EGU General Assembly 2020

Constraining the multi-fault rupture dynamic of the Norcia, Mw 6.5, 30 October 2016, Central Italy earthquake

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INGV terremoti vulcani ambiente

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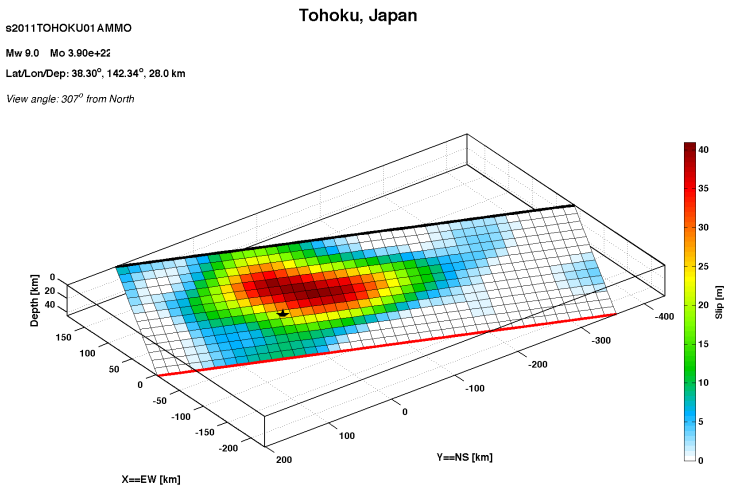
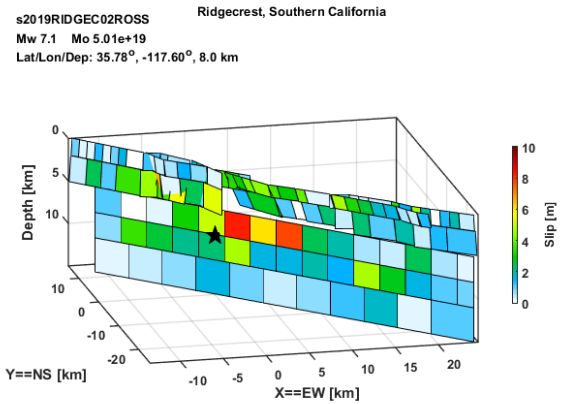
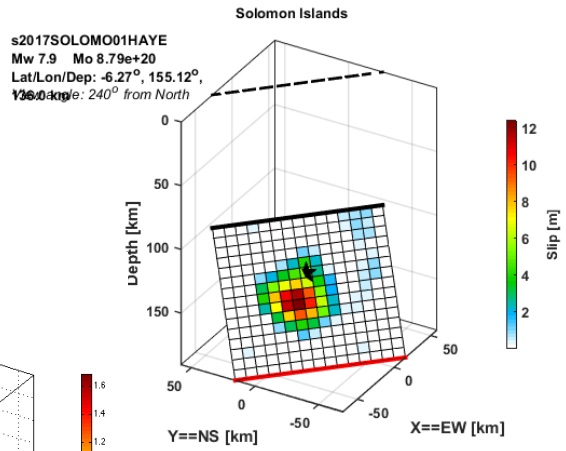
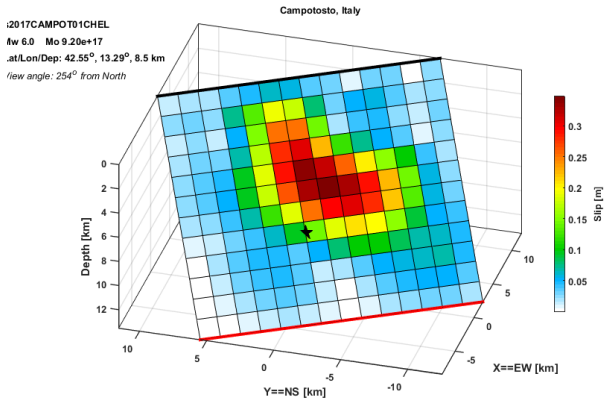
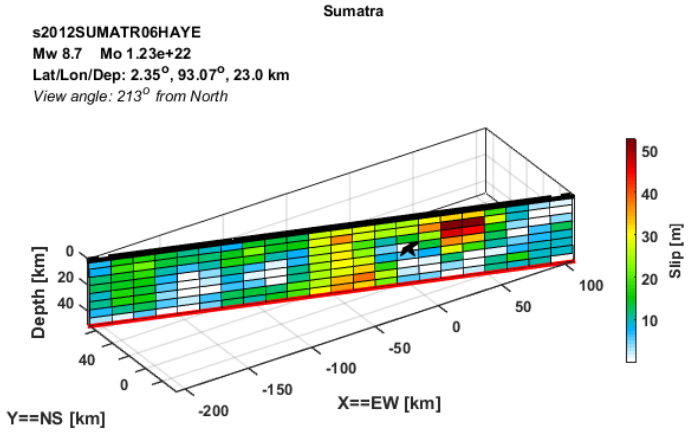
Nowadays in the literature we find a lot of kinematic models on extended fault that describe the complexity of the seismic events in terms of slip distribution, activated fault planes, fault geometry, rupture velocity, etc etc…

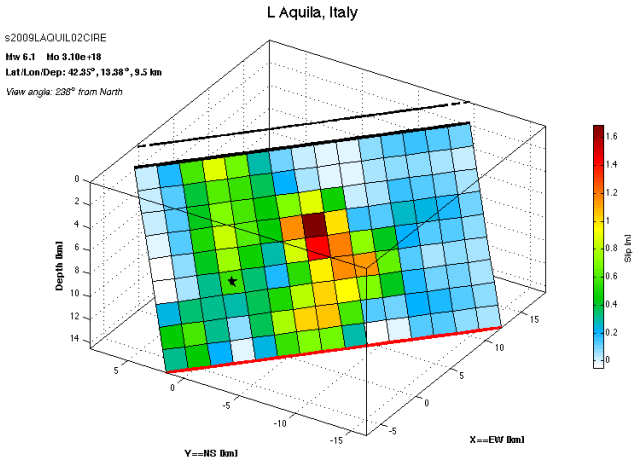


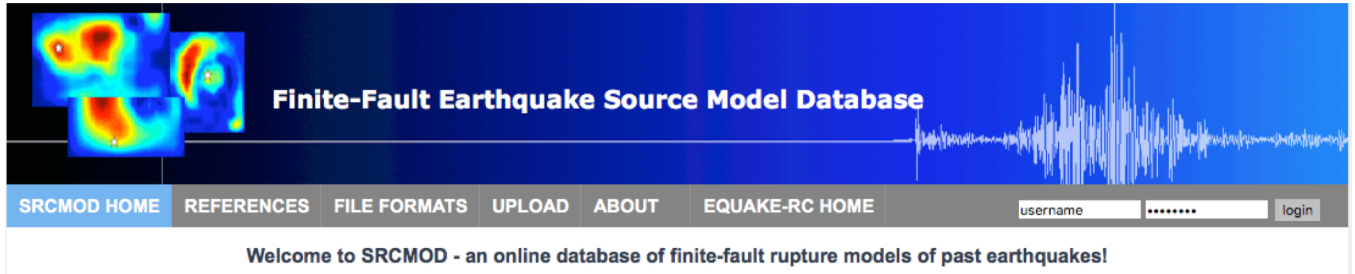












http://equake-rc.info/srcmod/

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

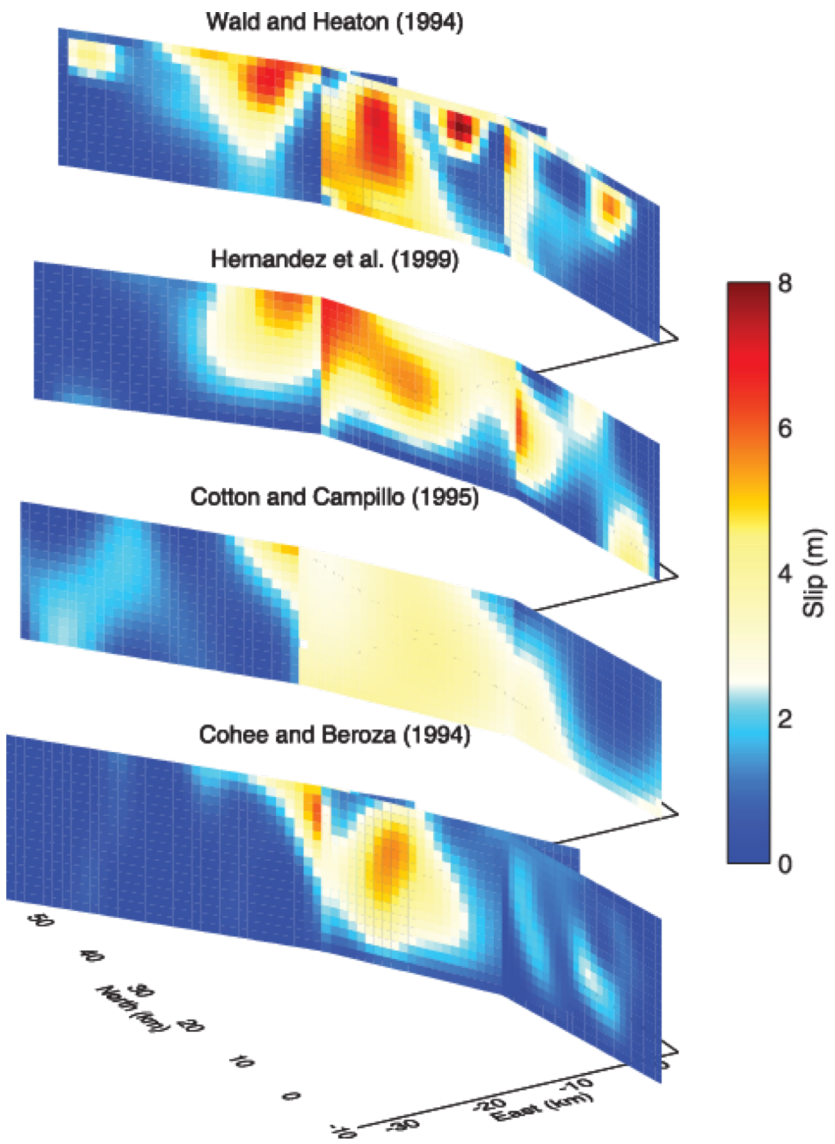
CURRENT MAIN GOALS and EFFORTS in

- ***KINEMATIC SOURCE INVERSIONS:***

It is necessary to improve and investigate the resolving capacity of data more and more (e.g., account for the uncertainties coming from errors in green function and data) and incorporate such uncertainties in source inversion problems (e.g., Bayesian approach or similar).

- ***DYNAMIC SOURCE MODELING:***

Dynamic models can provide insight on the mechanic viability of competing hypothesis.



Main goal of this work:

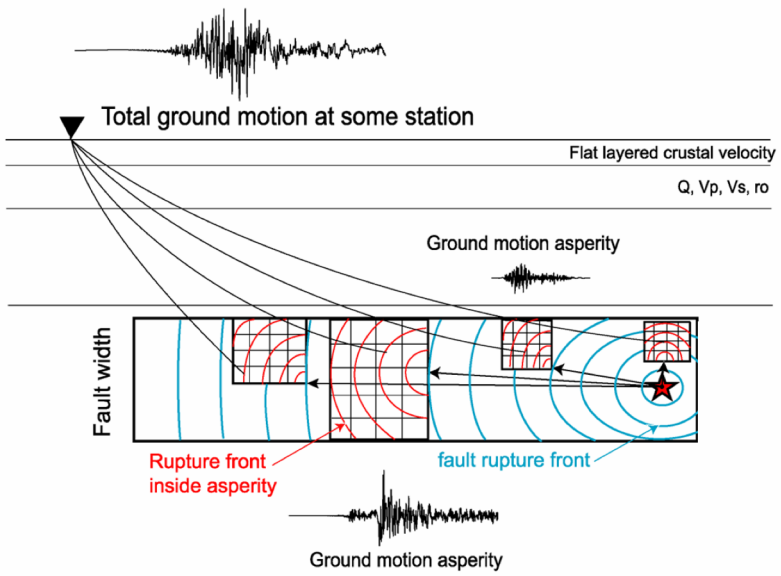
Assess the mechanic viability of the complex kinematic model proposed for Norcia, 30 October 2016, Mw6.5.

Can the kinematic models proposed in literature (by Scognamiglio et al 2018) spontaneously propagate ?

