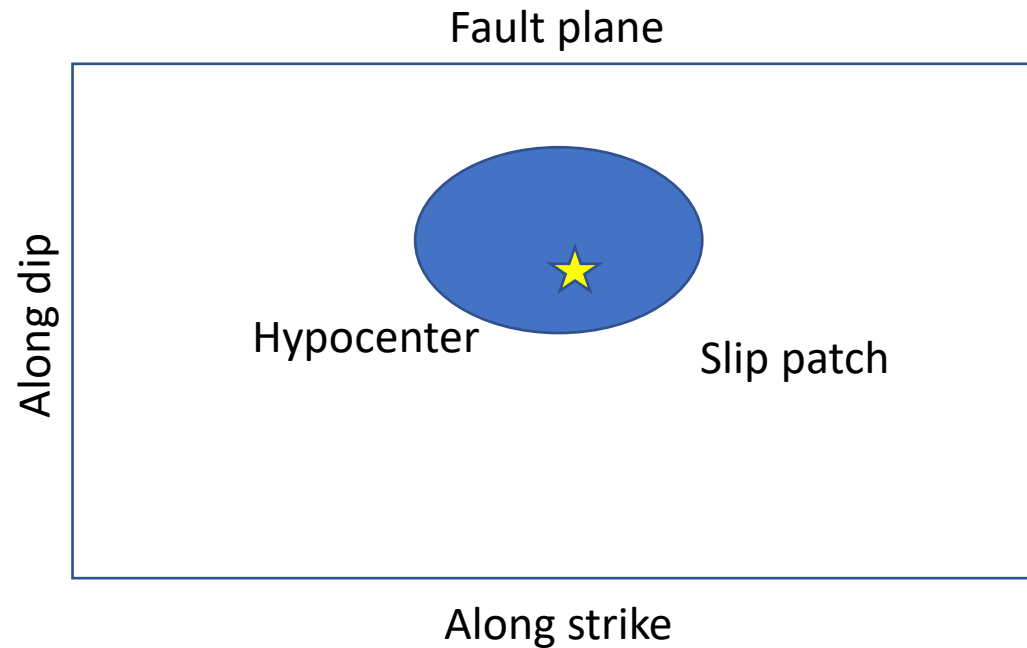
- Ingredients to build dynamic models
- Define families of dynamic models
- Application to the 2016 Norcia earthquake
- Discussions on lithological implications

Setup of dynamic parameters

- **Initial shear stress** τ_0
- **Yield strength:** depends on the static friction $\mu_S \rightarrow \tau_y = \mu_S \sigma_n$
- **Frictional strength:** depends on dynamic friction $\mu_d \rightarrow \tau_f = \mu_d \sigma_n$
- **Stress drop** $\Delta\tau$: $\rightarrow \tau_0 - \tau_f = \Delta\tau$
- **Direction of initial stress on the faults:** correlated with the punctual rake
- **Normal Stress** σ_n : function of depth. Lithostatic or hydrostatic conditions.
- **D_c:** slip weakening distance. Constant or heterogeneous on the fault?



From kinematic models to dynamic ones

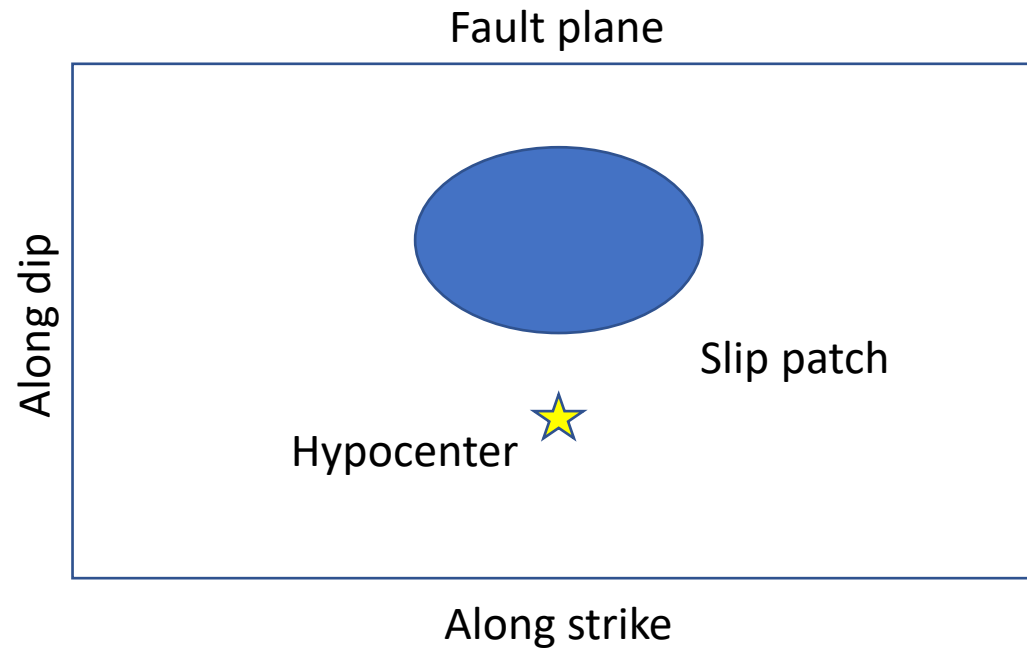


Stress drop would be released in the similar area of the slip patch

If we have a kinematic model with one simple slip patch...

How can be distributed the dynamic parameters describing the slip weakening law?

From kinematic models to dynamic ones



Stress drop would be released in the similar area of the slip patch

Weak nucleation

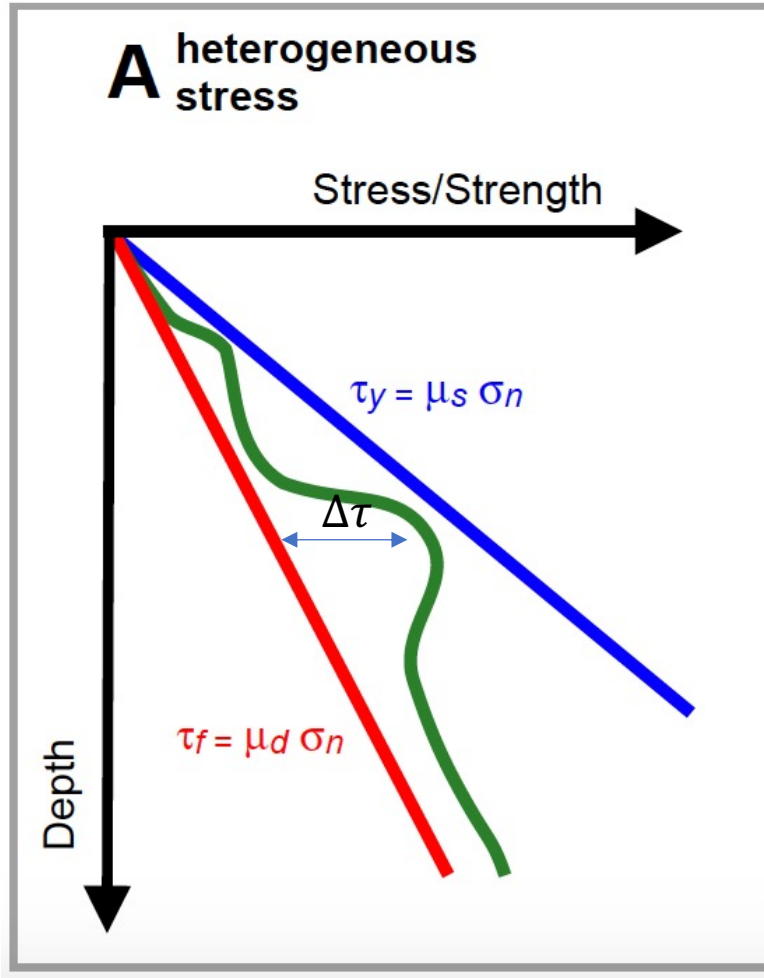
If we have a kinematic model with one simple slip patch...

How can be distributed the dynamic parameters describing the slip weakening law?

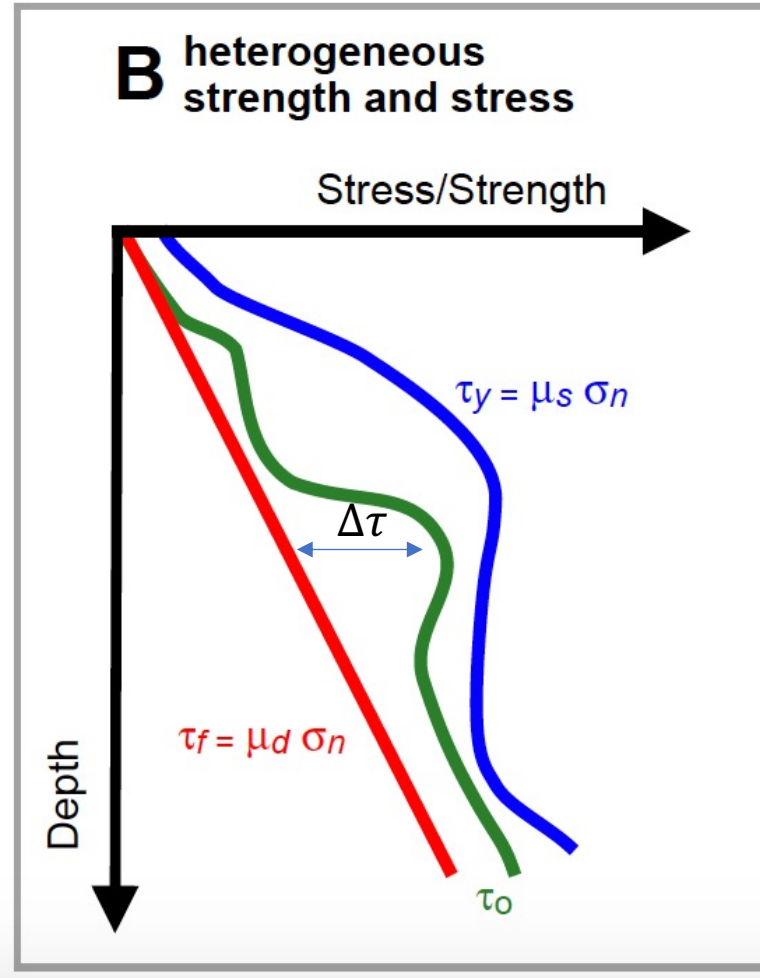
Families of dynamic models

Friction coefficients can be heterogeneous as well as the initial strength condition.