Kinematic Model

Rupture history:

- ✓ Slip distribution
- ✓ Slip velocity
- ✓ Rupture velocity
- ✓ Rise time

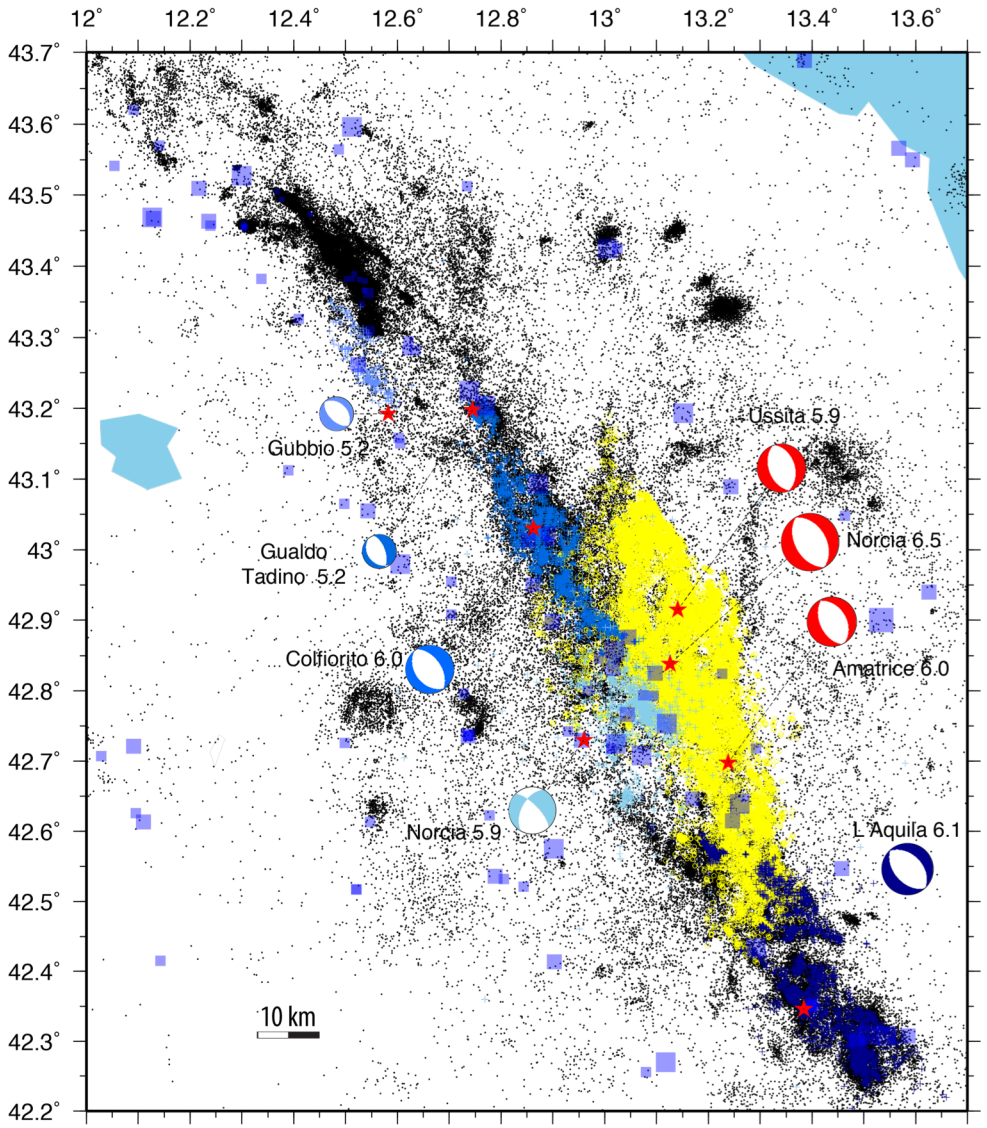


Dynamic Model

Friction law on the fault plane:

- ✓ Traction evolution
- ✓ Stress drop
- ✓ Constitutive parameters

Test study: Norcia Mw 6.5, 30 October 2016, Central Italy



1984

1997-98

2016-17

1979

2009-10

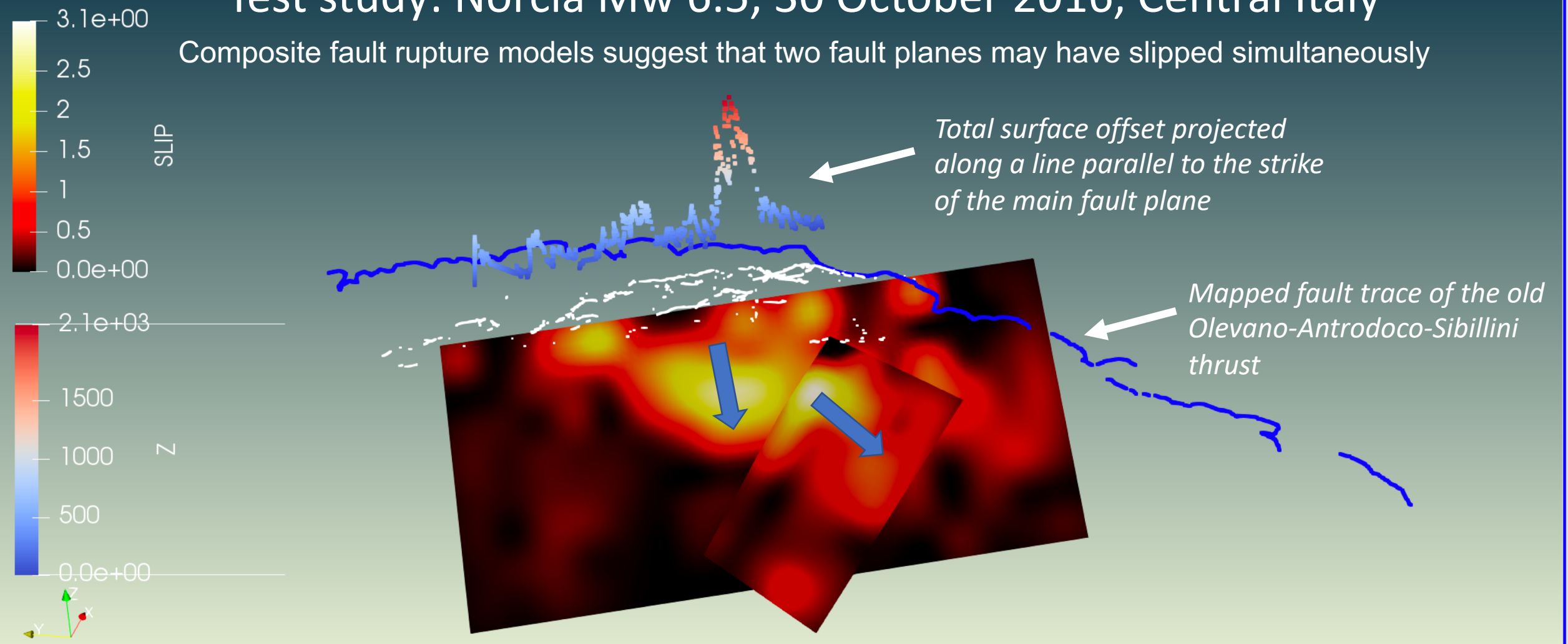
2009-19

Chiaraluce personal communication

Historical and instrumental seismicity

Test study: Norcia Mw 6.5, 30 October 2016, Central Italy

Composite fault rupture models suggest that two fault planes may have slipped simultaneously

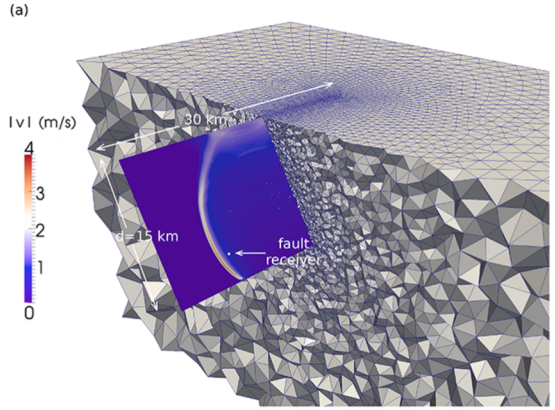


Main characteristics of kinematic model by Scognamiglio et al 2018:

1) Nucleation in an area with almost zero slip (<=20cm)
2) High slip (~3m)patch few km away from the hypocenter
3) Activation of a secondary fault which is misoriented with respect to the extensional tectonic stress regime
4) Spatial heterogeneity in slip and rake.

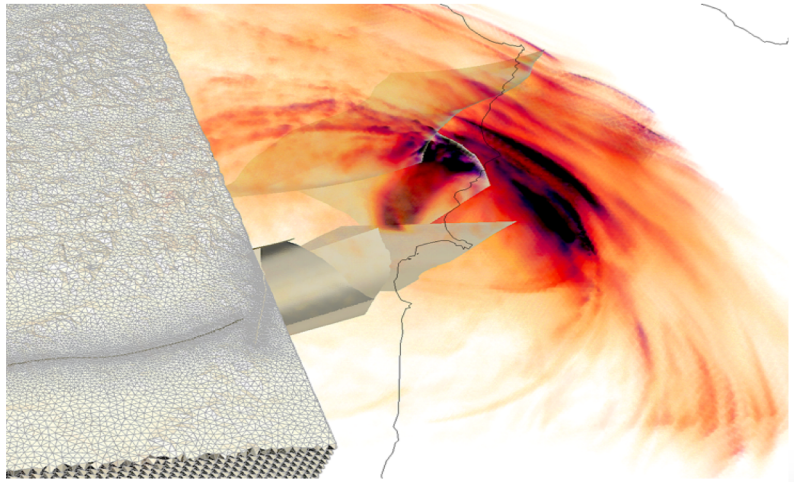
SeisSol - a discontinous Galerkin (DG) software for modern supercomputers

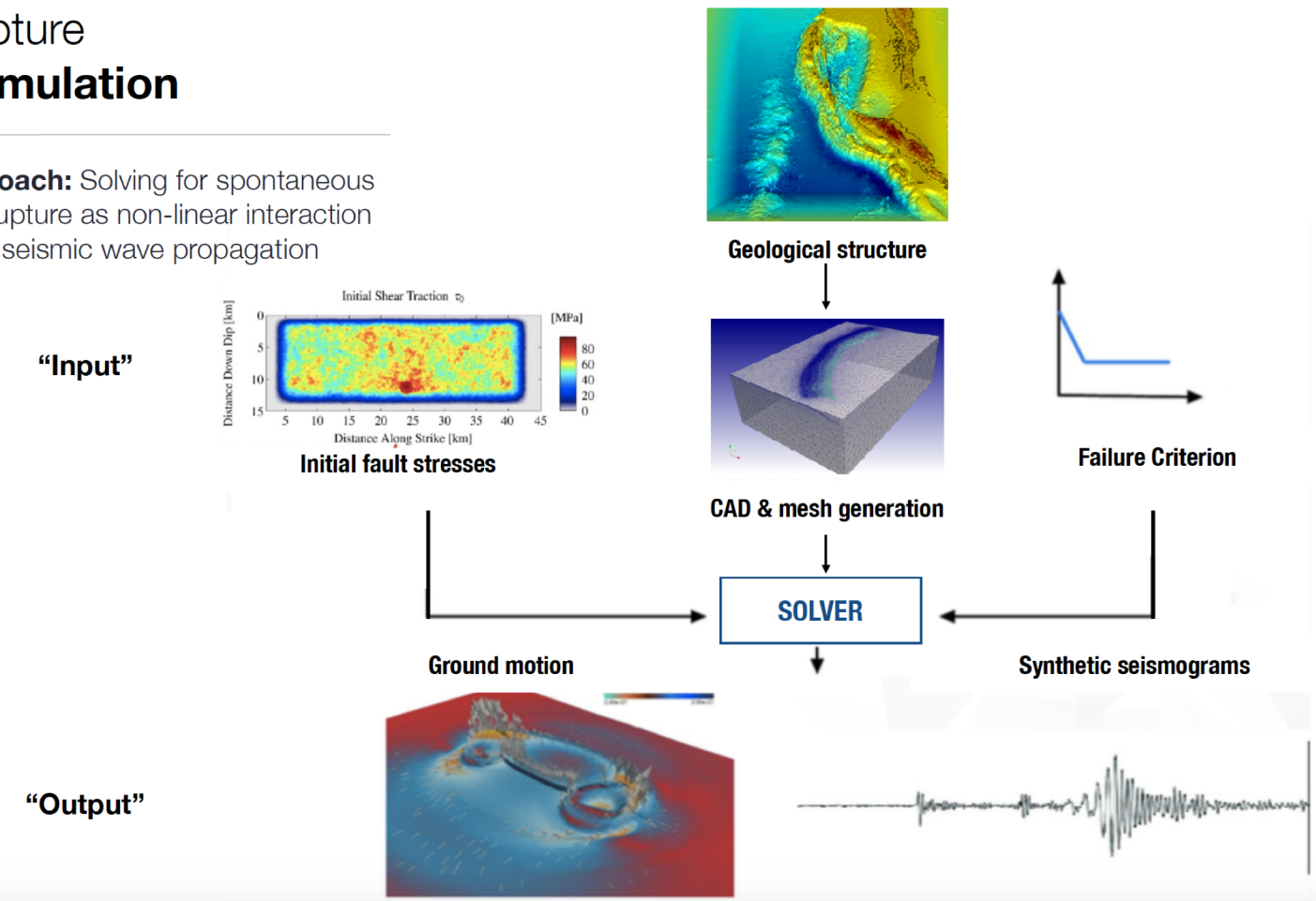
SeisSol is a software package for simulating, with unstructured tetrahedral meshes, wave propagation and dynamic rupture based on the arbitrary high-order accurate derivative discontinuous Galerkin method



3D dynamic rupture **earthquake simulation**

- **Physics-based approach:** Solving for spontaneous dynamic earthquake rupture as non-linear interaction of frictional failure and seismic wave propagation

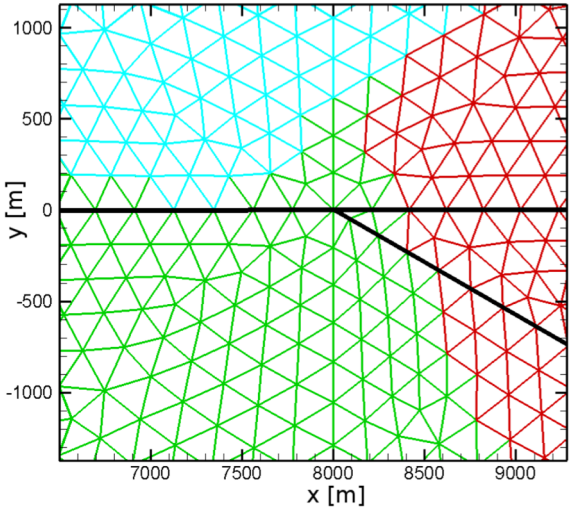


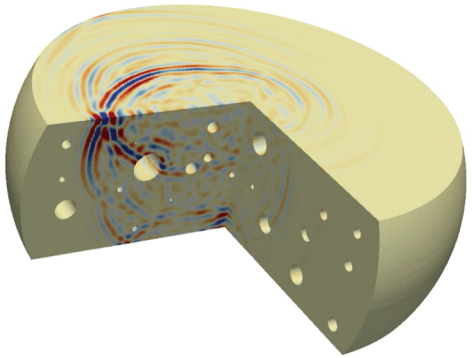


SeisSol - a discontinous Galerkin (DG) software for modern supercomputers

This method, permits:

- representing **complex geometries** - by discretizing the volume via a tetrahedral mesh
- modelling **heterogenous media** - elastic, viscoelastic, viscoplastic, anisotropic
- **high accuracy** & **high resolution**





Why DG? Low numerical dispersion, minor changes for dynamic rupture, intersecting and branching faults/structure

Why ADER? Equivalent high-order accuracy as in space using a single explicit time integration step. Increasing order of accuracy can be ‘cheap’ if hardware is exploited)

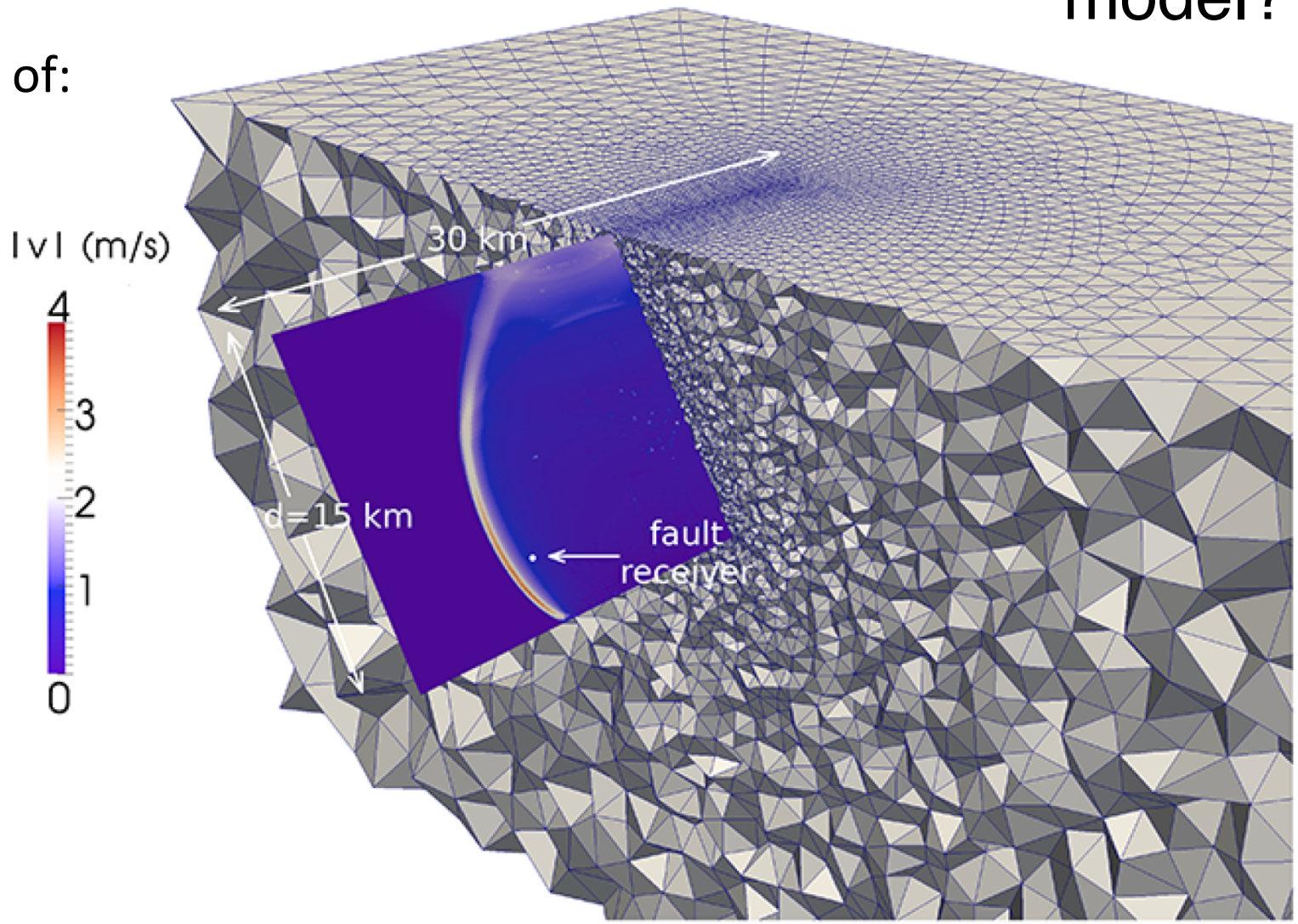
A software that allows for rapid setup of models with realistic non-planar and intersecting fault systems while exploiting the accuracy of a high-order numerical method

SeisSol

How to constrain the initial dynamic conditions to reproduce the Scognamiglio et al 2018 kinematic model?

Setup the dynamic model in terms of:

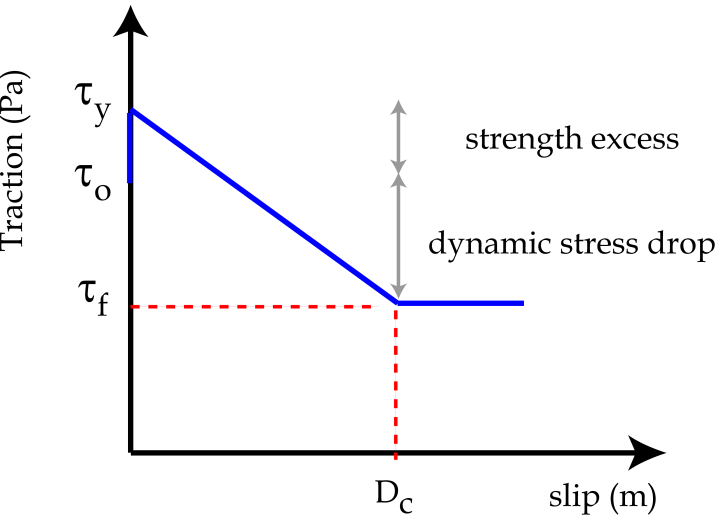
- Fault geometry
- Velocity structure
- Constitutive laws
- Initial conditions



Setup of the dynamic model

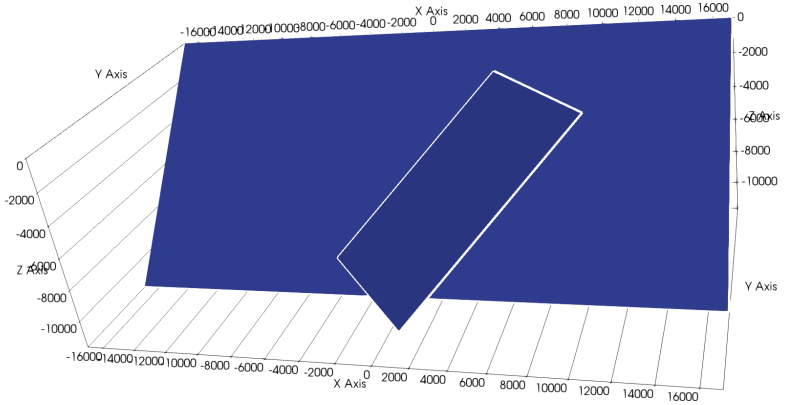
Constitutive law:

- Slip weakening (to simplify the choice of the initial conditions)

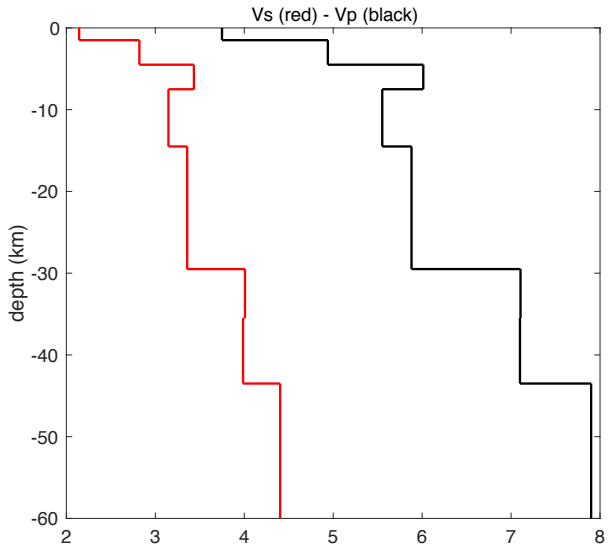


Fault geometry and velocity structure:

- 2 fault planes
  - **main fault** 34 km x 16 km, strike 155 and dip 47;
  - **secondary fault** 10 km x 16 km, strike 210, dip 36.

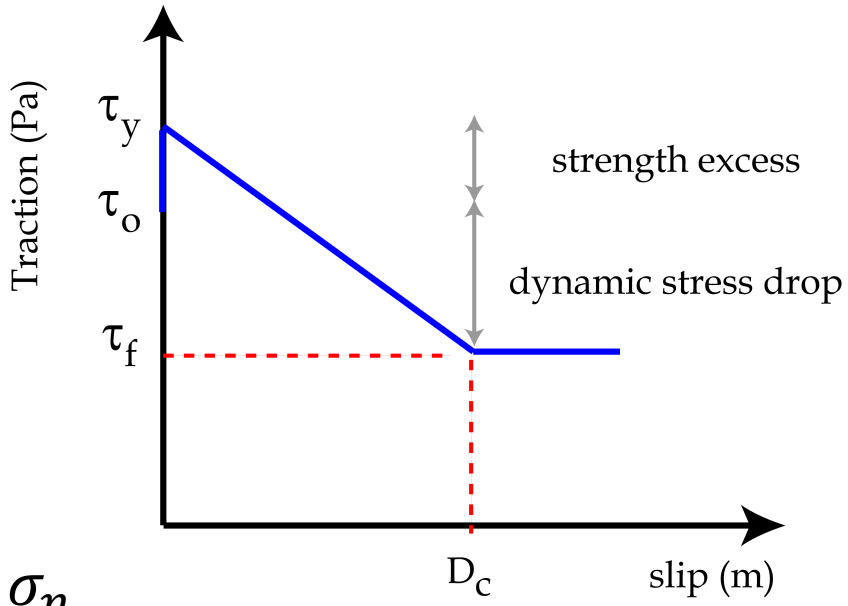


- 1D nncia model for Central Italy



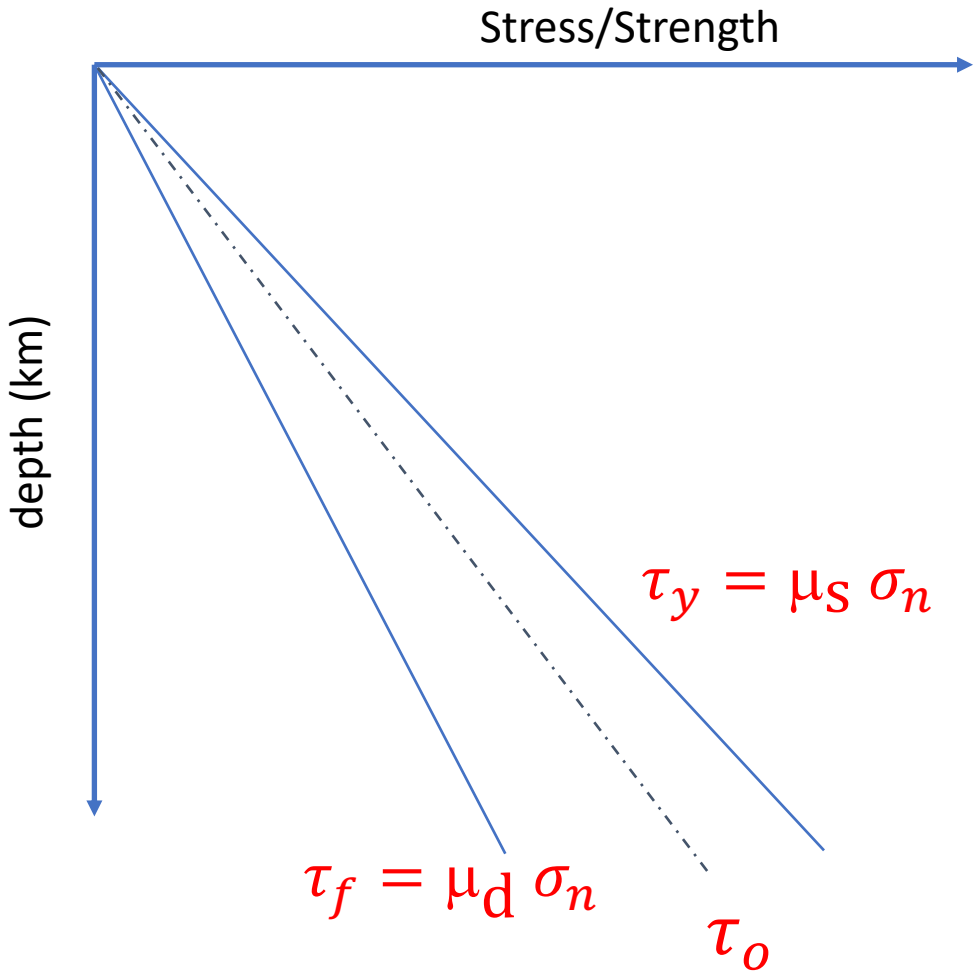
Secondary fault intersects the main fault (branch condition). The rupture interacts with both the fault plane!