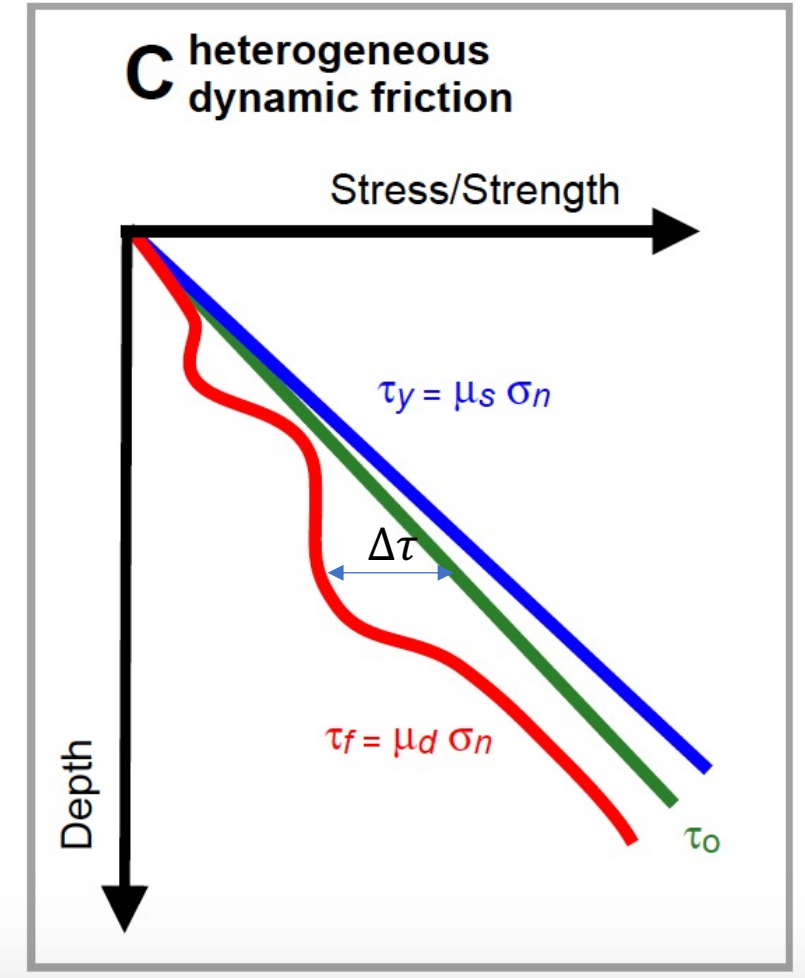
Constant μ_s and μ_d



Constant μ_d and Heterogeneous μ_s



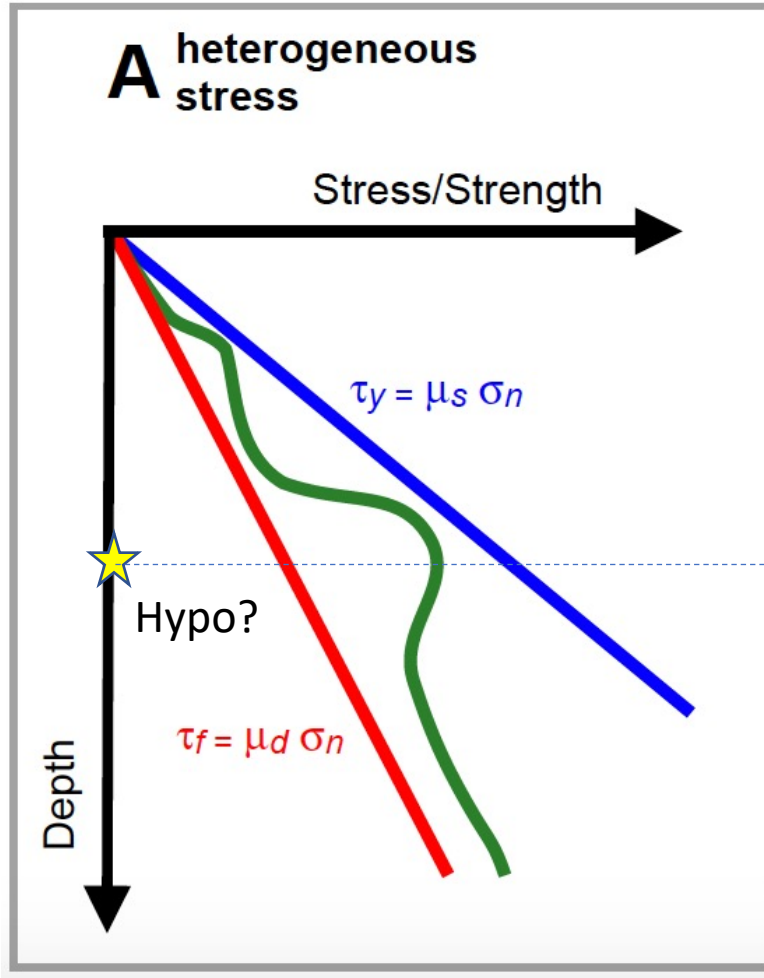
Constant μ_s and Heterogeneous μ_d



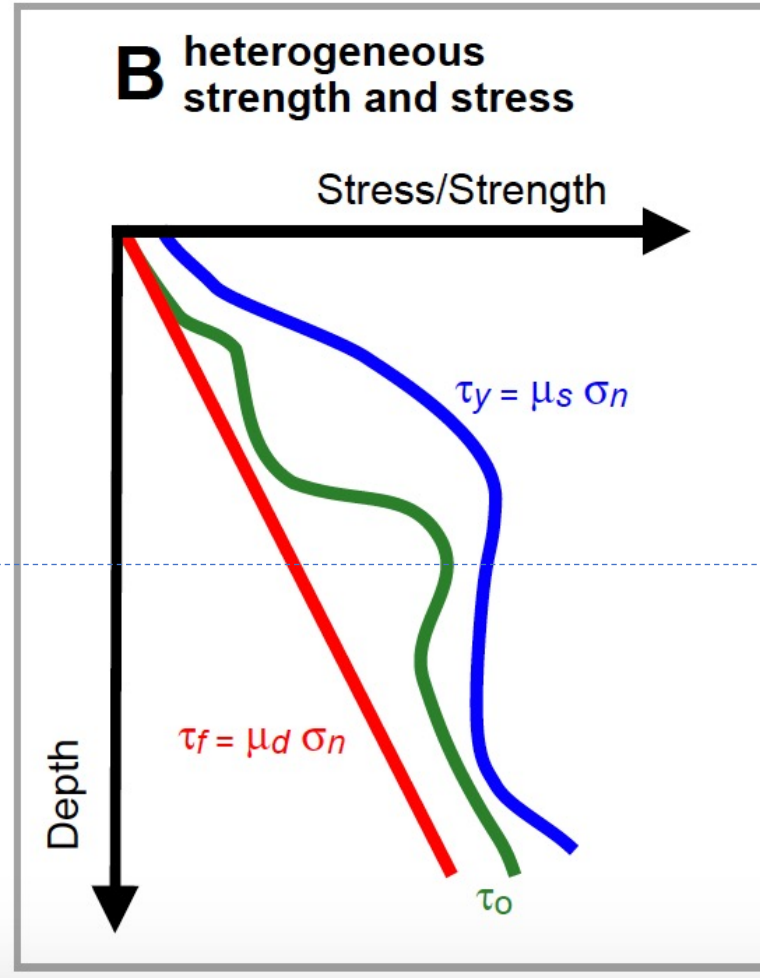
Families of dynamic models

Friction coefficients can be heterogeneous as well as the initial strength condition.

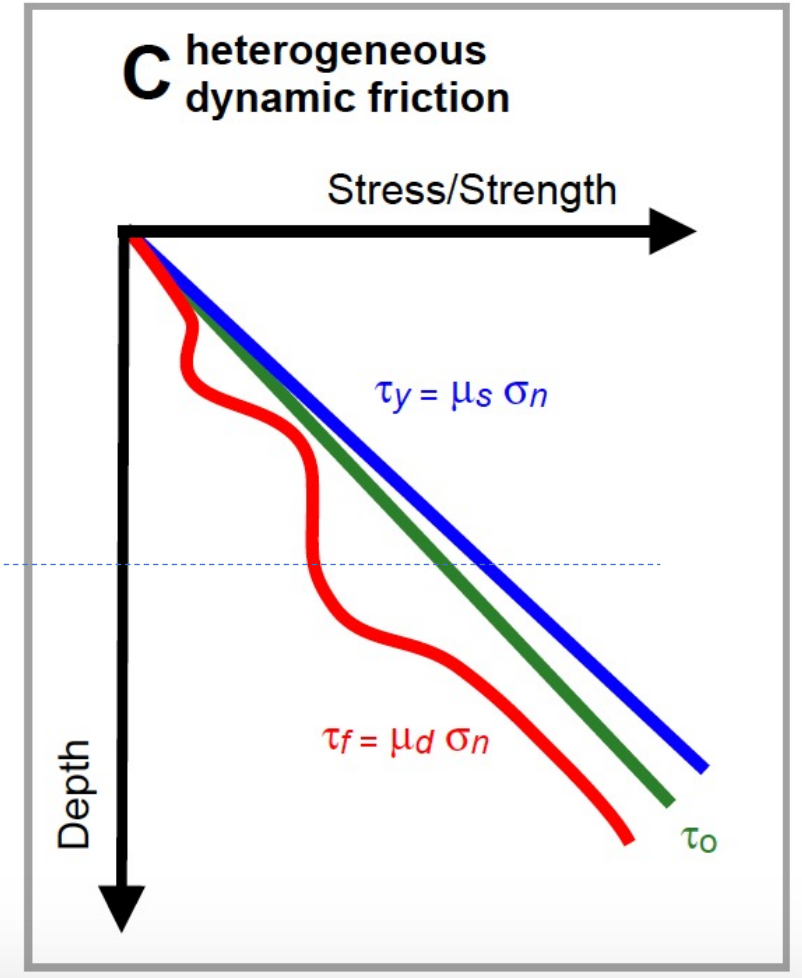
Constant μ_s and μ_d



Constant μ_d and Heterogeneous μ_s



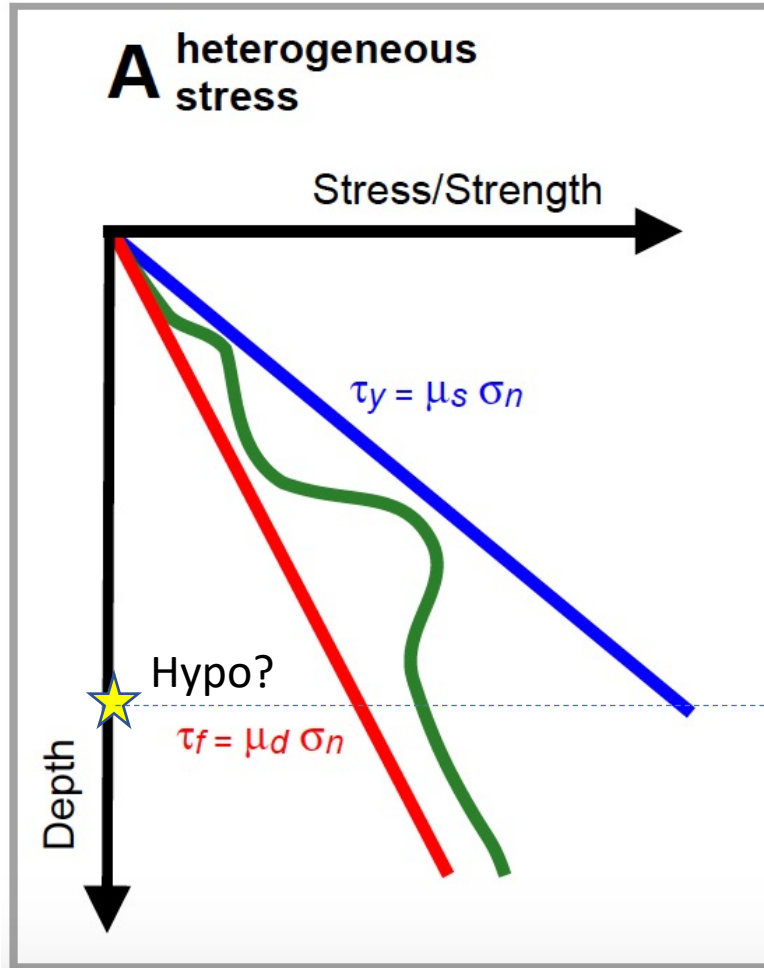
Constant μ_s and Heterogeneous μ_d



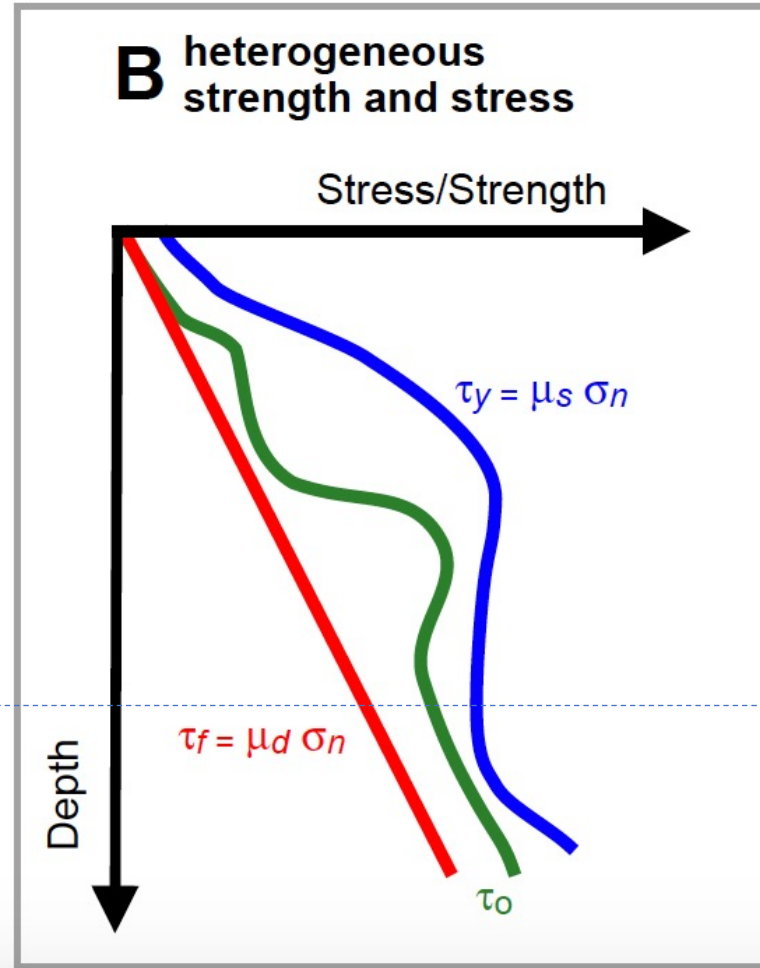
Families of dynamic models

Friction coefficients can be heterogeneous as well as the initial strength condition.