Setup of the dynamic model



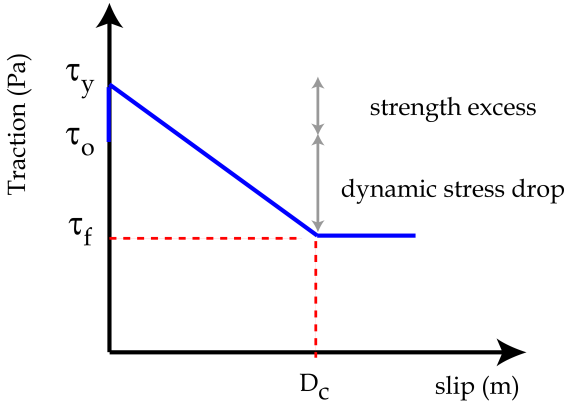
- **Initial stress** τ_0
- **Yield stress**: depends on the static friction μ_s → $\tau_y = \mu_s \sigma_n$
- **Frictional stress:** depends on dynamic friction μ_d → $\tau_f = \mu_d \sigma_n$
- **Stress drop** $\Delta\tau$: Proportional to slip distribution. —> $\tau_0 - \tau_f = \Delta\tau$
- **Direction of initial stress on the faults:** Rake from the kinematic model
- **Normal Stress** σ_n : Lithostatic pressure $(\rho g z)$. Gradient 26MPa/km or we can include fluids.
- **Dc:** slip weakening distance. Constant or heterogeneous on the fault?

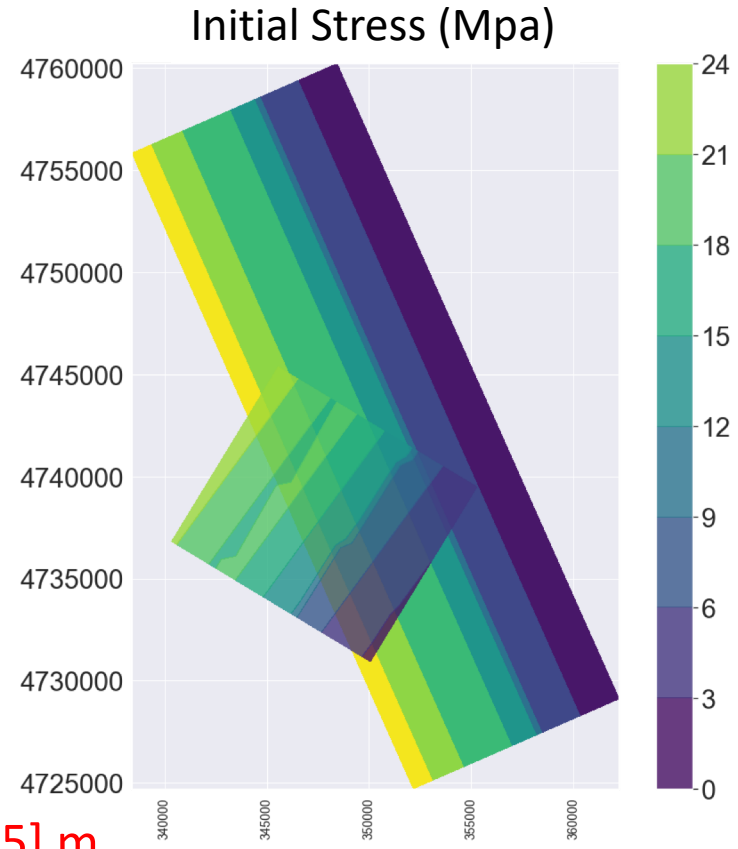
Spatial distribution of dynamic parameters: HOMOGENEOUS CONFIGURATION



If friction coefficients (static and dynamic) are constant there is only a dependence of depth due to normal stress.

$\mu_s = 0.6$ and $\mu_d = 0.2$



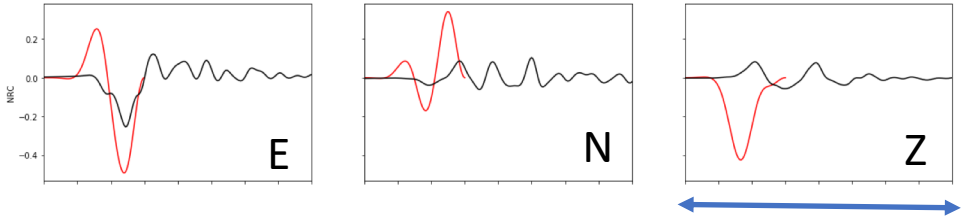


- **Initial stress** τ_0 = 65% τ_y
- **Direction of initial stress on the faults:** Pure normal faults
- **Normal Stress** σ_n : Lithostatic pressure $(\rho g z)$. Gradient 26MPa/km.
- **Dc:** slip weakening distance constant on the fault planes: different tests [0.5-1.5] m

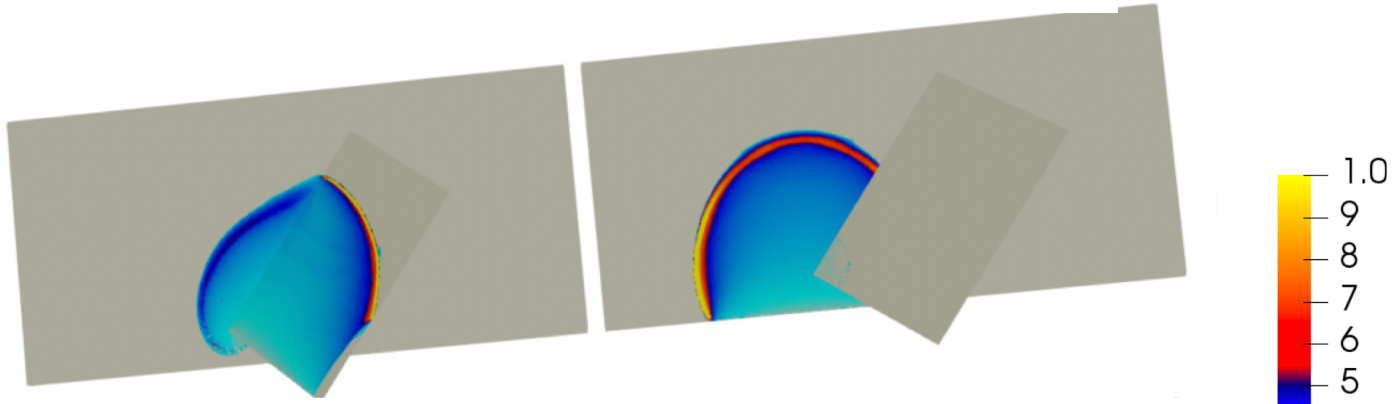
Spatial distribution of dynamic parameters: HOMOGENEOUS CONFIGURATION

The geometry allows for the simultaneous rupture on both the fault planes (even if the secondary fault is less favorited). The homogeneous dynamic conditions are very far from what happens during the event.

NRC station: black observed data; red synthetics



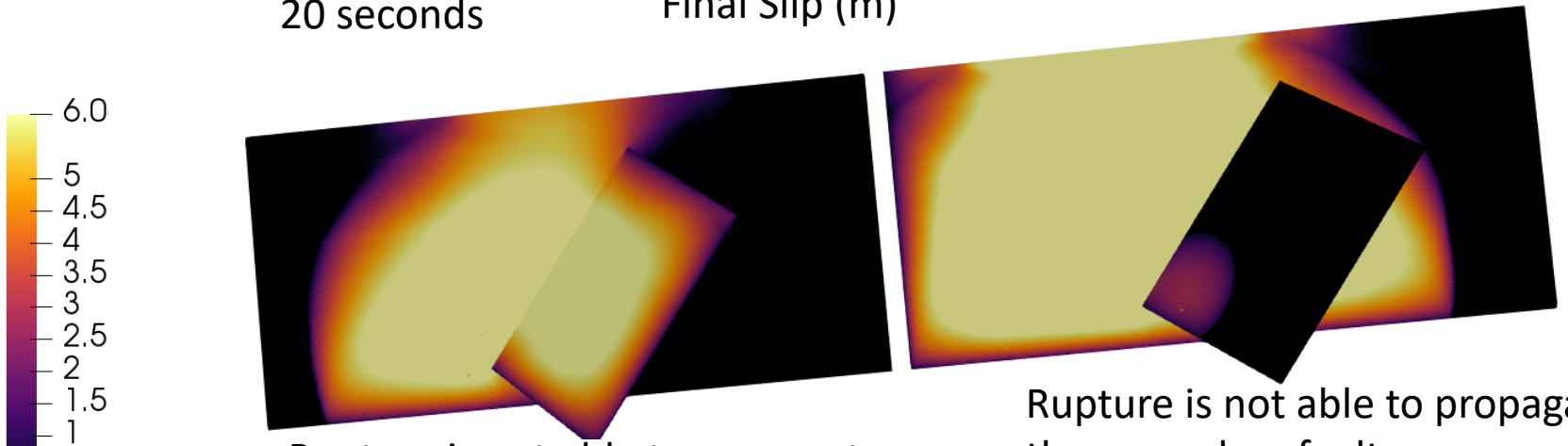
Slip Velocity snapshot (m/s) for two configurations



Dc_mainfault=1.3 m
Dc_secondaryfault=0.4m

Dc_mainfault=1.2 m
Dc_secondaryfault=0.6m

Final Slip (m)



Rupture is not able to propagate behind the secondary fault

Rupture is not able to propagate on the secondary fault

FROM HOMOGENEOUS TO HETEROGENEOUS CONFIGURATION

The simplest as possible distribution of dynamic parameters (homogeneous distribution) allows us only to test the fault geometry. These results show that the geometry allows for the simultaneous rupture on both the fault planes (even if the secondary fault is less favorited). However, the homogeneous dynamic conditions are very far from what happens during the event.

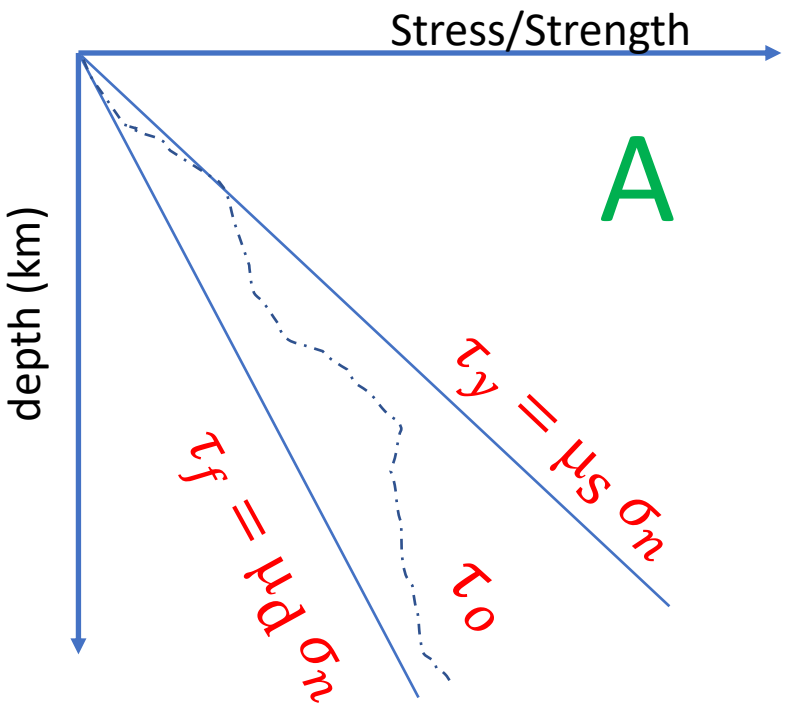
Norcia event occurred two months after the beginning of sequence. The temporal evolution of the occurrence of the three main events reinforces the hypothesis that the distribution of dynamic parameters have to be **strongly heterogeneous**.

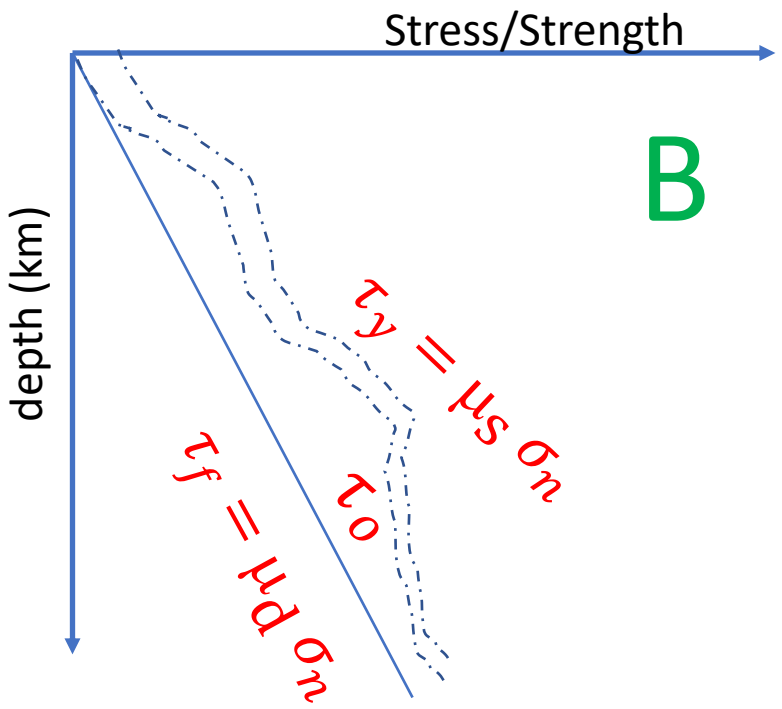
HOW CAN WE CLASSIFY THE HETEROGENEITIES OF STRESS PARAMETERS?

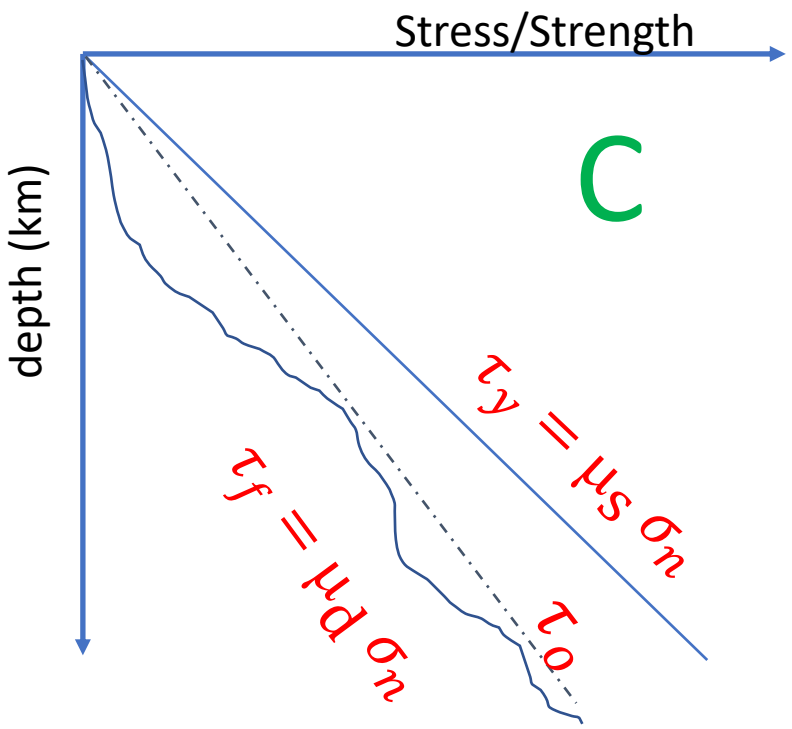
FAMILIES OF MODELS

Spatial distribution of dynamic parameters: HETEROGENEOUS CONFIGURATION

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





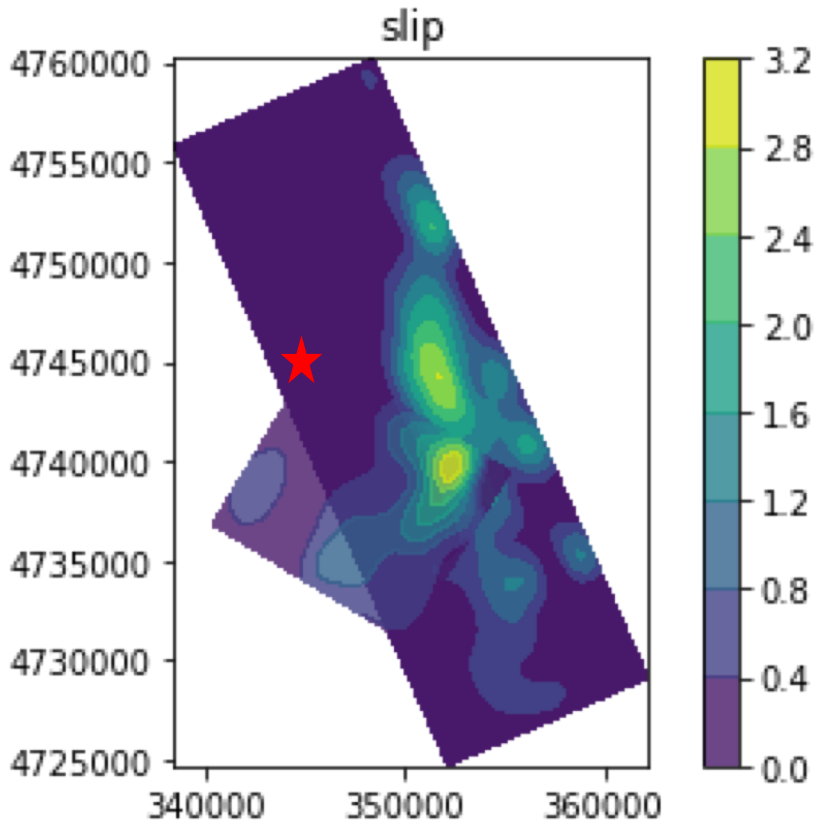


FAMILY-A:
Constant friction parameters & complex stress

FAMILY-B:
Constant dynamic friction & complex static friction and stress

FAMILY-C:
Constant static friction & complex dynamic friction and stress

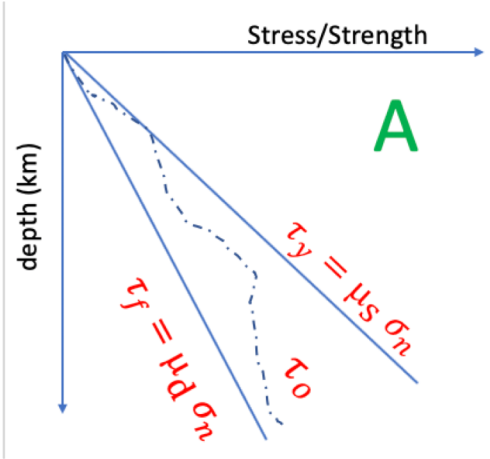
FAMILY-A:
Heterogenous initial stress & constant friction parameters



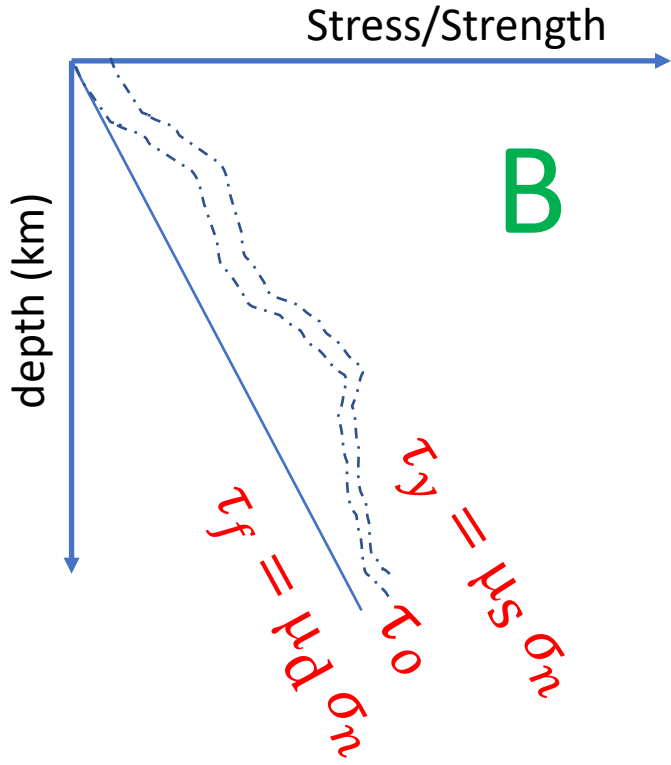
Slip from Scognamiglio et al 2018

We do not show this family of models because we didn't find dynamic parameters that allow spontaneous rupture and reproduce the slip distribution by Scognamiglio et al 2018.

We find models that do not propagate outside the nucleation (in this model the nucleation is far from the main patch) or models that produce a-causal ruptures (from the center of the main slip patch where fault first reaches instable conditions).

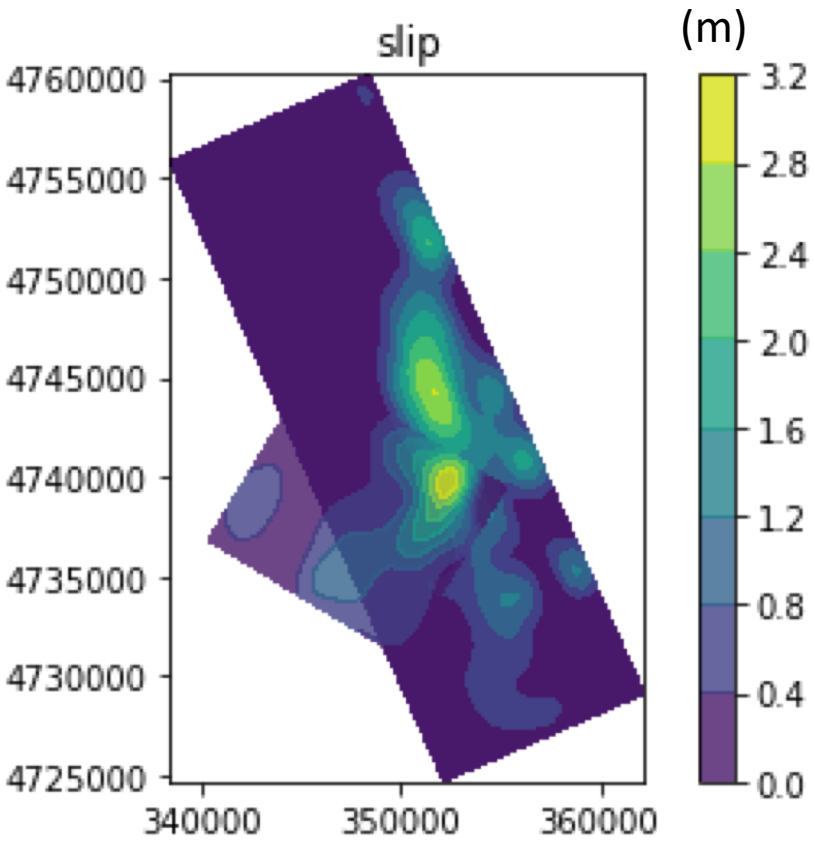


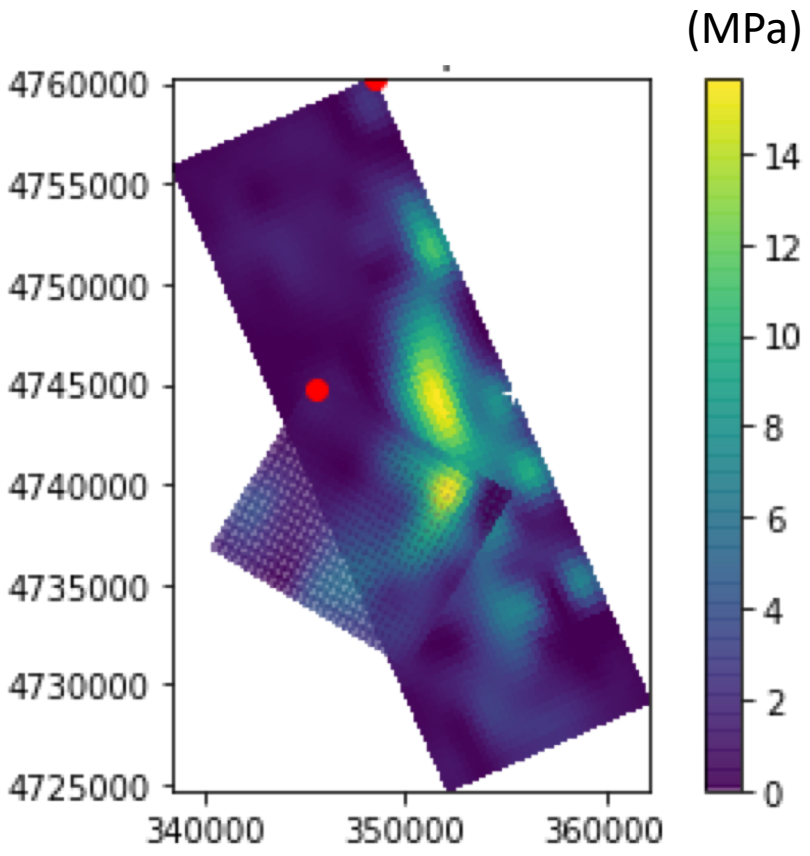
FAMILY-B:
Constant dynamic friction & complex static friction and stress

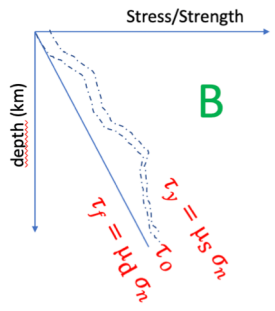


- **Frictional stress:** depends on **constant** dynamic friction μ_d → $\tau_f = 0.2\,\sigma_n$
- **Stress drop** $\Delta\tau (= \tau_0 - \tau_f)$: Proportional to slip distribution of the kinematic model.
- **Initial stress heterogeneous** $\tau_0 = \Delta\tau + \tau_f$: proportional to slip distribution.
- **Yield stress**: **heterogeneous** on the fault plane → strength excess: [0 - 3] Mpa
- **Direction of initial stress on the faults:** Rake from the kinematic model
- **Normal Stress** σ_n : Lithostatic pressure $(\rho g z)$. Gradient 16MPa/km (fluids are included).
- **Dc:** slip weakening distance. We tested constant or heterogeneous (percentage of total slip) values.