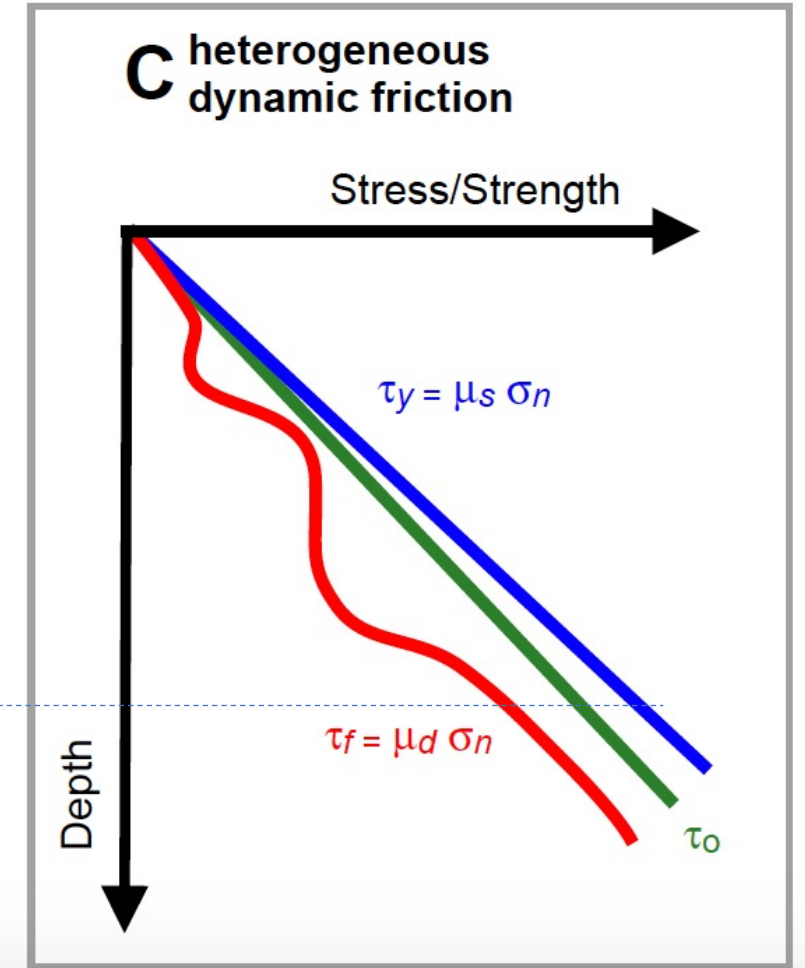
Constant μ_s and μ_d



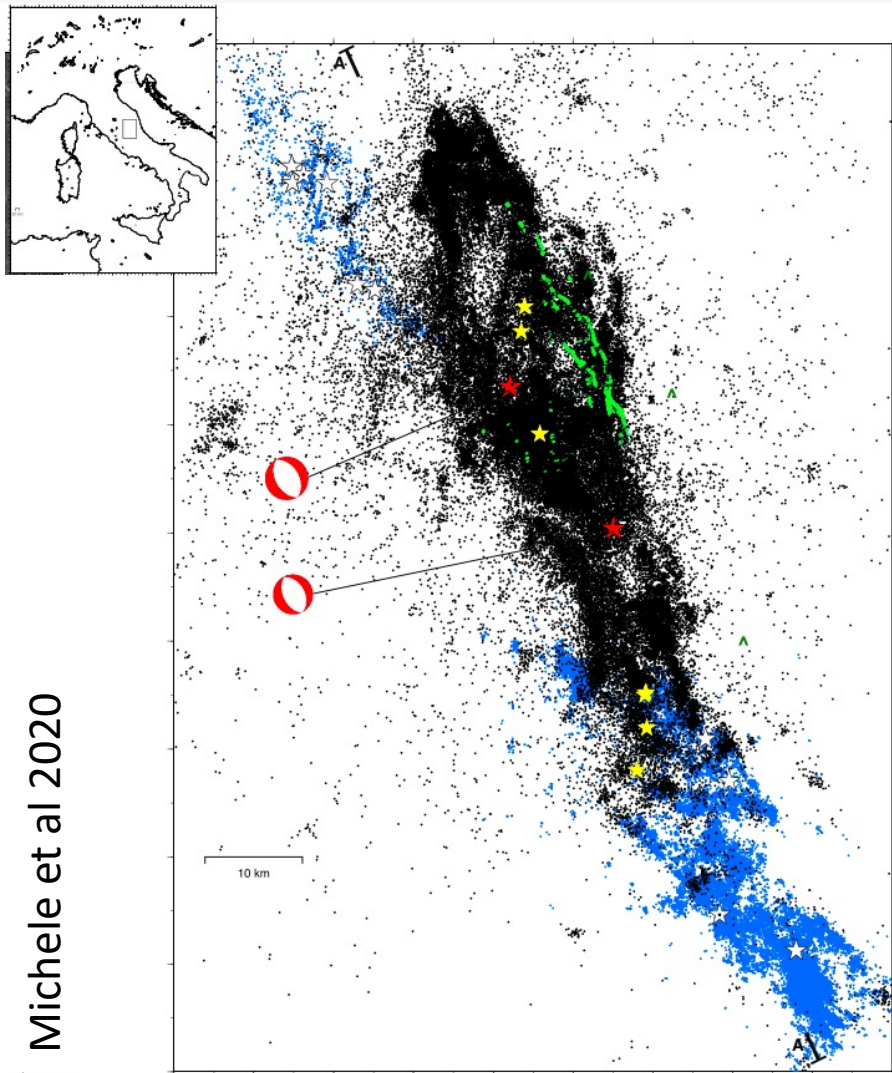
Constant μ_d and Heterogeneous μ_s



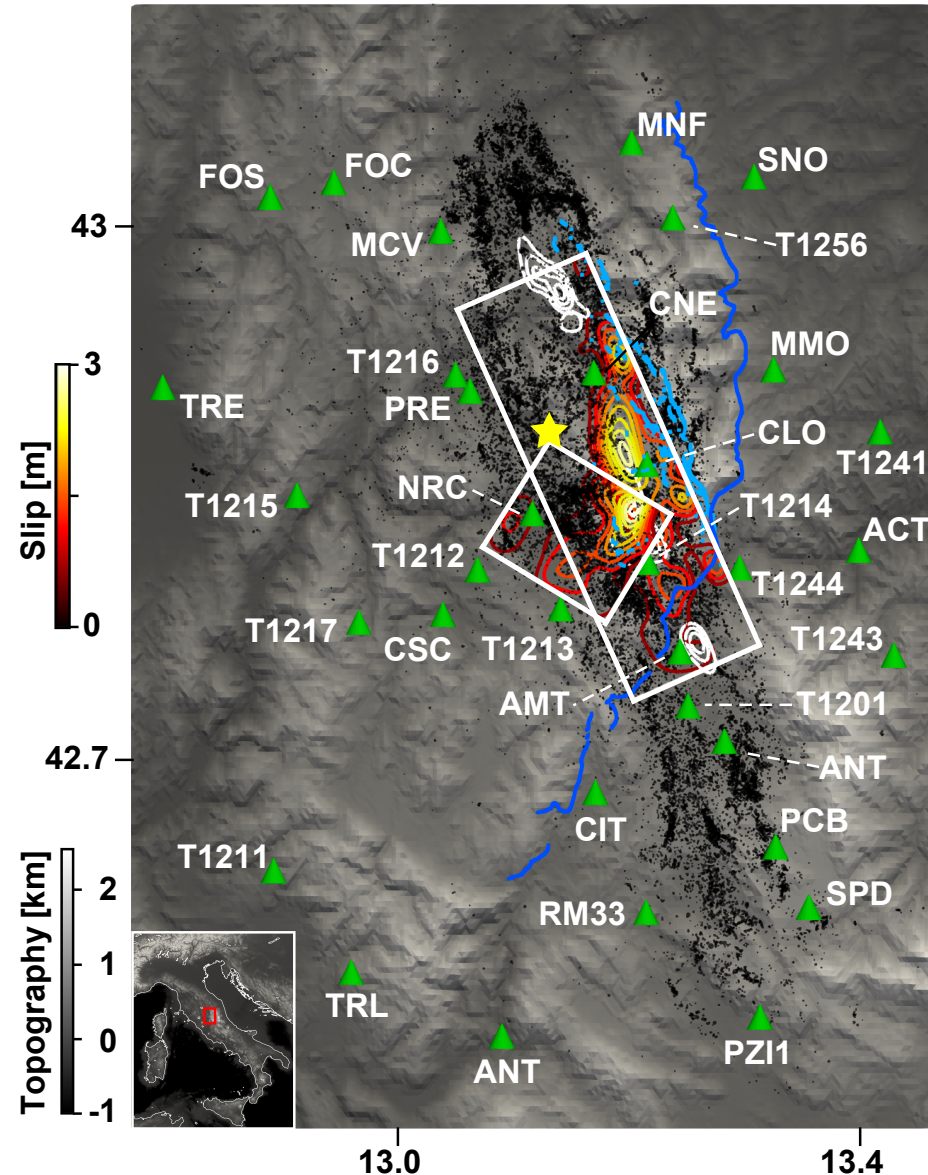
Constant μ_s and Heterogeneous μ_d



Case study: The Mw 6.5, 30 October 2016, Norcia event



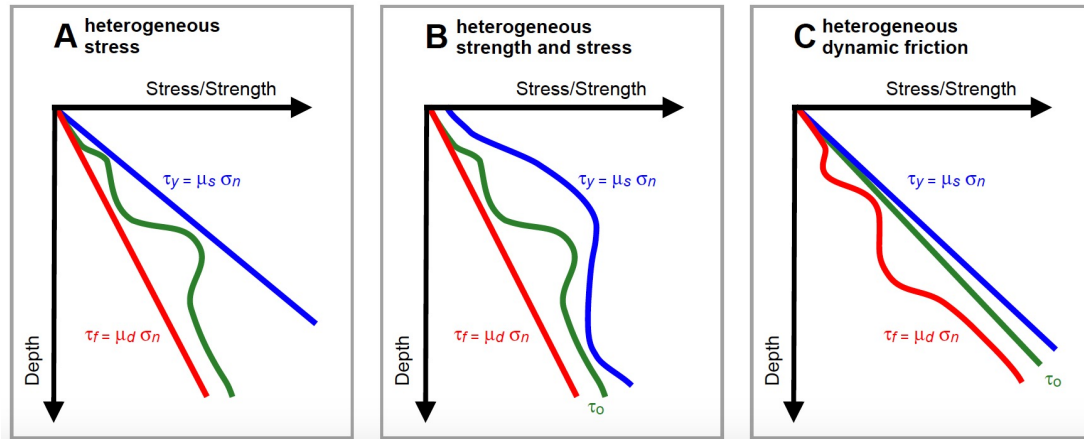
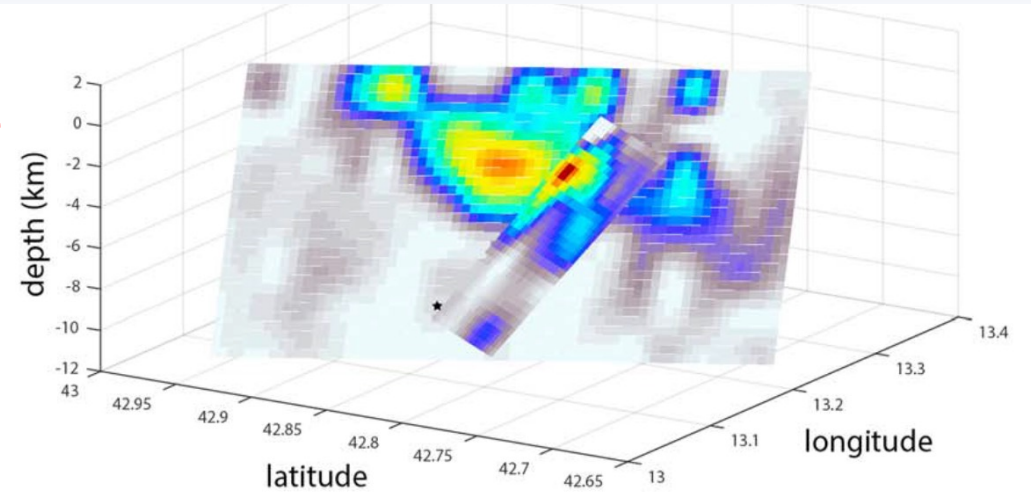
Michele et al 2020



Location of the closest strong motion stations. Colored contours represent the kinematic models proposed by Scognamiglio et al 2018

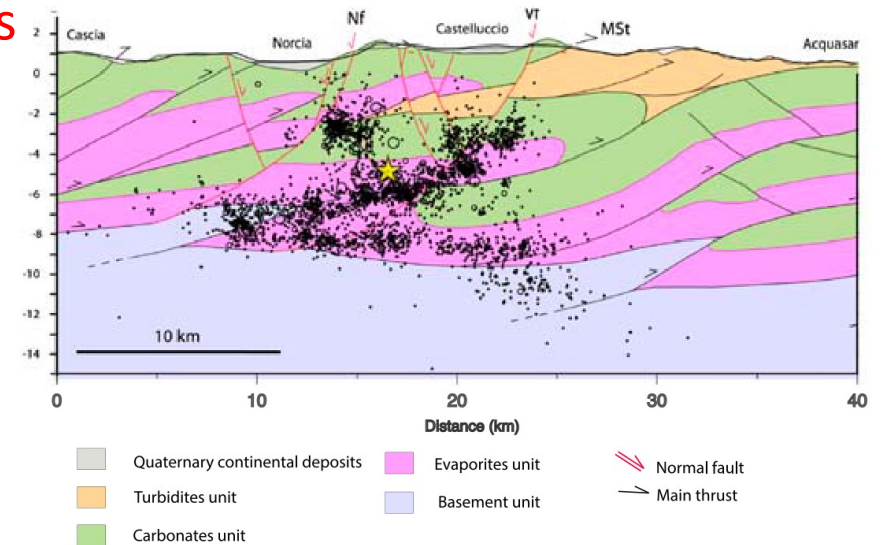
Case study: The Mw 6.5, 30 October 2016, Norcia event

- To validate the mechanical viability a kinematic rupture model proposed for the Mw 6.5, 30 October 2016 Norcia earthquake



- To introduce the “Families” of dynamic models characterized by a different parameterization of heterogeneities

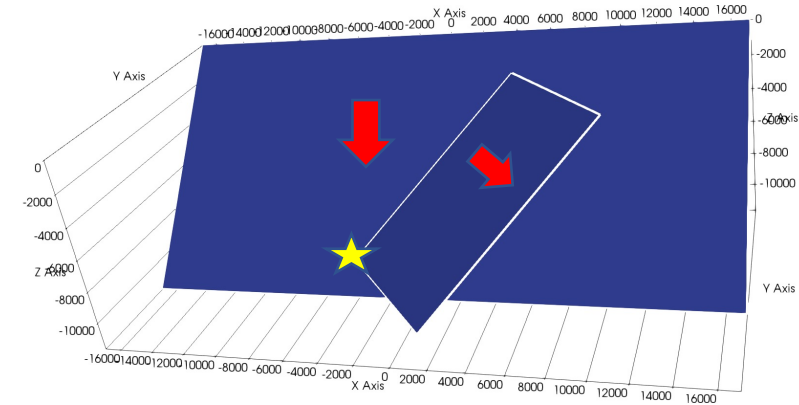
- To discuss the geological and lithological implications on the retrieved friction parameters



Questions: is this model dynamically consistent?

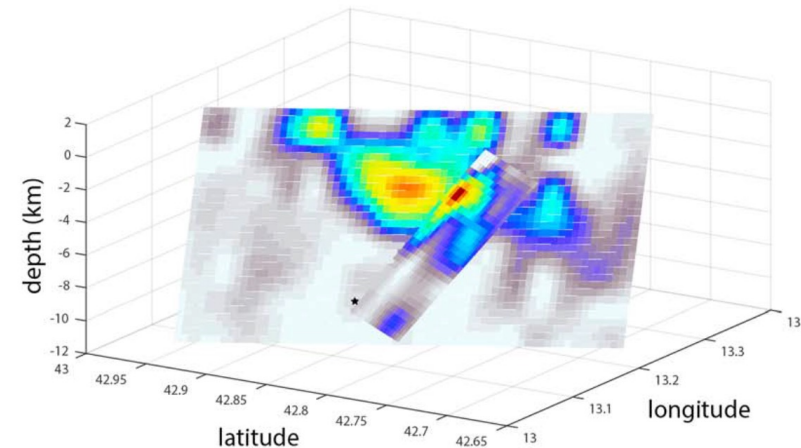
1) «FIRST ORDER»

- If fault **geometry** allows for a simultaneous rupture on both the fault planes
- If the different **rake** allows spontaneous dynamic ruptures (-90° main fault; -10° secondary fault)
- the **unfavored secondary fault** (36° of dip) can host the rupture
- it is possible to propagate the rupture **south of the intersection** with the secondary one



2) «SECOND ORDER»

- Check the mechanical viability of this specific kinematic rupture model
- there are any preferred models (**families**) to which to associate the dynamic heterogeneities reproducing specific kinematic characteristics
- the geological and lithological implications on the retrieved friction parameters



SeisSol software for 3D dynamic simulations

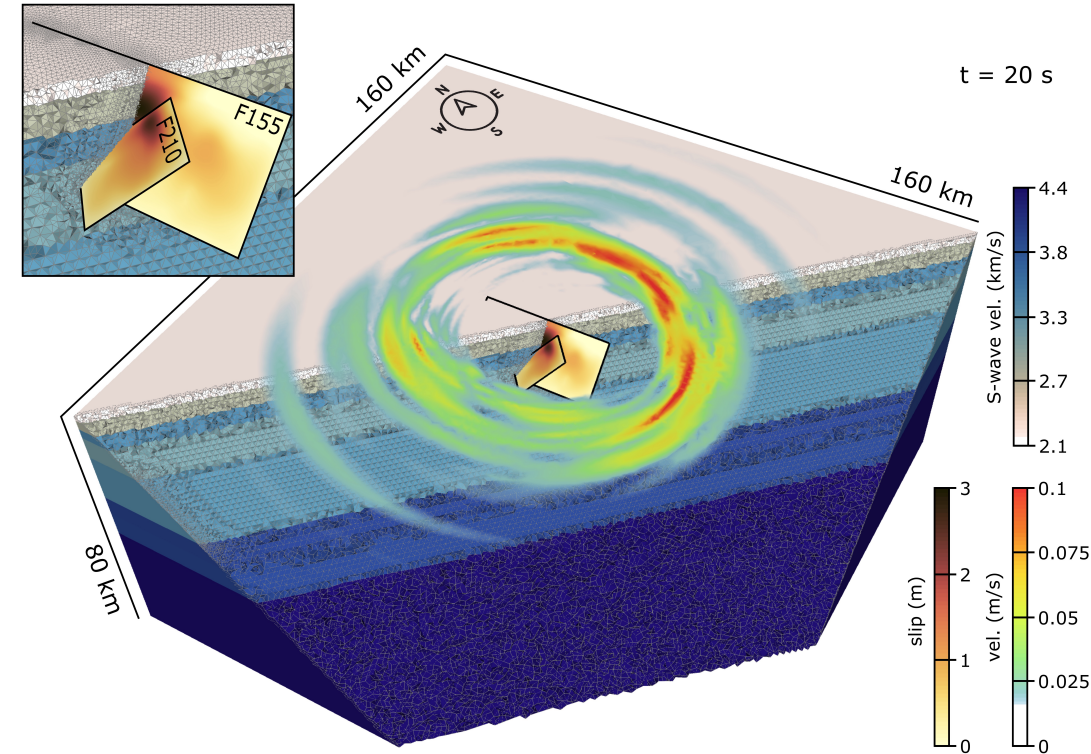
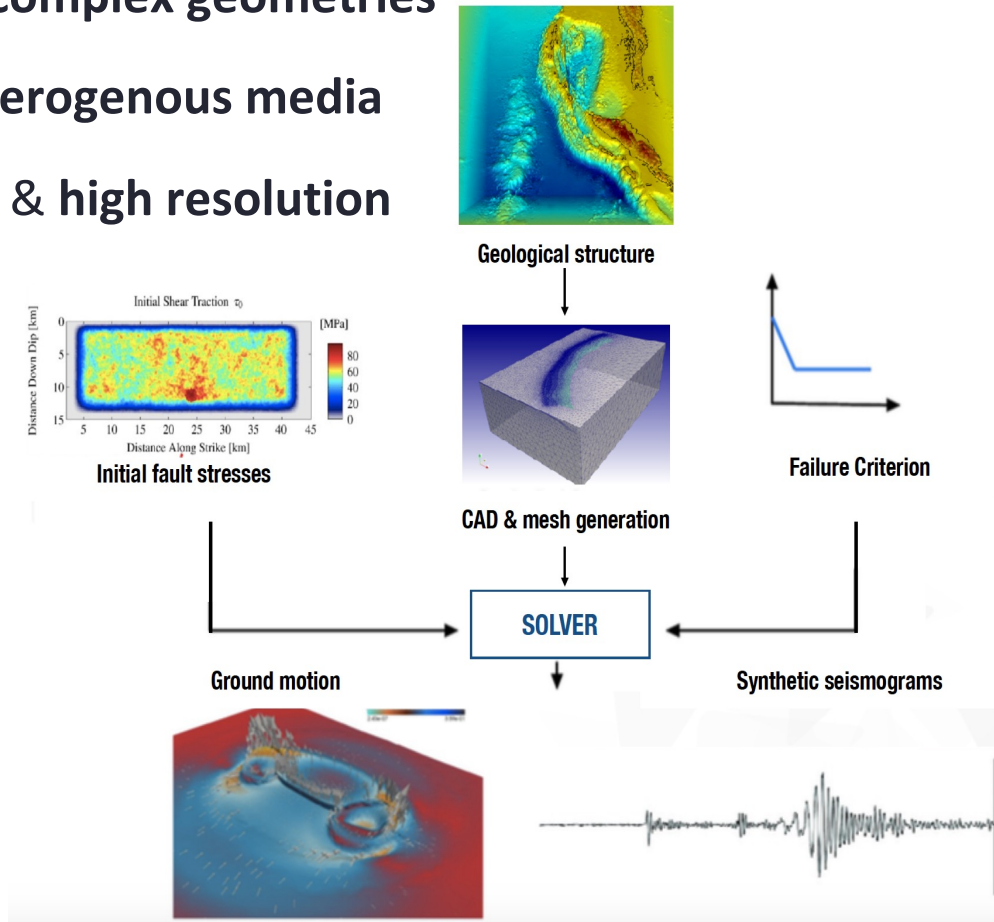
SeisSol is a software package for simulating, with unstructured tetrahedral meshes, wave propagation and dynamic rupture based on the arbitrary high-order accurate derivative discontinuous Galerkin method

This method has a lot of capabilities and in particular it permits:

representing **complex geometries**

modelling **heterogenous media**

high accuracy & high resolution

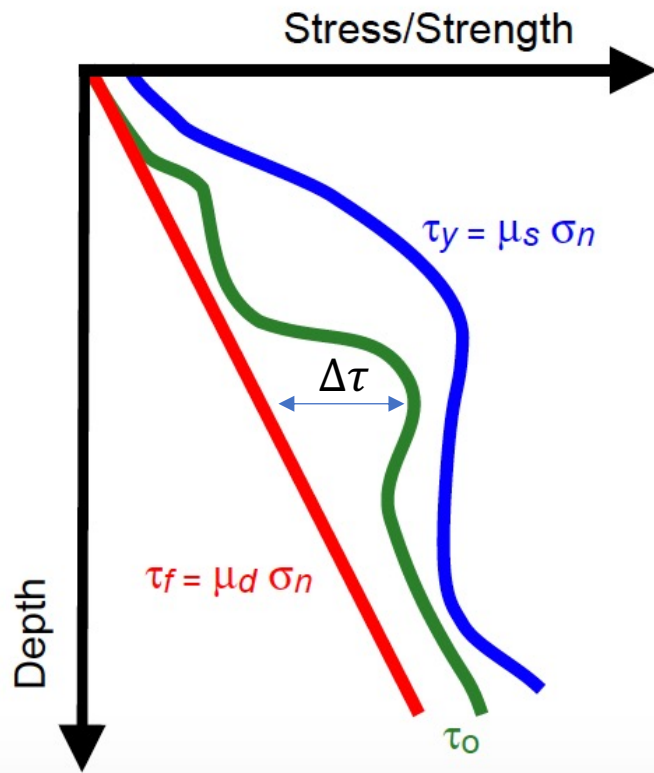


In this work we do not model complex geometries because the fault surfaces are simplified with two planes. We allow the rupture on two intersecting faults, e.g., we treat fault branching geometries.

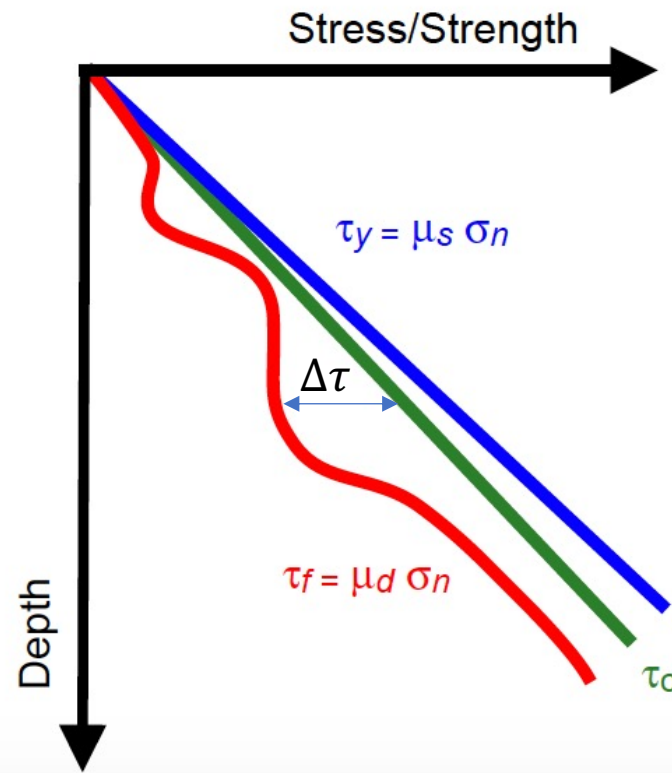
Results – heterogeneous initial conditions

Friction coefficients can be heterogeneous as well as the initial strength condition.

B heterogeneous strength and stress



C heterogeneous dynamic friction



➤ How to impose D_c ?

➤ How to impose stress drop?

Results – heterogeneous initial conditions

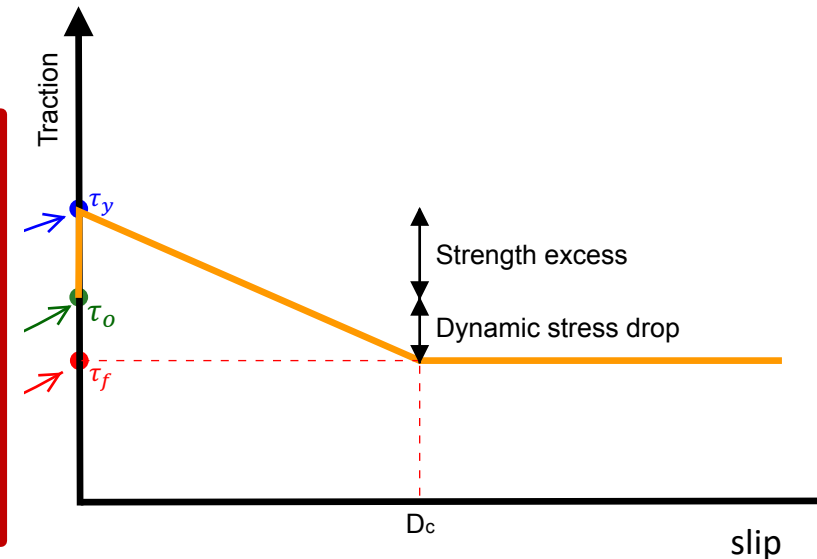
Dc can be assumed spatially constant or heterogeneous

- In the literature, D_c is one of the most difficult parameters to constrain
- Many authors discussed the potential biases in estimating this parameter from seismological data due to limited frequency band
- D_c can be affected by temperature-induced dynamic weakening

For this particular event a constant D_c value does not allow recovering a realistic rupture:

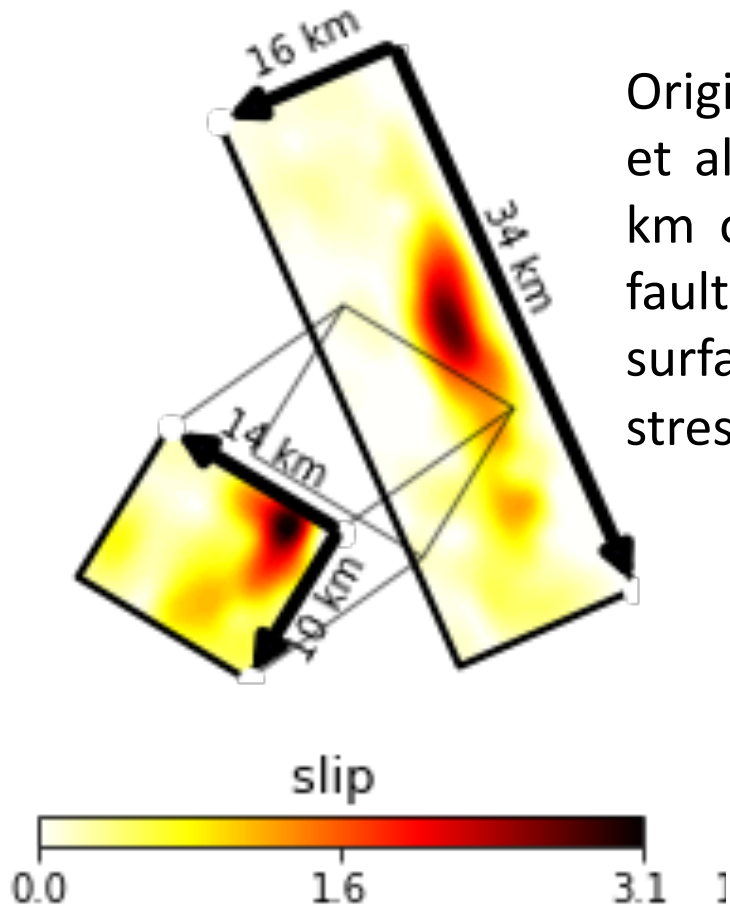
Imposing a constant value of $D_c \sim < 50$ cm leads models to super-shear rupture velocities;

Imposing a constant value of $D_c \sim > 50$ cm tends to prevent the rupture since not enough energy is available.



Results – heterogeneous initial conditions

Dc distribution proportional to slip

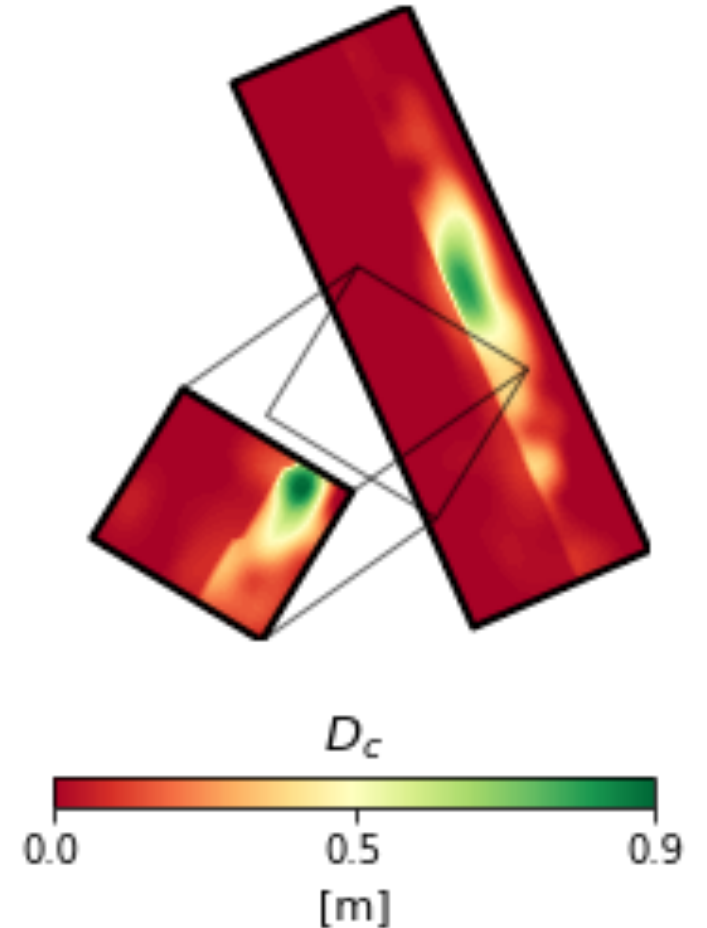


Original slip distribution of Scognamiglio et al 2018. (we only remove the first 2 km of fault patches to avoid significant fault reactivation due to rupture-free-surface interaction and small normal stress)

The distribution of D_c is retrieved from two different constant ratio D_c/slip for different depths:

$D_c/\text{slip}=0.1$ (10%) around the nucleation

$D_c/\text{slip}=0.3$ (30%) at shallow depths where there are the main slip patches.



Results – heterogeneous initial conditions

How to impose the stress drop?

The stress drop distribution corresponding to a prescribed distribution of slip can be retrieved in different ways:

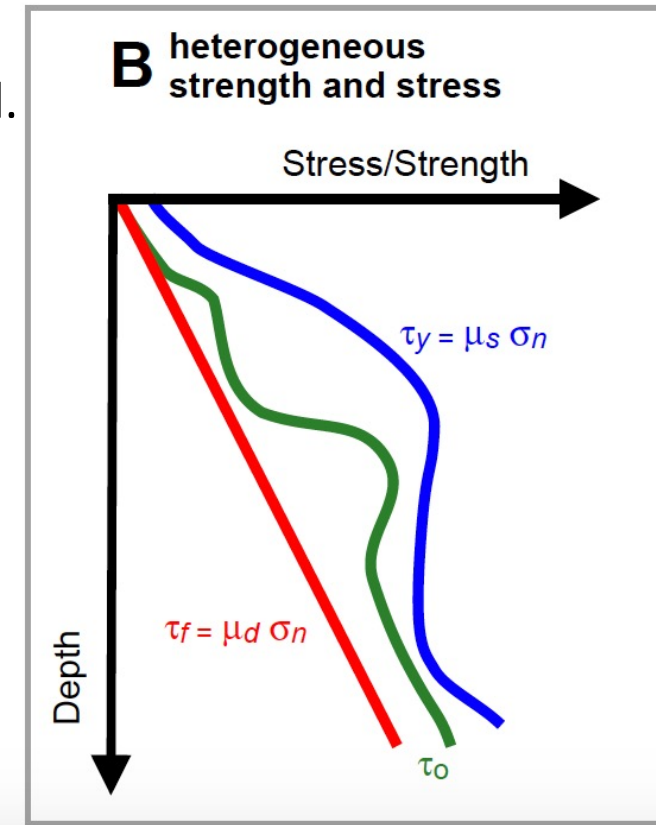
- By relating stress drop and slip in the wave number domain (originally proposed by Andrews 1980 and updated by Mai and Ripperger 2004). This procedure has been further simplified **by assuming the stress drop proportional to the slip.**
- **By solving the elasto-dynamic equation** and using the entire slip-time history at each point of the fault (Ide and Takeo 1997, Bouchon 1997, Tinti et al 2005, Causse et al 2014)