FAMILY-B: Setup of the dynamic model: stress distribution





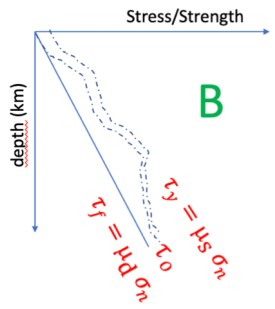


Slip distribution from kinematic model of Scognamiglio et al. 2018

Imposed **static stress drop** $\Delta\tau$ similar to distribution inferred with pseudo-dynamic models or by using Ripperger and Mai (2004) formula

FAMILY-B:

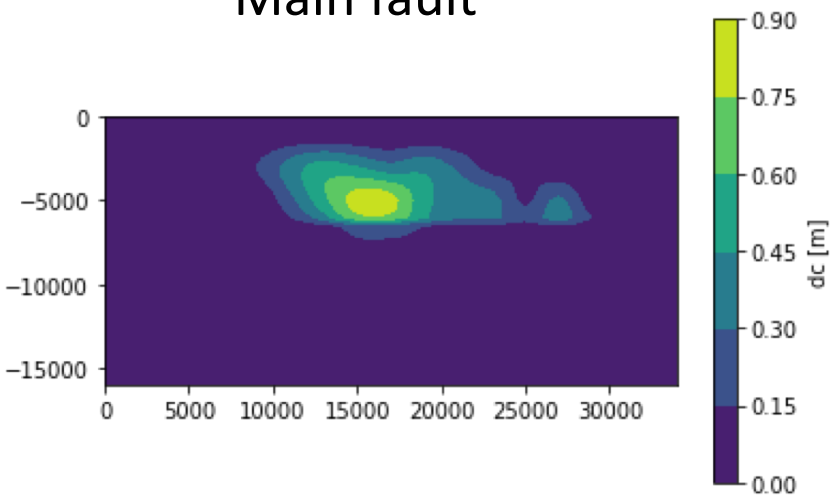
Setup of the dynamic model: Dc



We show an example with heterogeneous Dc distribution

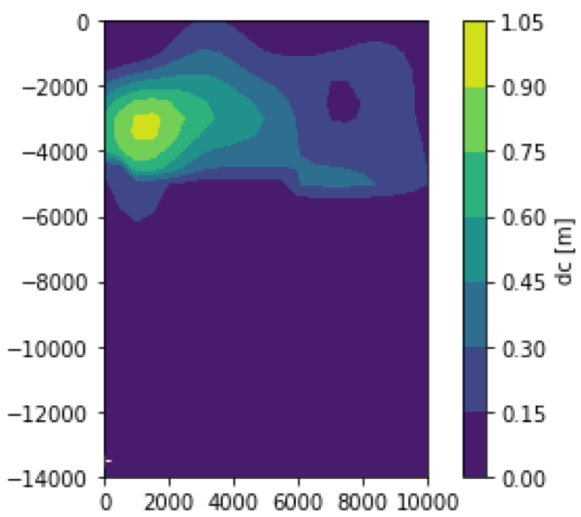
Dc/slip=30% in the area of main patch while Dc/slip=10% around the nucleation

Main fault



Dc_{MAX}= 0.84 m

Secondary fault

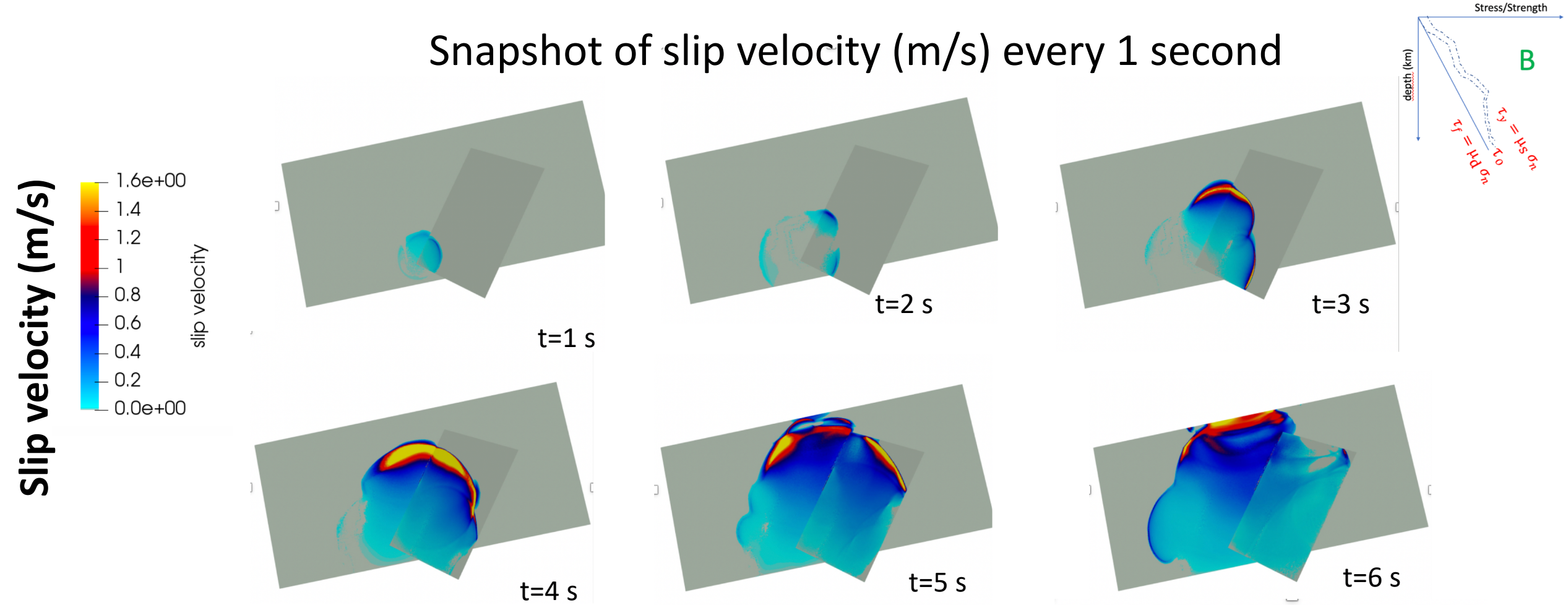


Dc_{MAX}= 0.94 m

minimum Dc value = 2 cm

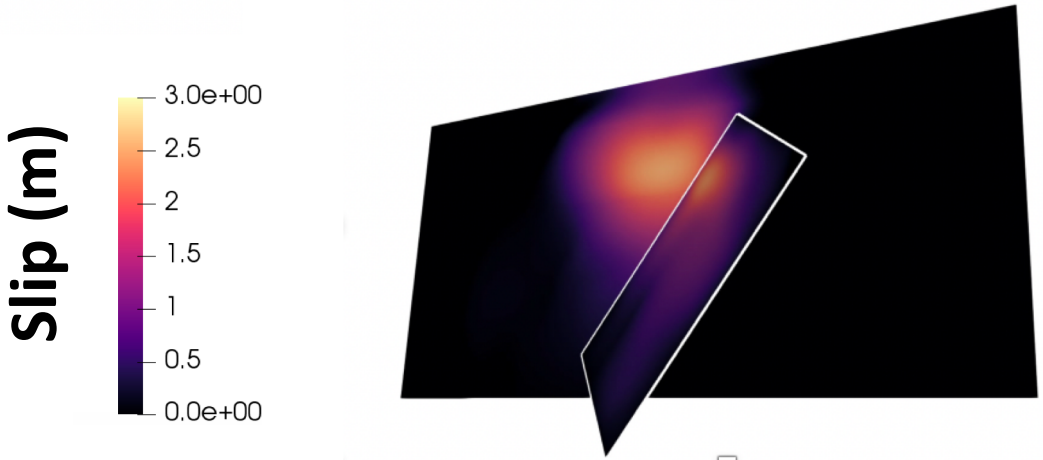
MODEL B3

Snapshot of slip velocity (m/s) every 1 second

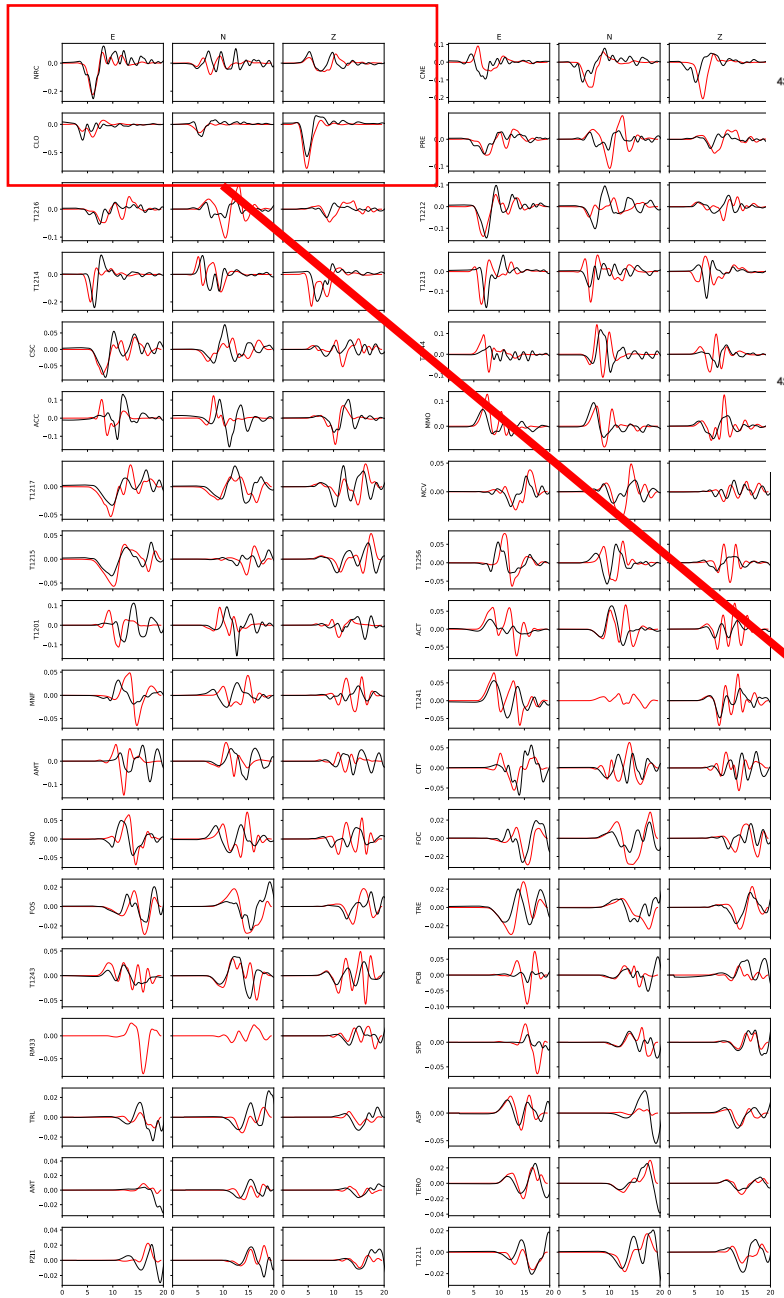


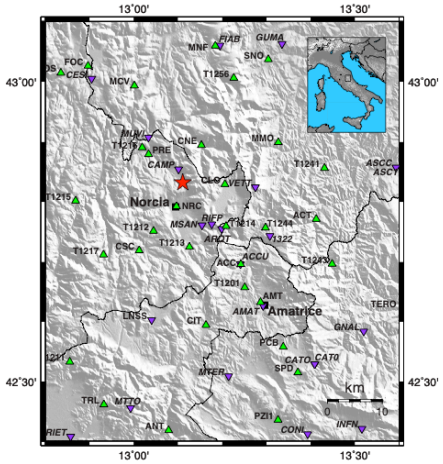
Temporal evolution of slip velocity for a spontaneous rupture propagation.

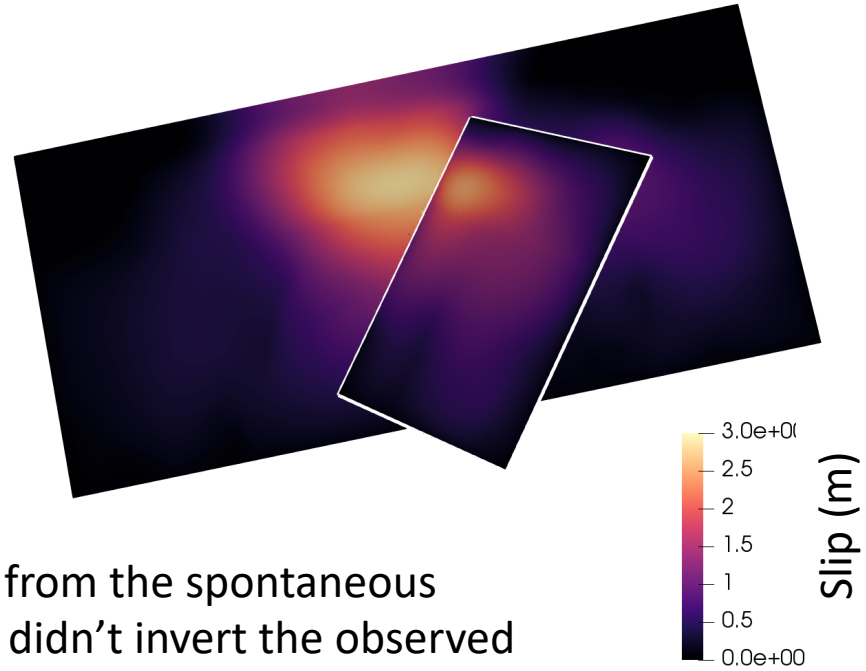
Final slip distribution is very similar to Scognamiglio et al. 2018

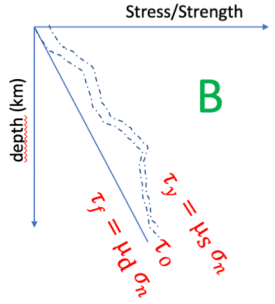


Red synthetics and Black real data filtered between 0.02 – 0.5 Hz.