We tested both the procedures but I show only the first one today 😊

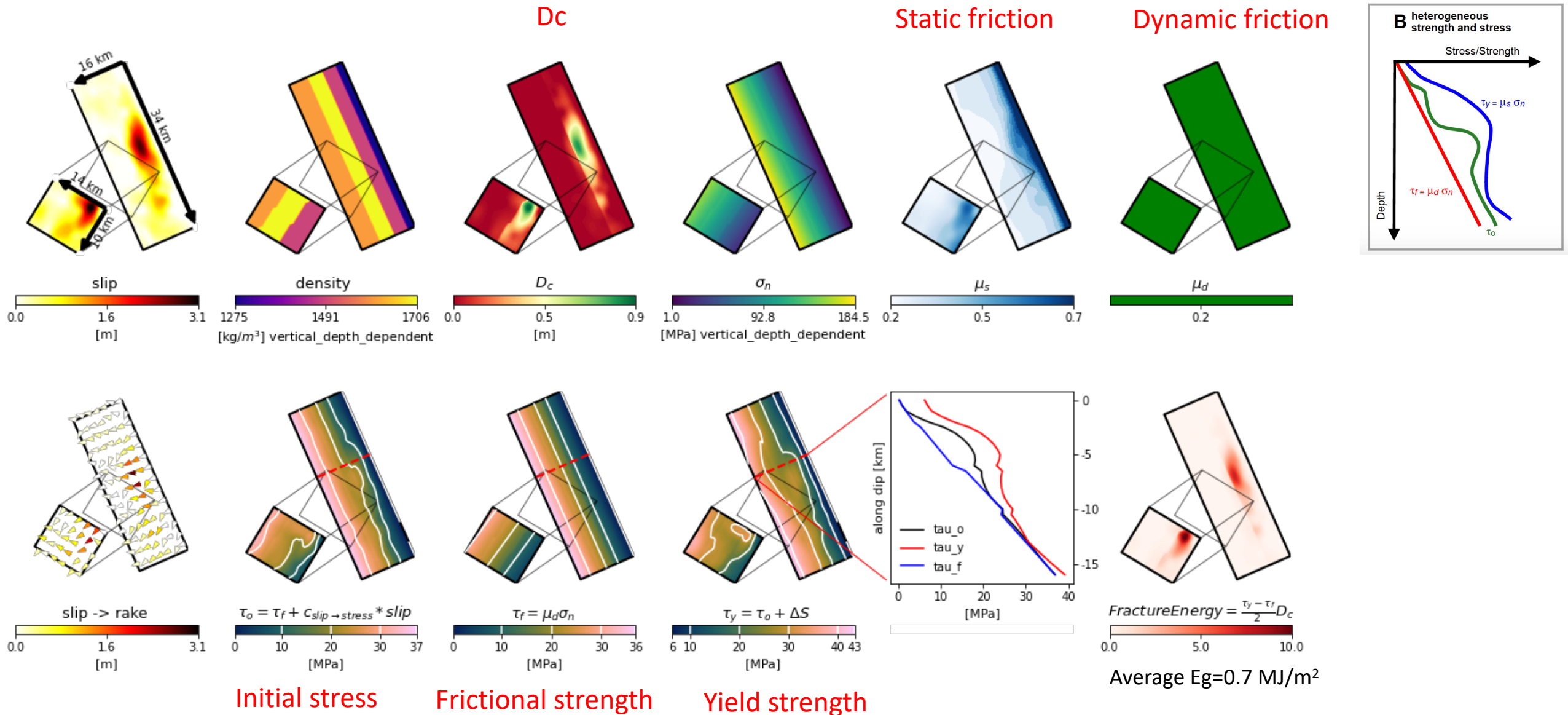
Results- Family of heterogeneous strength and stress

- **Frictional strength:** depends on dynamic friction $\mu_d \rightarrow \tau_f = 0.2 \sigma_n$ **constant**
- **Stress drop** $\Delta\tau (= \tau_0 - \tau_f)$: Proportional to slip distribution of the kinematic model.
- **Initial shear stress** **heterogeneous** $\tau_0 = \Delta\tau + \tau_f$: proportional to slip distribution.
- **Yield strength:** **heterogeneous** on the fault plane \rightarrow strength excess: [0 - 3] Mpa
- **Direction of initial stress on the faults:** Rake from the kinematic model
- **Normal Stress** σ_n : near-hydrostatic pressure. Gradient 16MPa/km.
- **Dc:** slip weakening distance. Dc is a percentage of kinematic slip distribution.

MODEL B

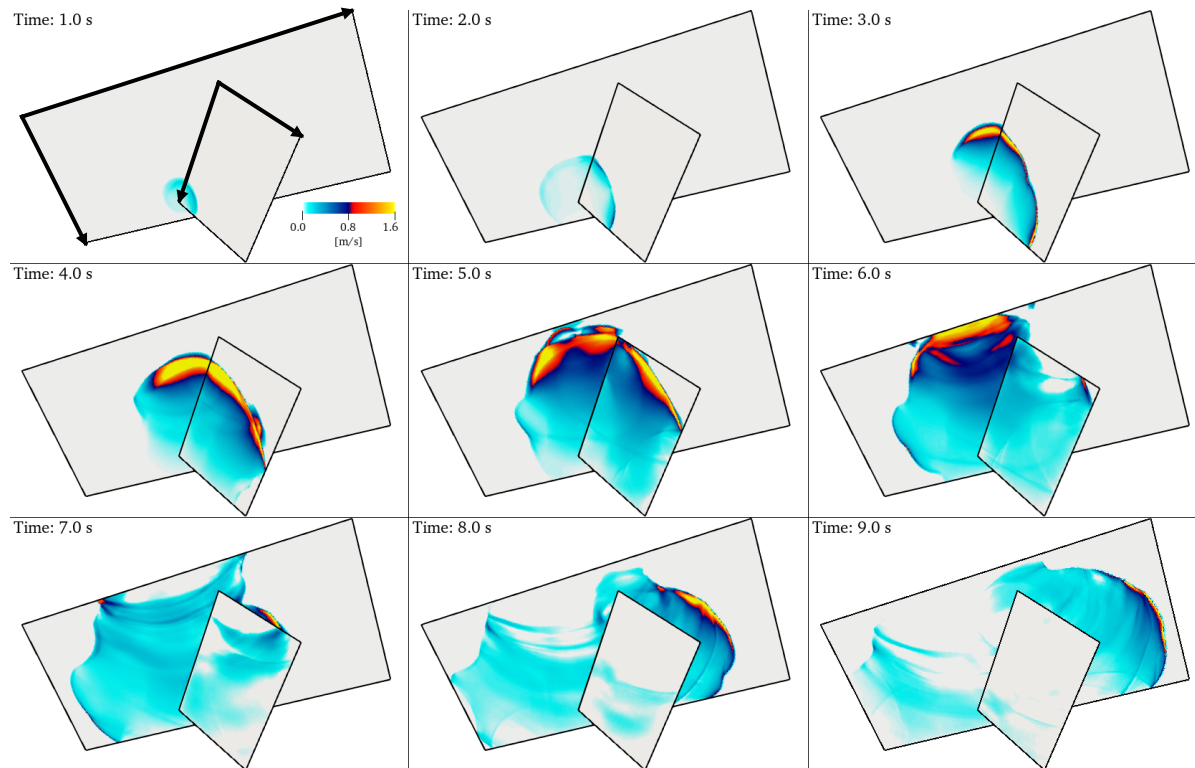


Results- Family of heterogeneous strength and stress

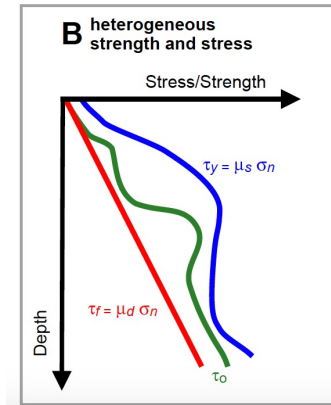
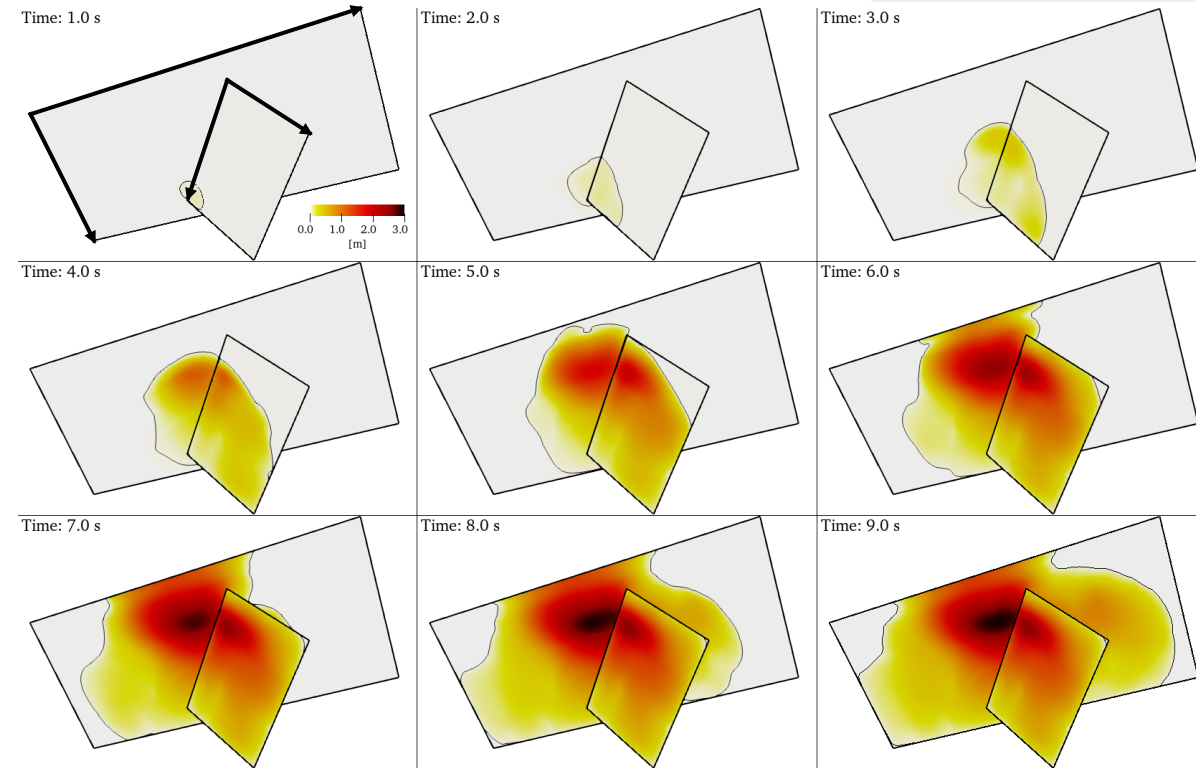


Results- Family of heterogeneous strength and stress

Snapshots of slip rate



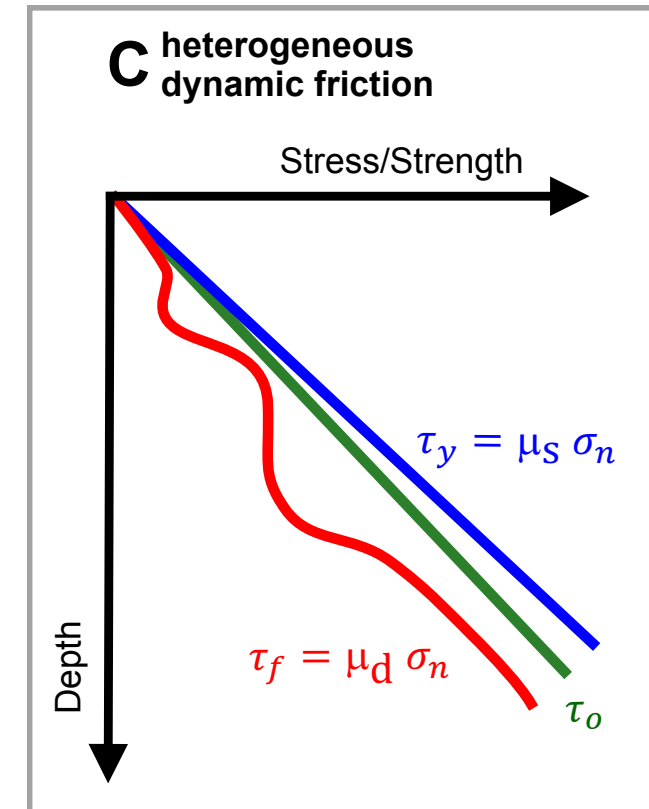
Snapshots of slip



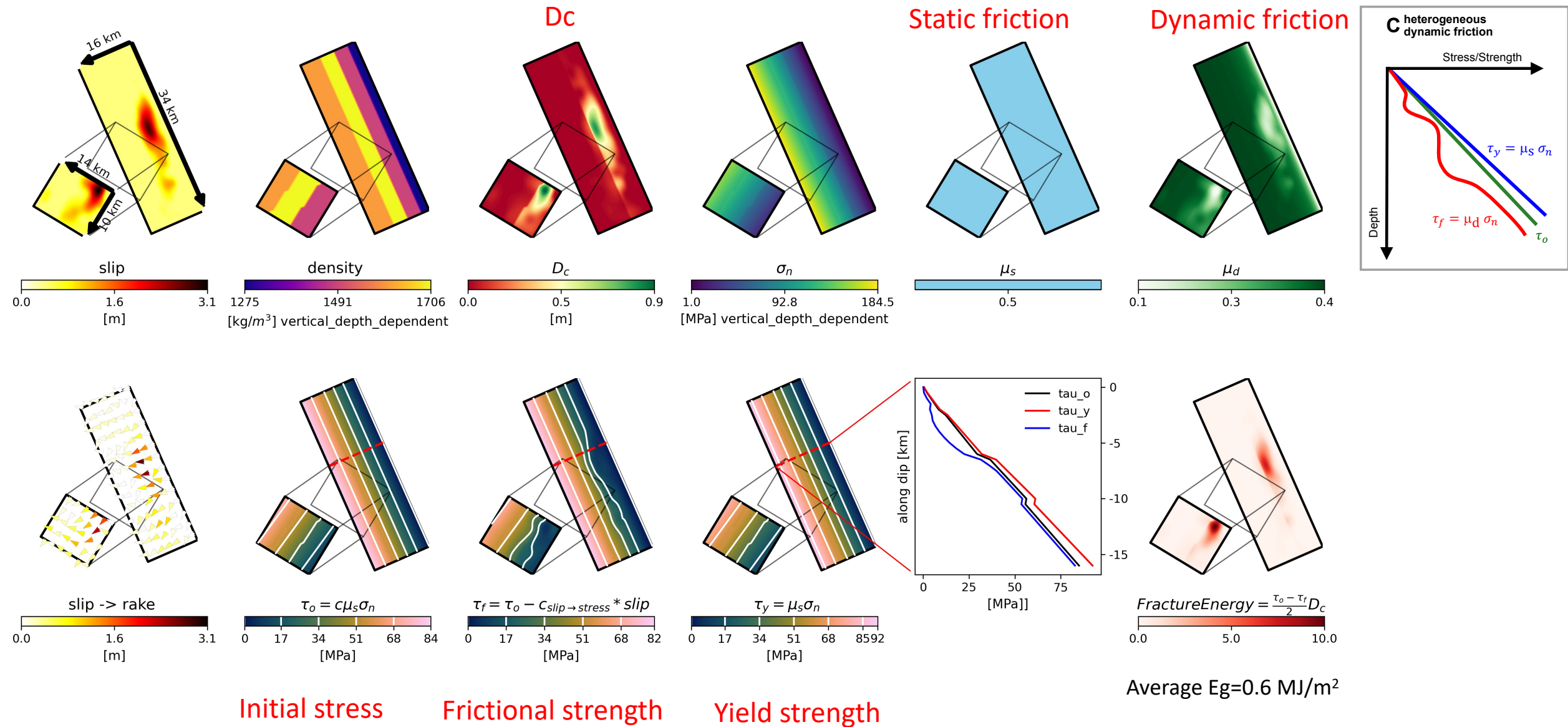
Results – Family of heterogeneous dynamic friction

- **Frictional strength:** $\tau_f = \tau_0 - \Delta\tau$ proportional to slip distribution
dynamic friction $\mu_d \rightarrow$ **heterogeneous**
- **Stress drop** $\Delta\tau$: Proportional to slip distribution of the kinematic model.
- **Initial shear stress** τ_0 (linearly depth dependent) **homogeneous** $\tau_0 = \% \tau_y$
- **Yield strength:** **homogeneous** on the fault plane: $\mu_s = 0.5$
- **Direction of initial stress on the faults:** Rake from the kinematic model
- **Normal Stress** σ_n : near-hydrostatic pressure. Gradient 16MPa/km.
- **Dc:** slip weakening distance. Dc is a percentage of kinematic slip distribution.

MODEL C

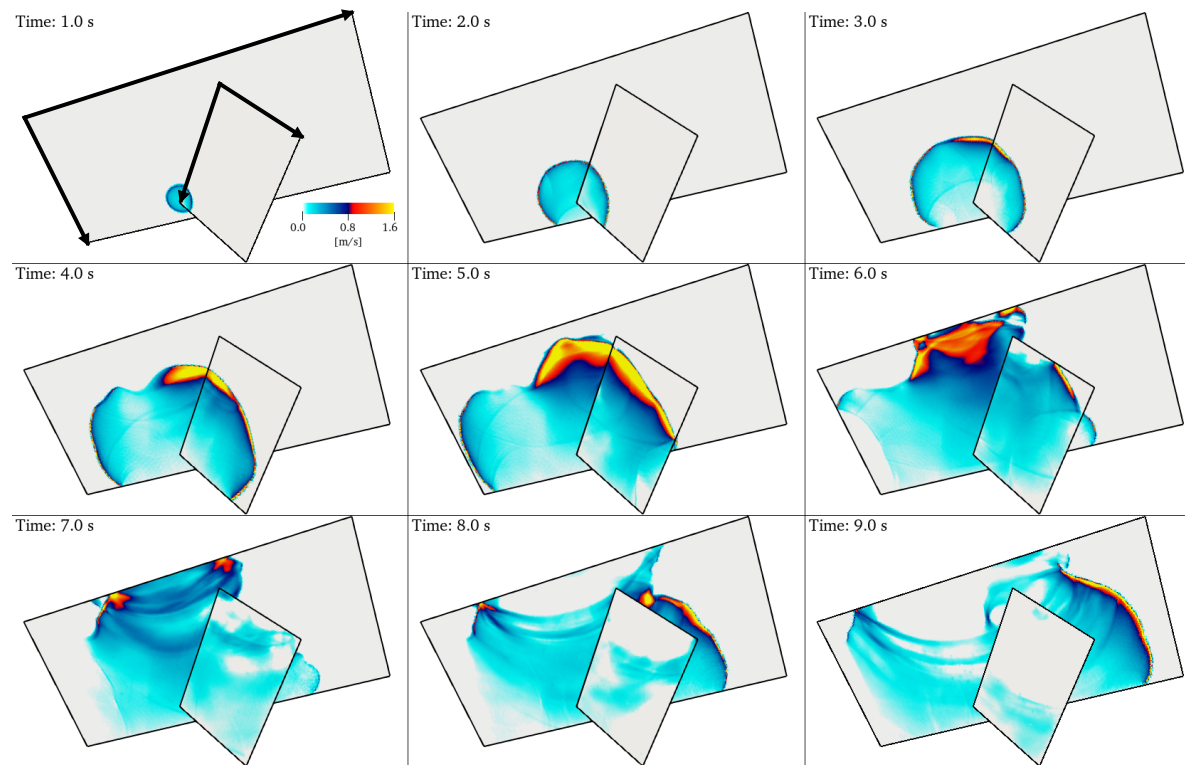


Results - Family of heterogeneous dynamic friction

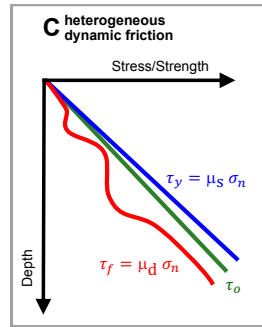
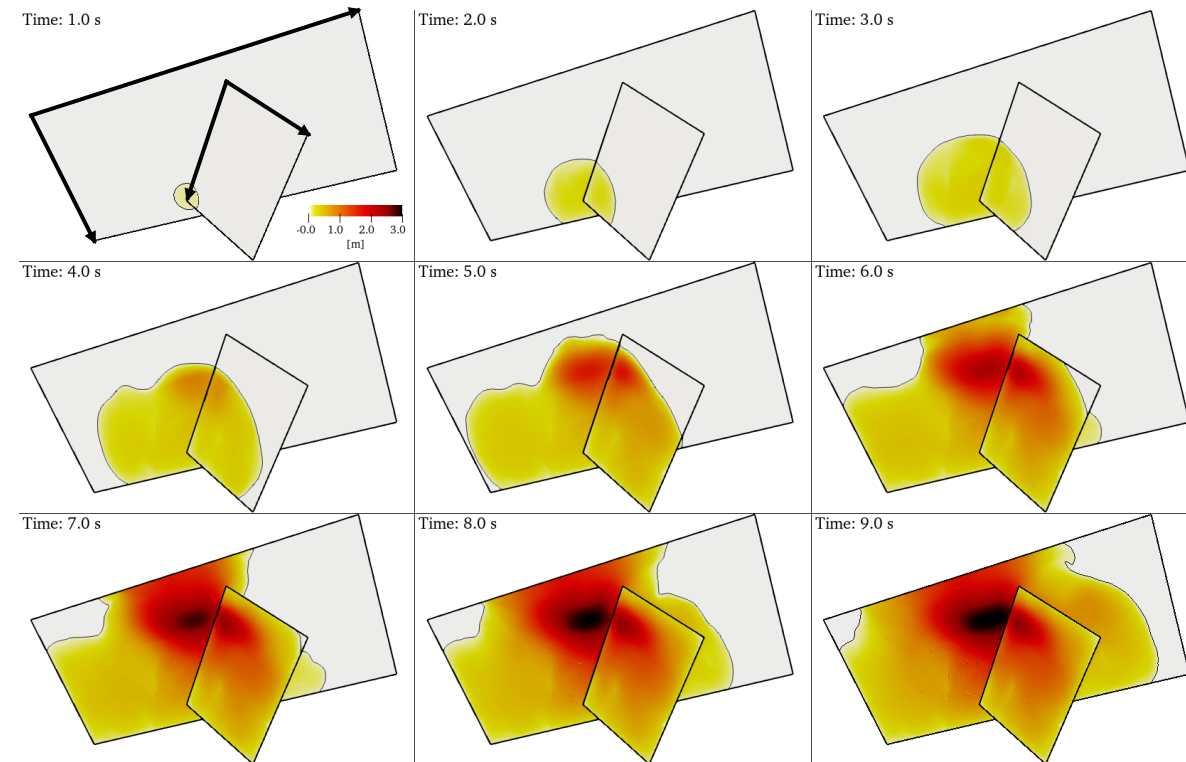


Results - Family of heterogeneous dynamic friction

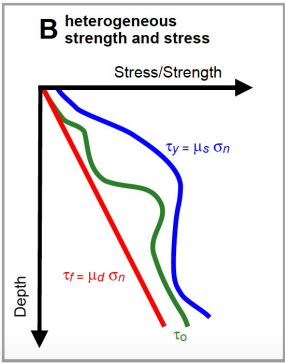
Snapshots of slip rate



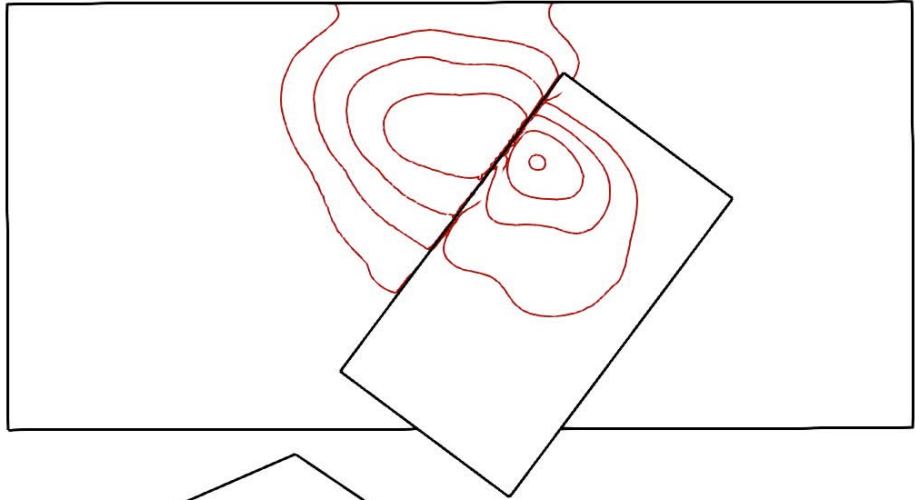
Snapshots of slip



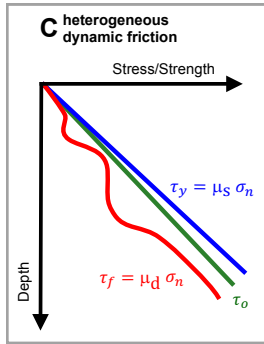
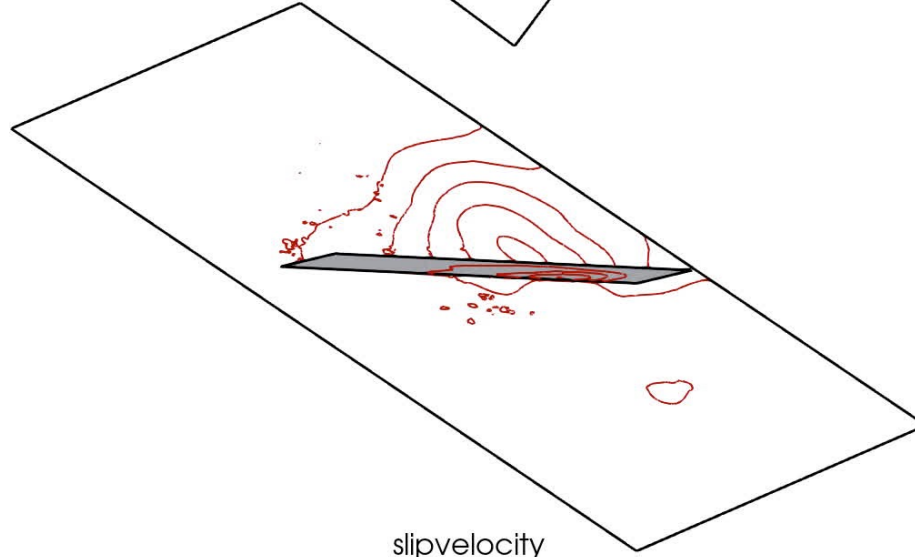
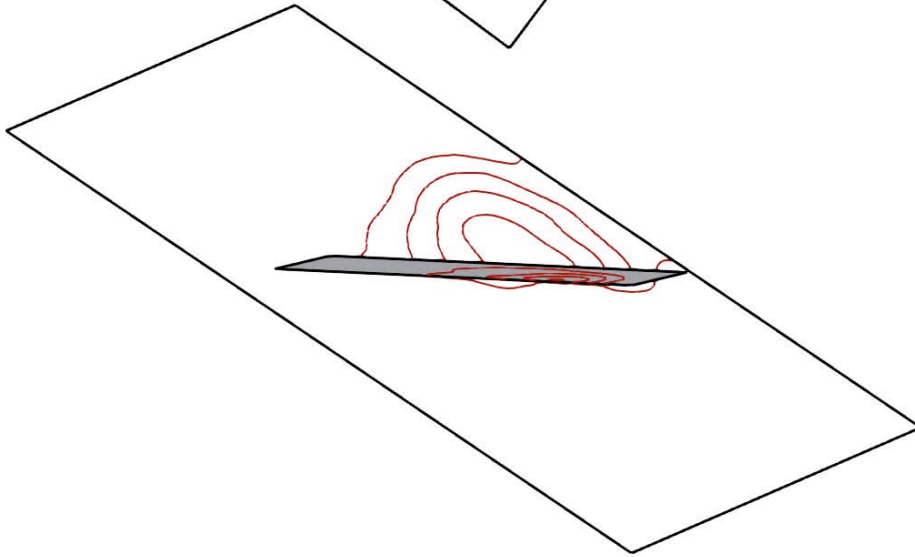
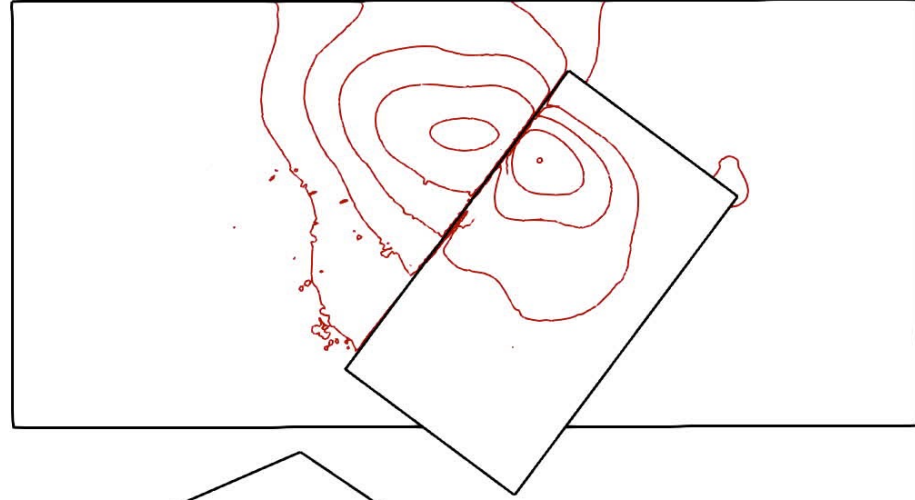
Results - Family of heterogeneous dynamic friction