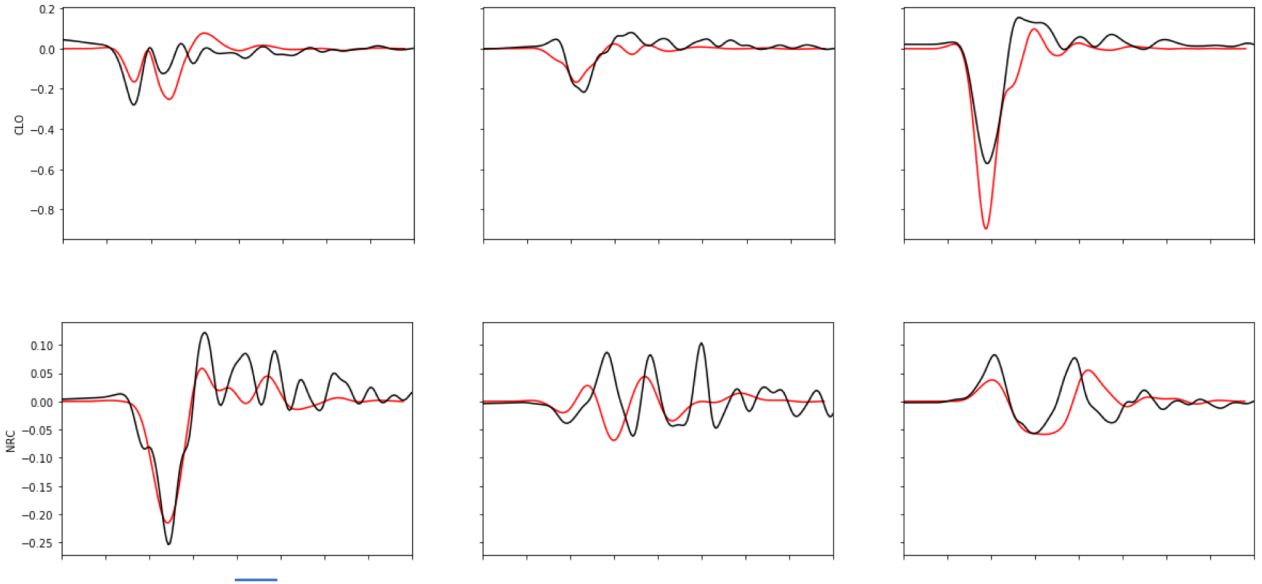








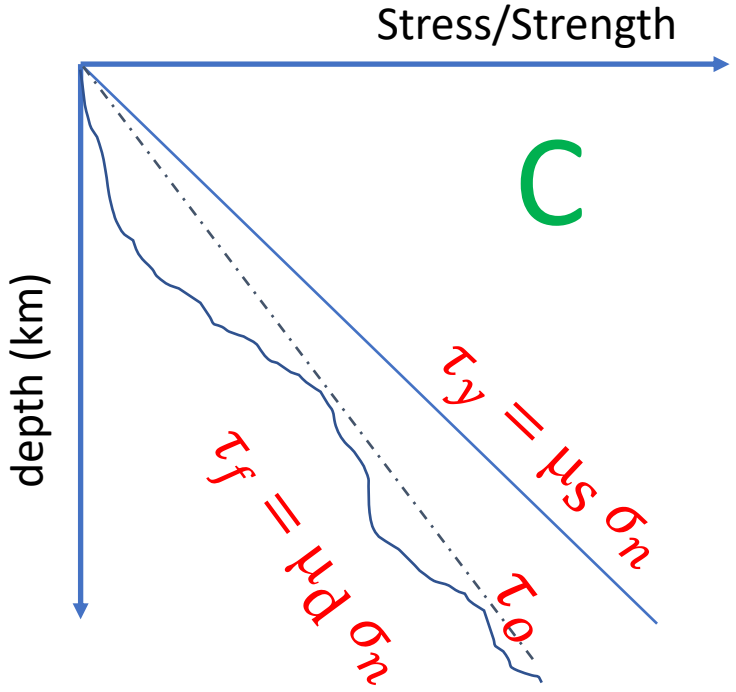
The sythetics are retrieved from the spontaneous dynamic model. Even if we didn't invert the observed data, the synthetics are very similar to the data.



5sec

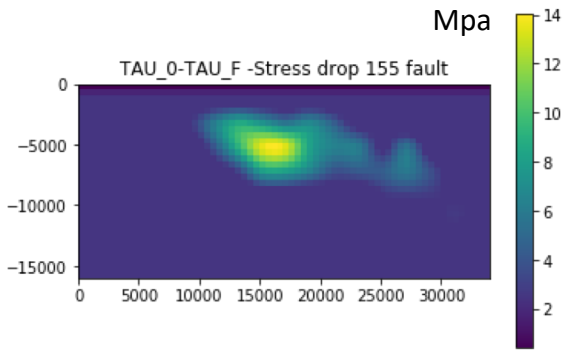
Time (s)

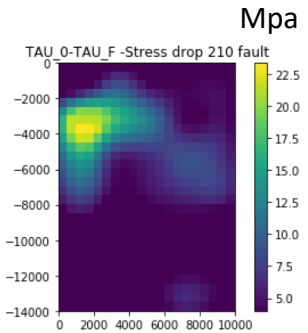
FAMILY-C:
Constant static friction & complex dynamic friction and stress

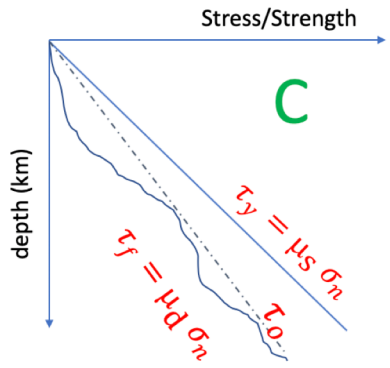


- **Frictional stress:** depends on **heterogeneous** dynamic friction μ_d
- **Stress drop** $\Delta\tau$: Proportional to slip distribution of the kinematic model.
- **Initial stress** $\tau_0 = \Delta\tau + \tau_f$
- **Yield stress**: **homogeneous** on the fault plane: $\mu_s = 0.6$
- **Direction of initial stress on the faults:** Rake from the kinematic model
- **Normal Stress** σ_n : Lithostatic pressure $(\rho g z)$. Gradient 16MPa/km (fluids are included).
- **Dc:** slip weakening distance. Constant value or percentage of total slip.

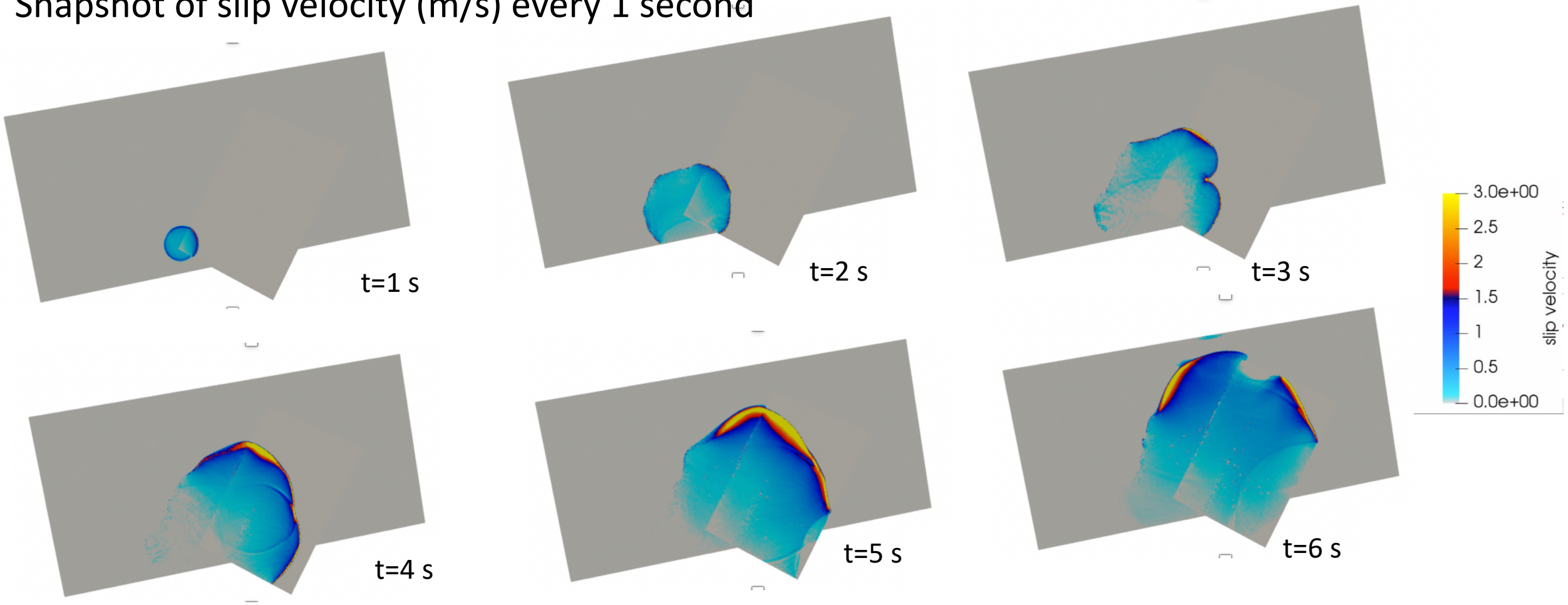
Initial conditions: $\Delta\tau = \tau_0 - \tau_f$