FB



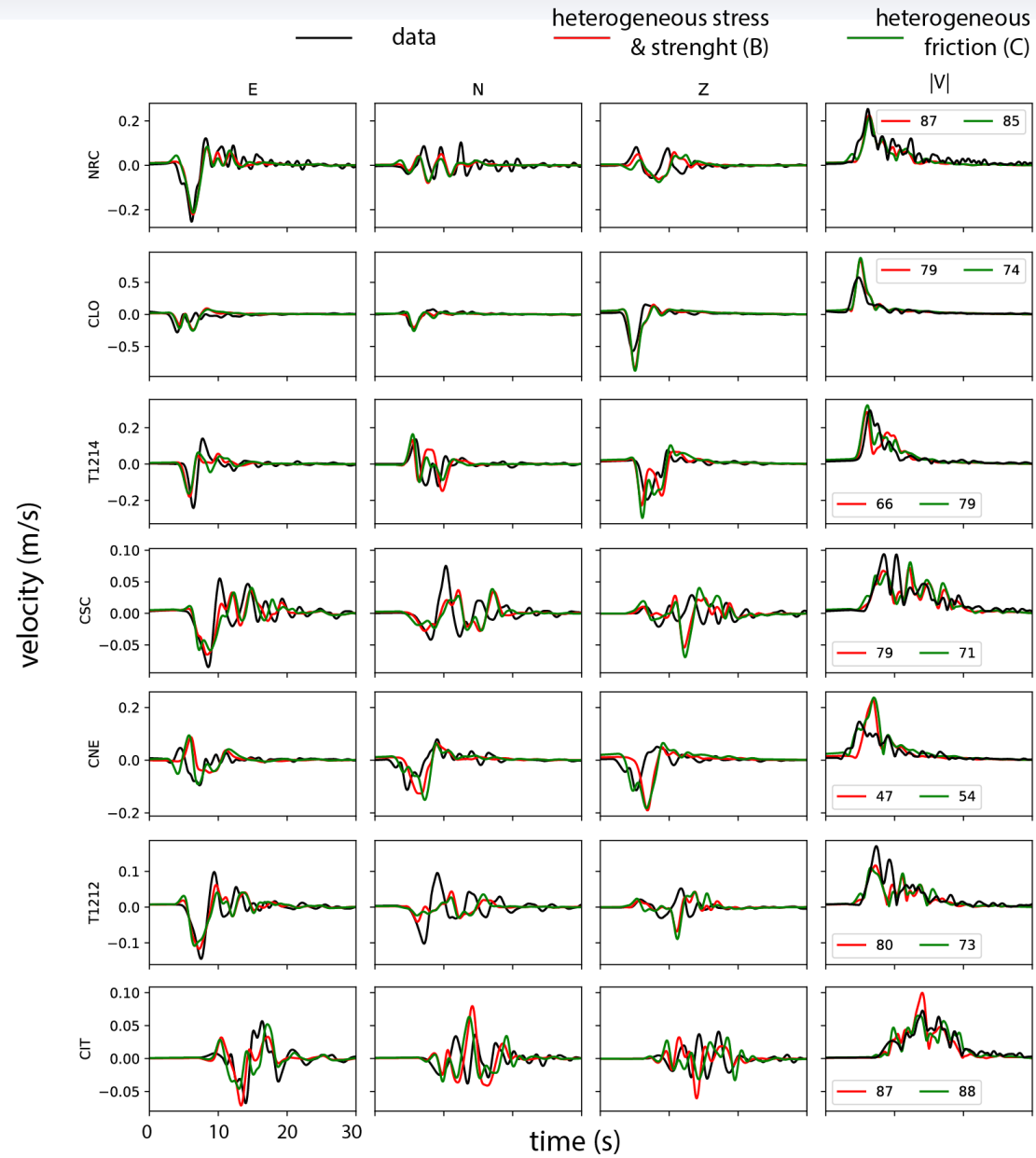
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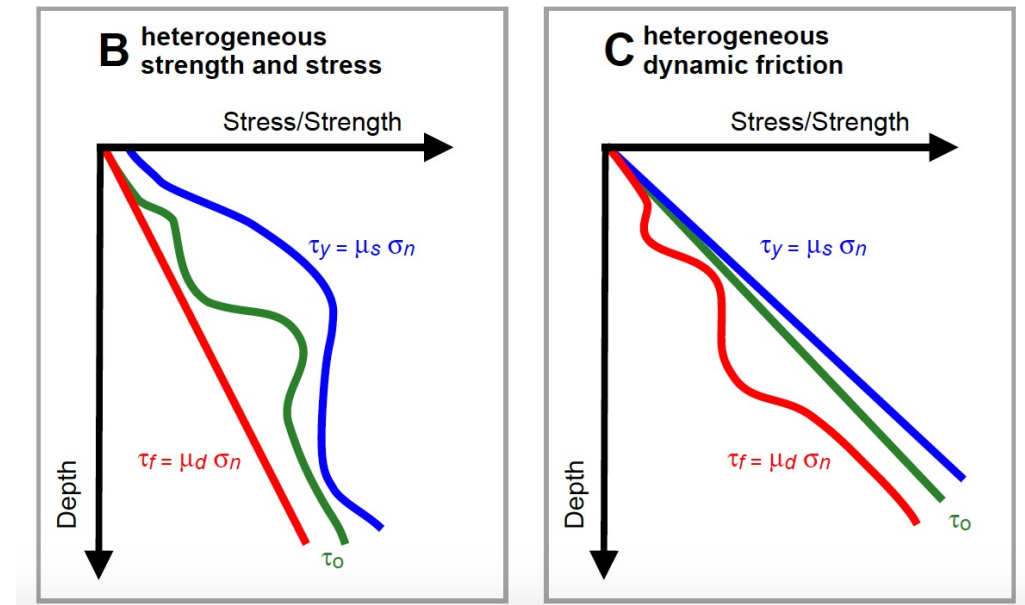
Time: 0.00 s



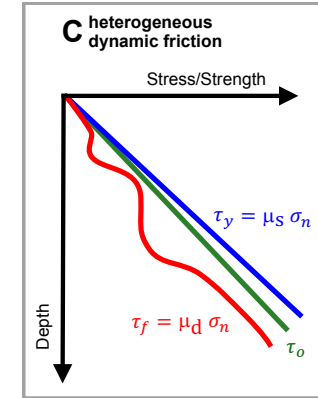
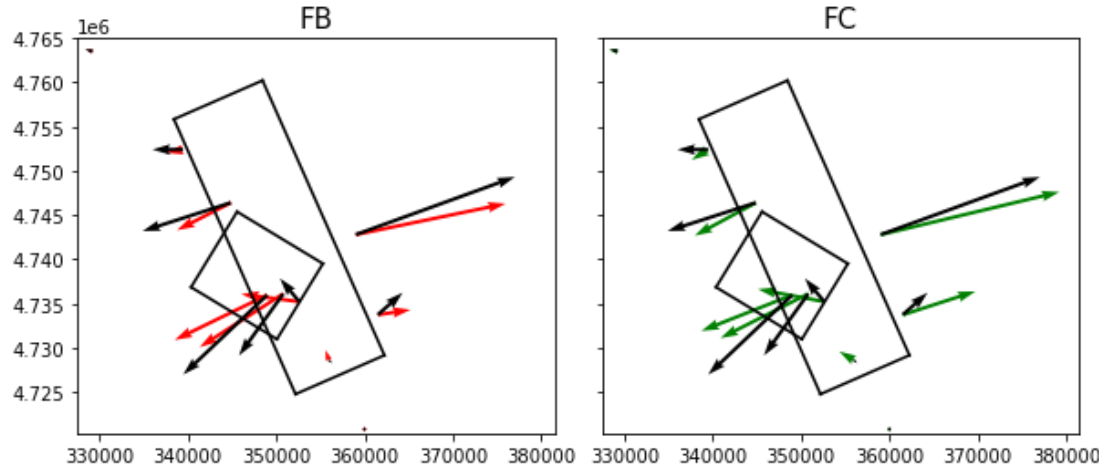
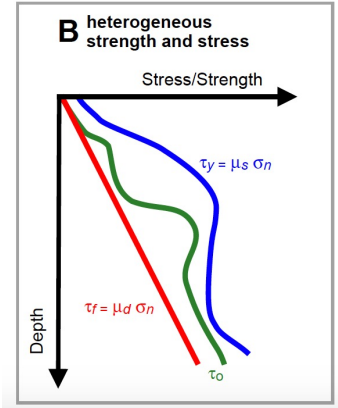
Velocity waveforms



The forth column represents the 3D absolute vector in velocity as a function of time. The goodness of fit is computed as the Variance reduction without applying any time shift.

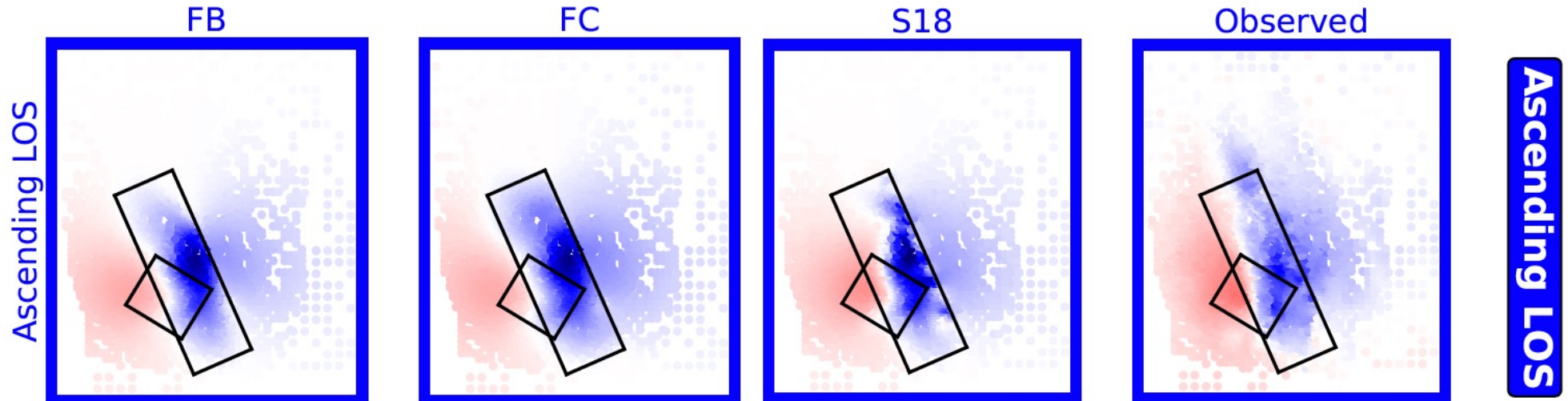


Static displacement



Top panels: models with stress drop proportional to slip.

Static displacements are similar across the families when we use the same procedure to infer stress drop

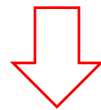


Discussions – lithological constraints

These results suggest the existence of potential dynamic models for both the families able to support the original kinematic model.

However the dynamic conditions of family B and C are very different:

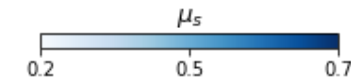
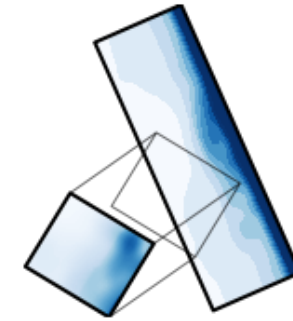
- in Family B we assume homogeneous dynamic friction (0.2) and heterogeneous static friction (0.2 - 0.7). Lower values are located in the area of small slip.
- in Family C we assume homogeneous static friction (0.5) and heterogeneous dynamic friction (0.1 - 0.4). Higher values are located in the area of small slip.



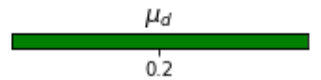
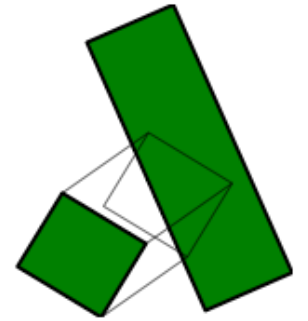
These two different assumptions have implications on the physical processes occurring in the fault plane. In particular, the choice of reliable friction coefficients has to be related to the rocks where the event nucleates, propagates and generates the large slip patches.

Family B – heterogeneous stress & strength

Static friction

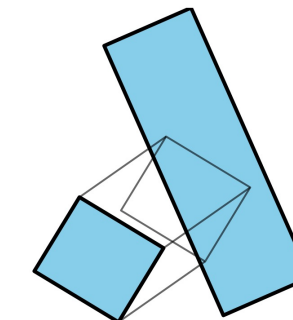


Dynamic friction

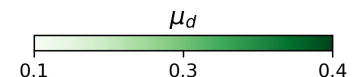
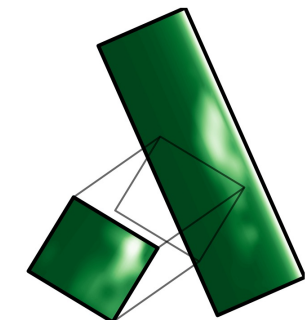


Family C – heterogeneous dynamic friction

Static friction



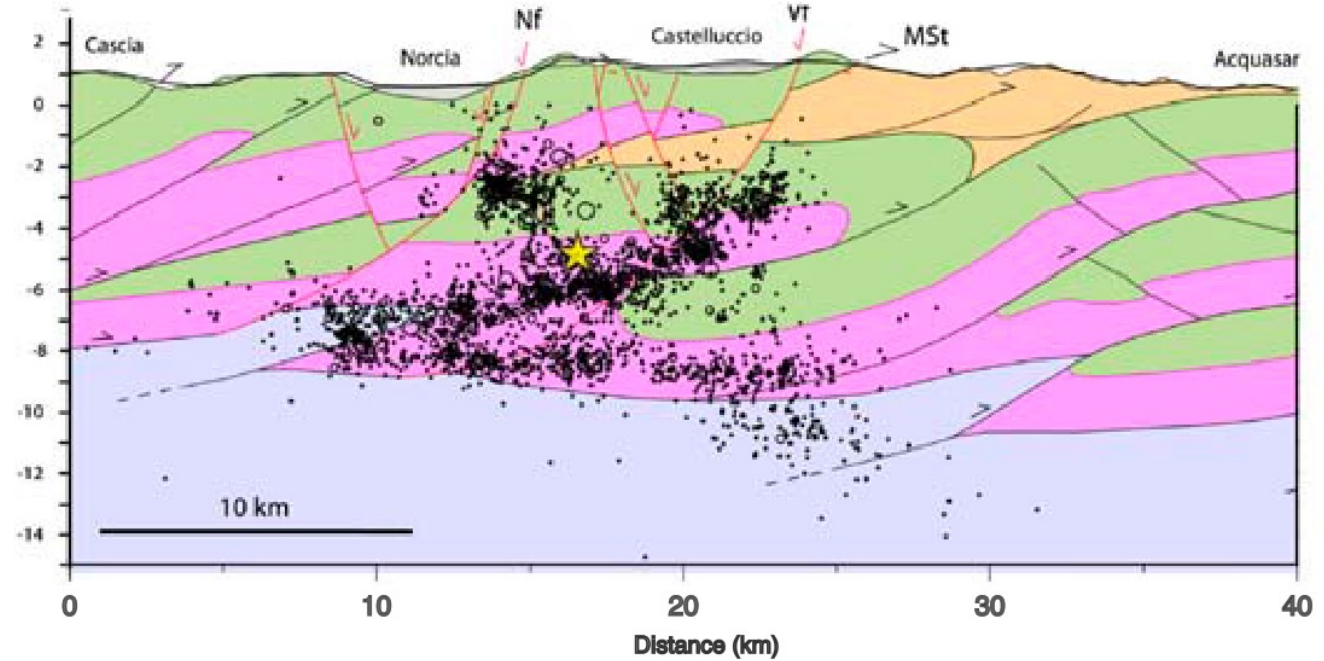
Dynamic friction



Discussions – lithological constraints

The integration of seismic reflection profiles with seismological data shows that

- the mainshock nucleated within the Triassic Evaporites.
- the main patch of slip seems to be located within carbonates.