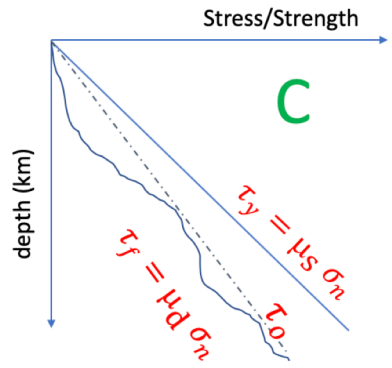


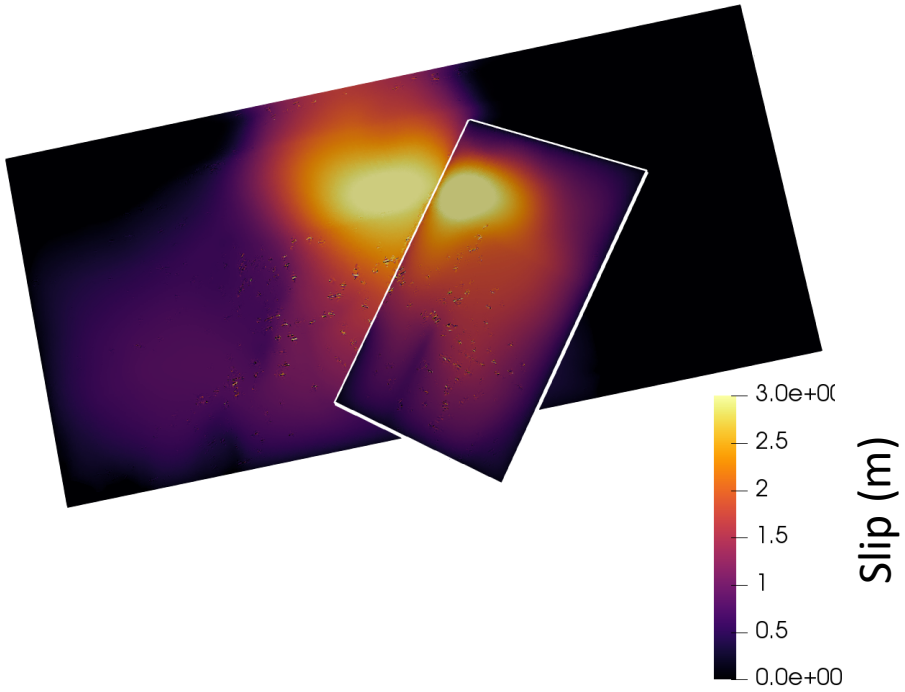


Snapshot of slip velocity (m/s) every 1 second



FAMILY-C:
Constant static friction & complex dynamic friction and stress

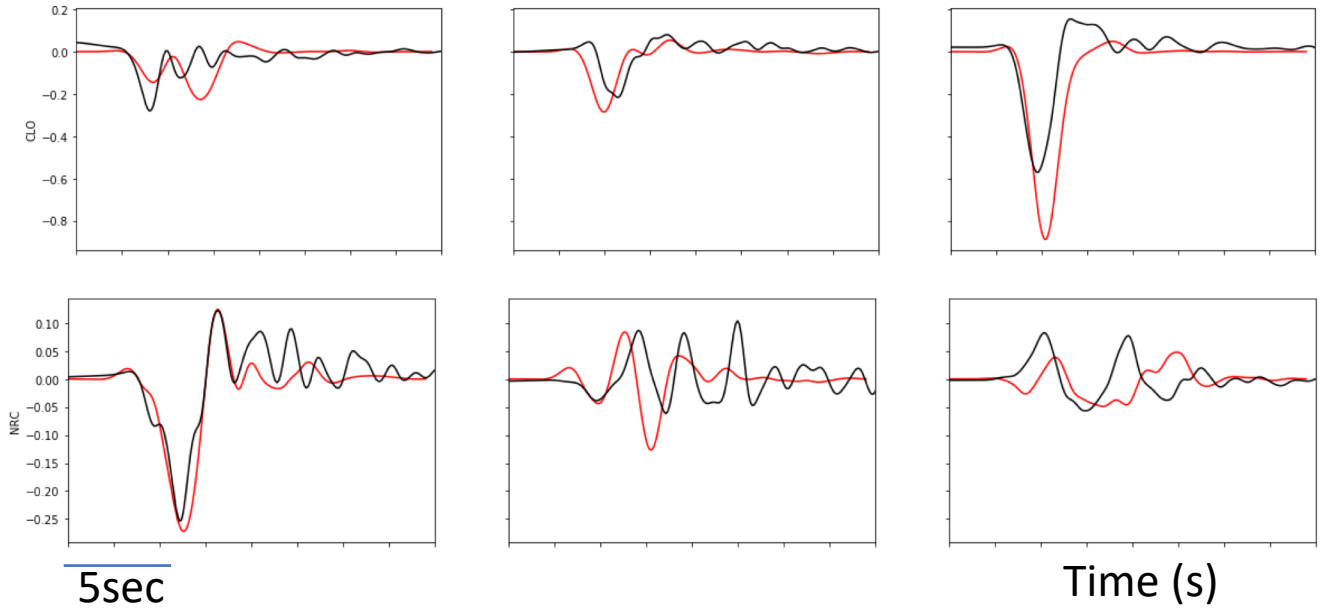




Final slip distribution is very similar to Scognamiglio et al. 2018

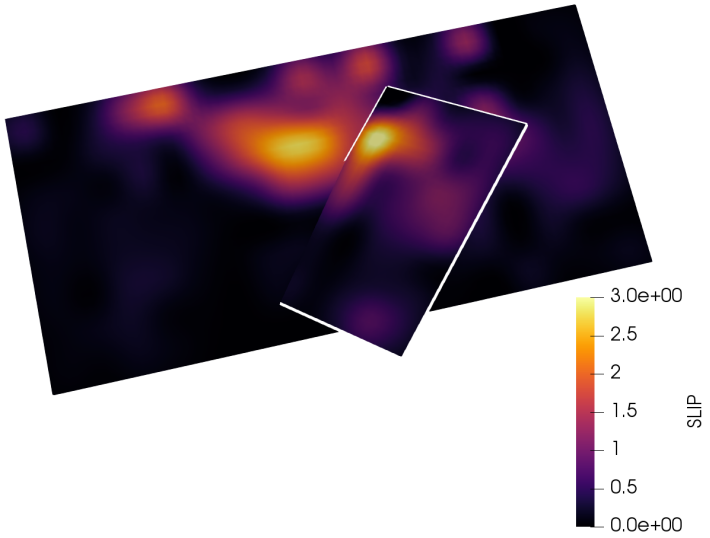
The sythetics are retrieved from the spontaneous dynamic model. Even we didn't invert the observed data, the synthetics are very similar to the data.

Closest stations

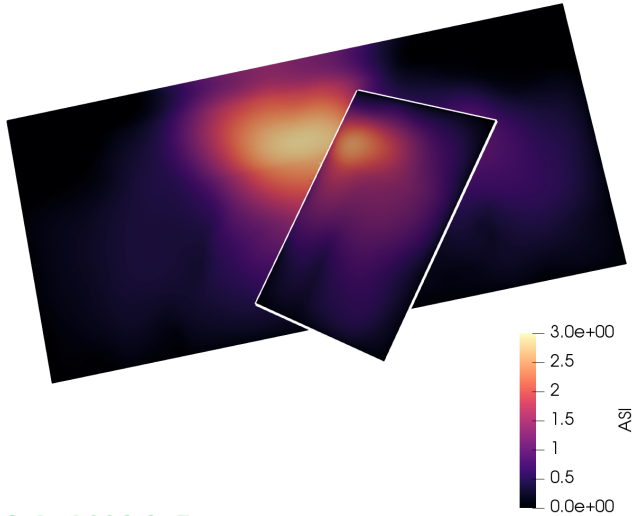


FAMILY-B & FAMILY-C

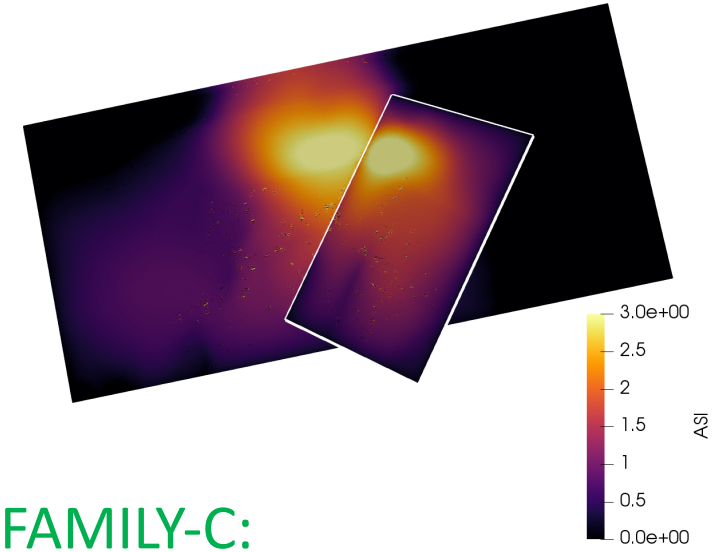
The models of family B and C with the spatially heterogeneous dynamic parameters allow us to retrieve slip distribution similar to Scognamiglio et al 2018 and a satisfactory fit with the observed waveforms even if we are not inverting any seismic data. These results suggest the existence of families of potential dynamic models able to support the kinematic model proposed by Scognamiglio et al 2018.



Original kinematic slip model by Scognamiglio et al 2018

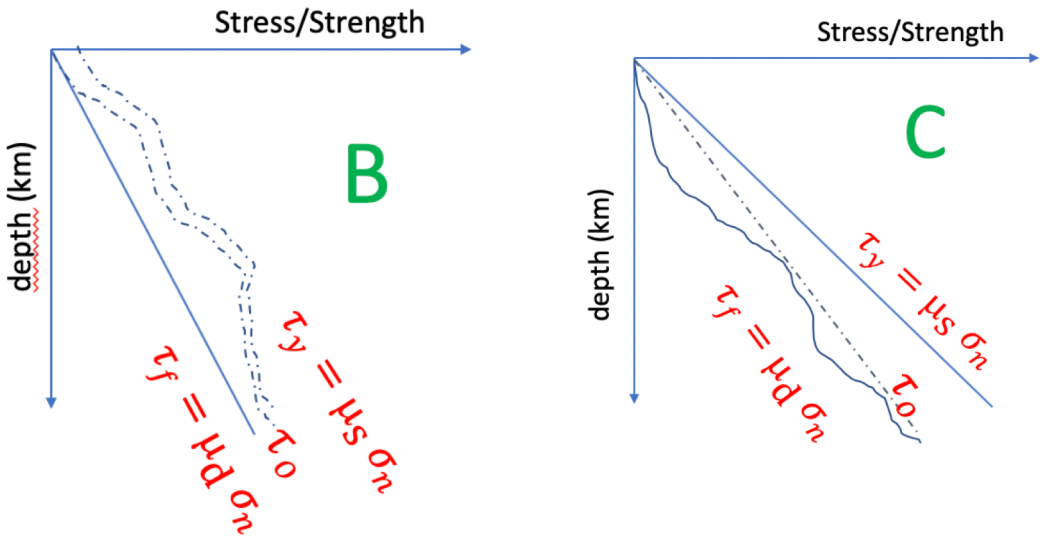


FAMILY-B:
Constant dynamic friction & complex static friction and stress



FAMILY-C:
Constant static friction & complex dynamic friction and stress

FAMILY-B & FAMILY-C



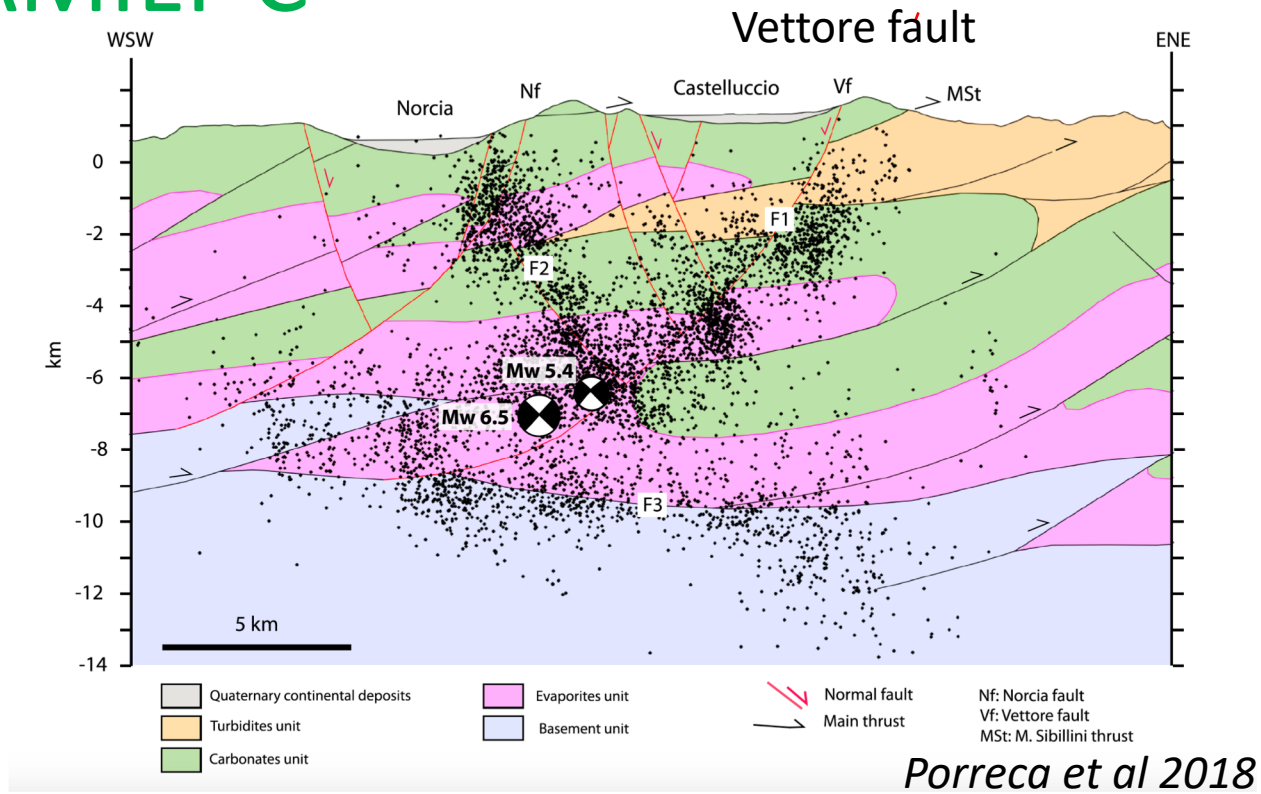
- The dynamic conditions of models B and C are very different:
  in MODEL B we assume homogeneous dynamic friction (0.2) and heterogenous static friction (0.2 - 0.6).
  in MODEL C we assume homogeneous static friction (0.6) and heterogenous dynamic friction (0.1 - 0.4).

These two different assumptions have implications on the description of the chemical-physical processes occurring in the fault plane. In particular, the choice has to be related to the rocks where the event nucleated and the rocks where the event propagated and generated a strong slip patch.

Discussions: FAMILY-B & FAMILY-C

The integration of seismic reflection profiles with seismological data shows that the mainshock nucleated within the Triassic Evaporites and laboratory data show that fault rocks in this lithology are characterized by a static friction in the range of 0.5-0.6.

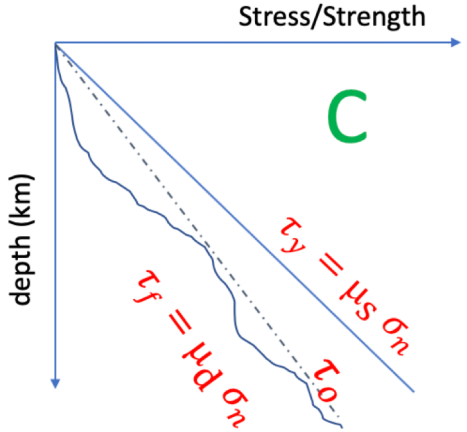
In addition, the main patch of slip is located in the carbonates where dynamic friction can be as low as 0.2 (e.g. De Paola et al., 2015).



Porreca et al 2018

Following this simple interpretation the models belong to family C represent the more plausible physical conditions and allow us to interpret the occurrence of a smooth nucleation (low energy) and the dynamic propagation at shallow depths.

However, a mixture of carbonates and evaporites (heterogeneous not only in depth) can characterize the fault, allowing the family of models B be potentially realistic.



Conclusions

- Even if the fault 210 is misoriented respect to the actual extensional field characterizing the central Apennines and it has a small dip angle (37°) is able to allow a spontaneous rupture propagation with a significative left-lateral slip component.

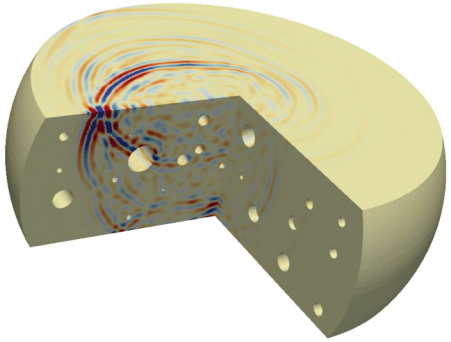
- Physics-based modeling provides mechanically viable insight into the physical conditions that allow ruptures on complex fault systems and helps constraining competing processes during earthquake ruptures.

- The showed dynamic models are not the best dynamic models but they represent potential models families describing what happened during the event.

- Seismic reflection profiles and laboratory experiments can help us to refine and corroborate our dynamic models. Due to the limited resolution of seismological data (e.g., no inferences can be done on Dc parameters), these information can further improve the new generation of dynamic model inversions.

- Advances in high-performance computing and dense observations can allow us to improve the reliability of released kinematic and dynamic models and to quantify the uncertainties.

Thanks



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