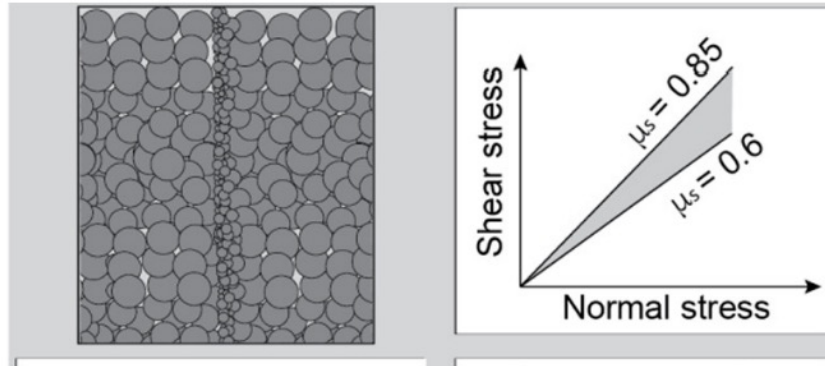
Nf: Norcia fault
Vf: Vettore fault
MSt: M. Sibillini thrust

Michele et al 2020

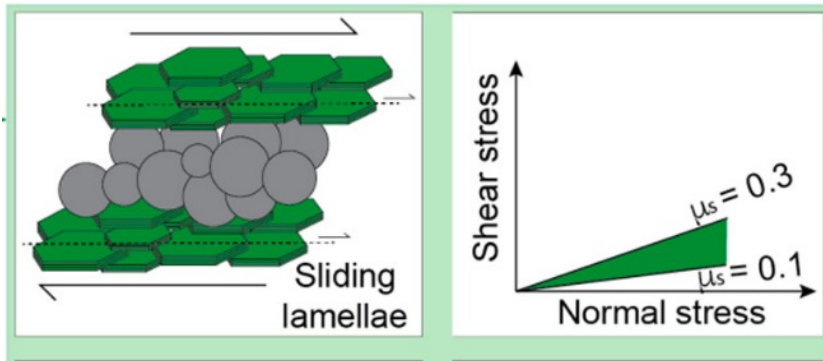
Friction values from laboratory experiments

Static friction coefficient

Strong faults

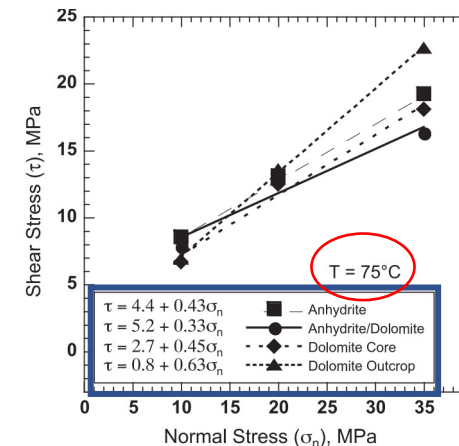
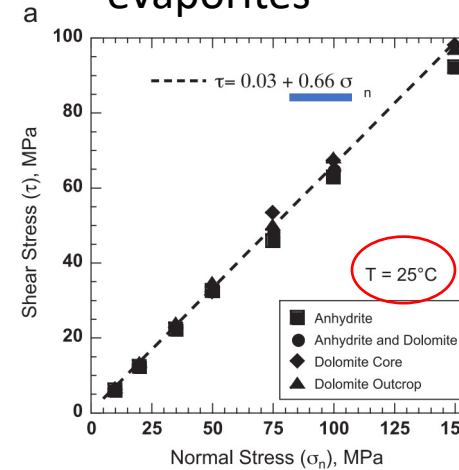


Weak faults



Collettini et al 2019

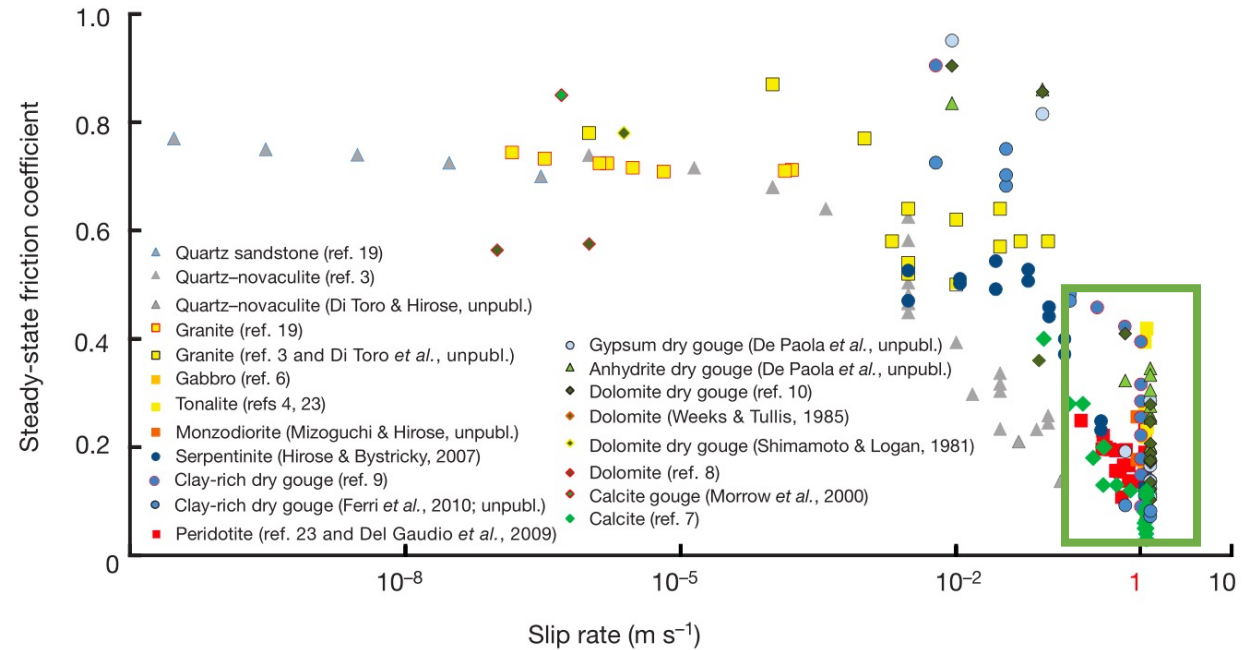
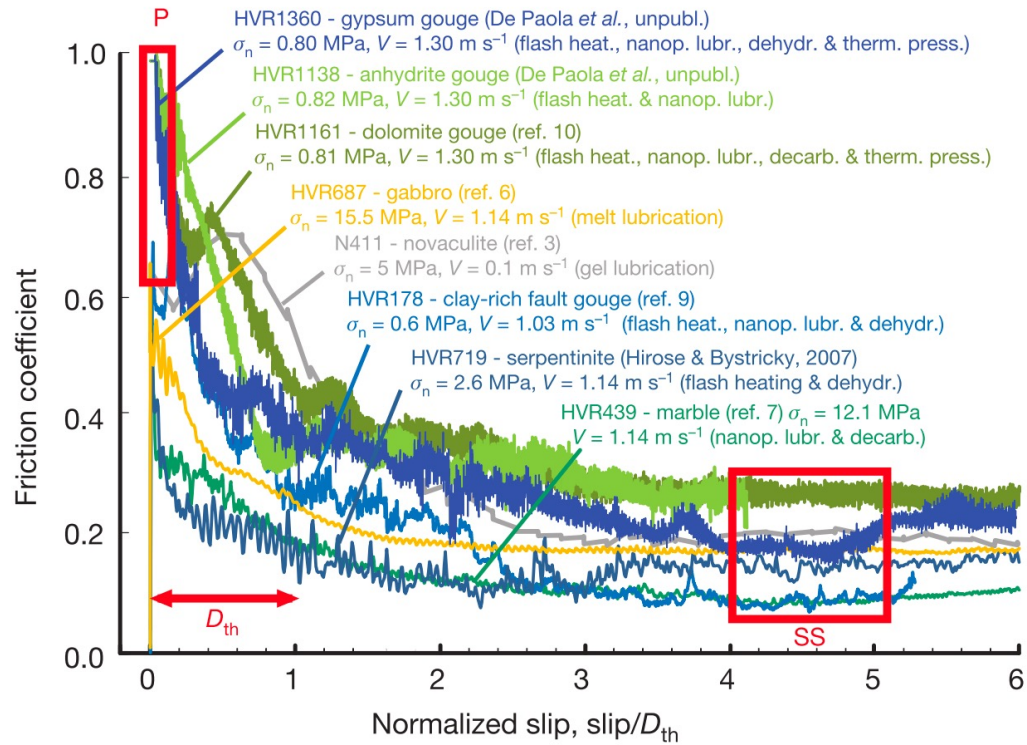
Experiments on Triassic evaporites



Scuderi et al 2013

Friction values from laboratory experiments

Dynamic friction coefficient



Steady-state friction coefficient at high velocity can represent a dynamic friction coefficient during the co-seismic phase at higher slip velocity.

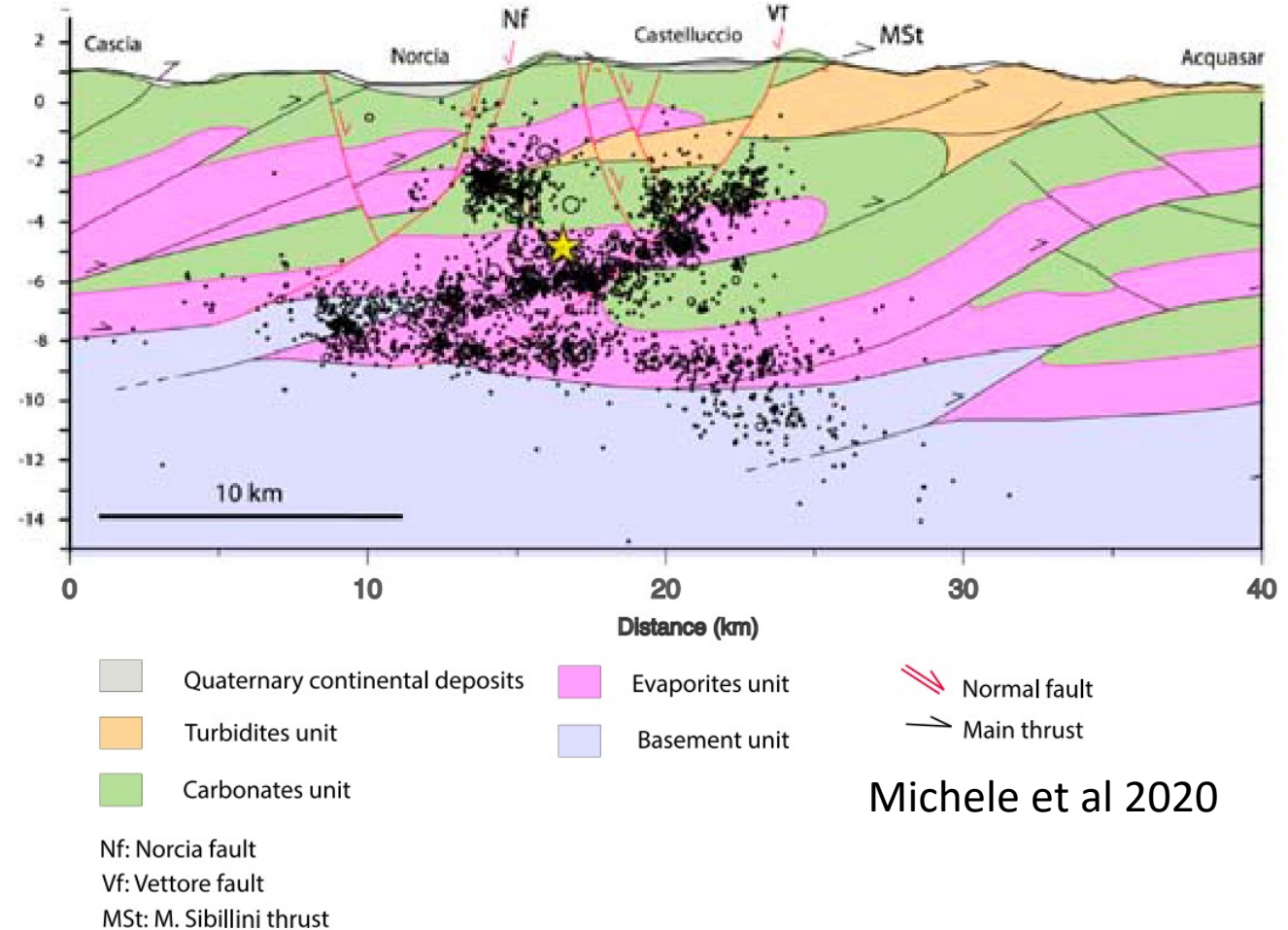
Di Toro *et al* 2011

Discussions – lithological constraints

If the mainshock nucleated within the Triassic Evaporites: **fault rocks in this lithology has a static friction around 0.5-0.6** [values can drop as low as 0.4 for high temperatures].

The main patch of slip seems to be located within carbonates: static friction is around Bayerlee value (0.6) and **dynamic friction can be low as 0.2**.

Static friction as low as 0.2-0.3 can be found only in clay rich rocks (phyllosilicates). Frictional experiments with increasing content of clay show a transition from velocity weakening to strengthening behavior.



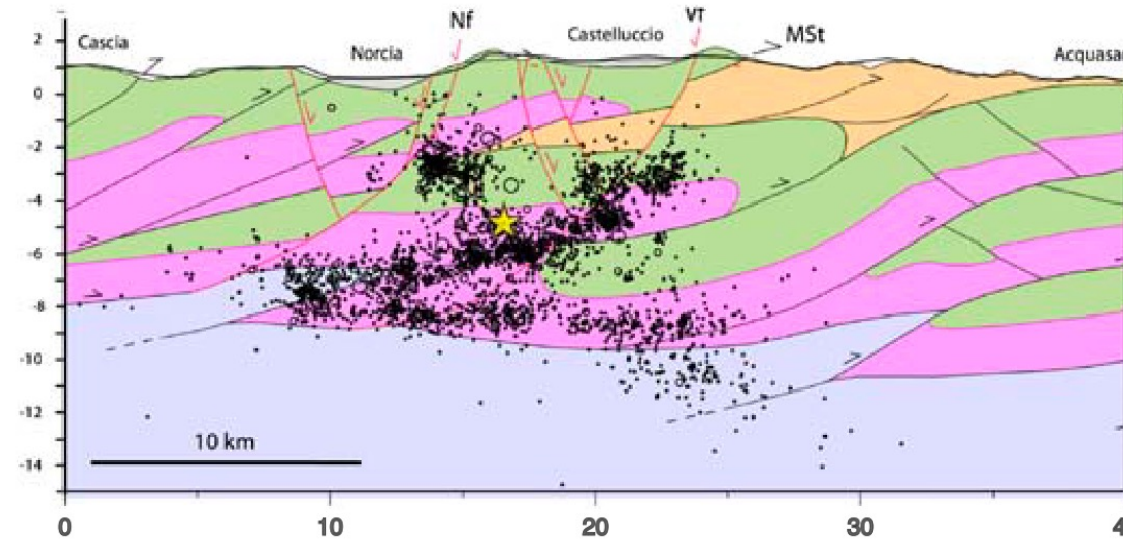
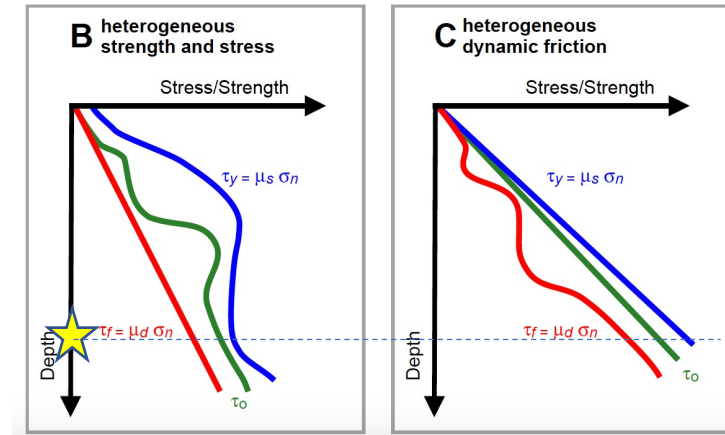
Michele et al 2020

Discussions – lithological constraints

Family B could be plausible when considering rocks rich in phyllosilicates.

However, the low static friction values are located around the nucleation. Because these values make the rock velocity strengthening, this would be less prone to nucleate. Can this family be reliable with a **pre-seismic creep**?

Family C are promising candidates to better represent the friction values of the seismogenic area in Central Appennines, even if they are not usually considered in dynamic rupture modeling. With this family it is possible to explain the occurrence of a smooth nucleation (low energy) and the dynamic propagation at shallow depths.



Thanks

