Calibration of subsurface dynamic parameters and fault geometry from surface fault rupture observations: an example from the shallow 2019 Mw4.9 Le Teil (France) event.

Sassi Rihab, Hok Sébastien, Klinger Yann, Delouis Bertrand

Calibration of Subsurface Dynamic Parameters and Fault Geometry From Surface Fault Rupture Observations: An Example From the Shallow 2019 mw4.9 Le Teil, France, Event

Rihab Sassi (1), Sébastien Hok (1), Yann Klinger (2), Bertrand Delouis (3)
(1) Institute for Radiological Protection and Nuclear Safety (IRSN), (2) Institut de Physique du Globe de Paris, (3) Geoazur-Université Côte d'Azur

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Abstract

We investigate the impact of several friction, stress drop and fault geometry on surface fault rupture amount and patterns. Based on a shallow reverse surface rupturing Mw4.9 earthquake which occurred in southeastern France in November 2019, and models derived from data collected (InSAR, waveforms), we set up a rupture scenario that is consistent with the observations. From this kinematic scenario we constrain the dynamic parameters of the deeper part of the rupture (300-2 km depth), while we test the shallow part parameters (<300m). The surface rupture produced by the different models are then compared to the surface deformation patterns and amplitude.

We show that the shallow surface layers are likely slip-strengthening, but also that the surface rupture is not a passive marker of the deeper rupture process: they are both linked. The frictional behavior (Dc, Stress drop, weakening or strengthening) directly modulates the amount of surface rupture. Dynamic rupture history notably differs from the kinematic model, although the friction evolution of the first was directly derived from the second. Adding a secondary structure in the northern part improves significantly the surface rupture fit, as well as the rupture history. Finally, such a shallow reverse fault earthquake seen through its dynamics emphasizes a puzzling question: what is the absolute level of stress on a seismogenic fault so close to the surface?

Le Teil (Mw 4.9) Earthquake, France

On November 2019, a damaging Mw 4.9 earthquake stroke the Rhone valley river, close to the city of Montelimar in the south east of France, a densely populated area with several operating nuclear power plants.

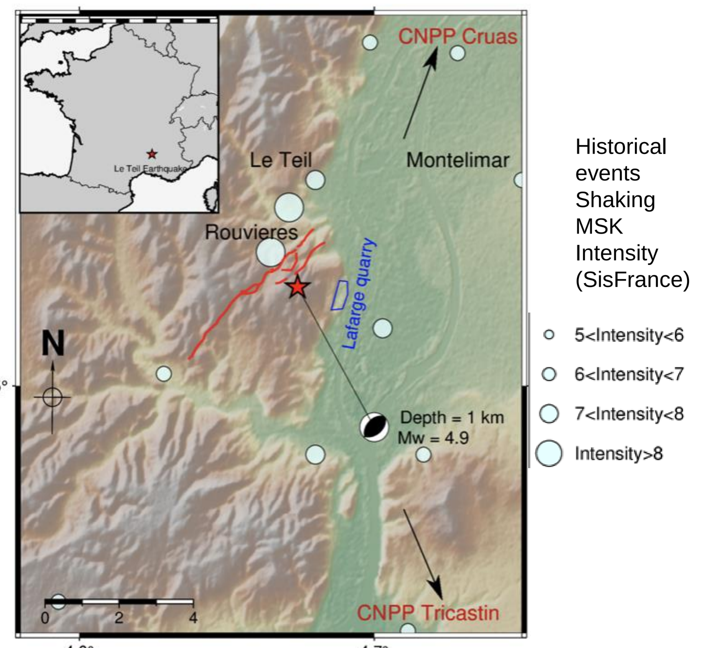


Fig. 1 The Le Teil earthquake context

The earthquake propagated along the La Rouvière fault, an ancient normal fault reactivated in reverse faulting during the Le Teil earthquake.

Its hypocentral depth is shallow, about 1 km (Delouis et al 2021), and it ruptured more than 4.5 km of ground surface (Ritz et al 2020).

In this study, we investigate the surface rupture associated to the Le Teil earthquake through physics-based source modelling. The question addressed is how can surface deformation can be related to deep rupture features and fault geometry? In a first part, we study the impact of subsurface frictional properties on permanent surface displacement. In the second part, we examined the impact of fault geometry on ground surface deformation. We used InSAR surface deformation data to validate our theoretical models.

Method

- We simulate both kinematic and dynamic rupture propagation on a fault plane using a 3D Boundary Integral Equation Method to compute the rupture history and the permanent ground surface deformation (Hok & Fukuyama 2011). Due to this simple formulation, we use homogeneous elastic half space for those models.
- The fault geometry : Planar fault in agreement with geological mapping InSAR inversion and focal mechanism.
- The initial stress state : We assume a compressive stress field stress then estimate normal and shear stress considering the fault orientation.
- The fault is NOT well oriented to generate a thrust-mechanism rupture… + quite SMALL asperities (Δσ ~20MPa at 500m) => large stresses at shallow depth ?

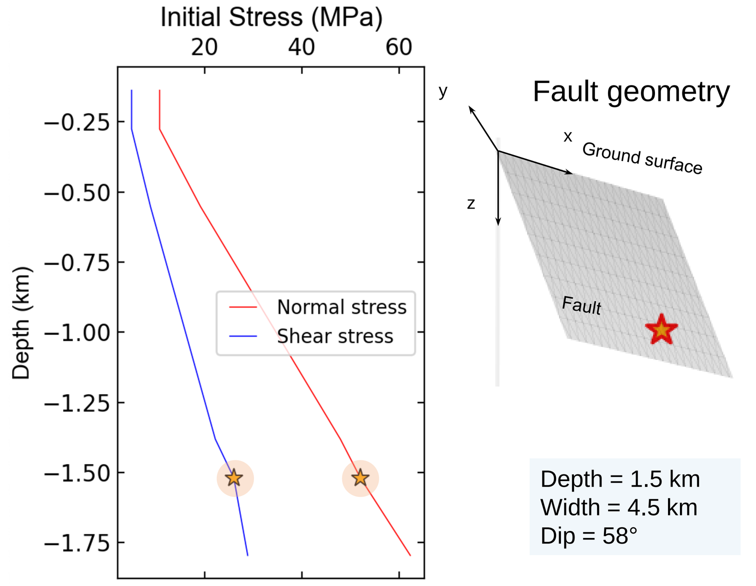
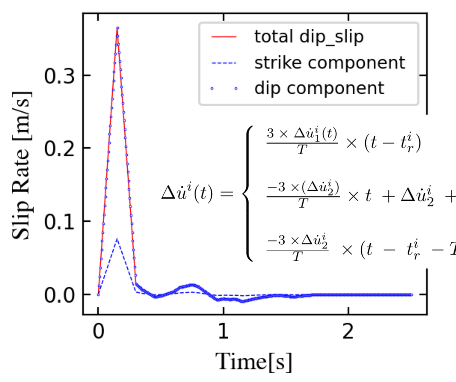


Fig.2 Initial stress field and fault geometry used for dynamic simulations

Procedure and model settings

1/ Source rupture model from kinematic wave inversion

Fig.3 Source Time Function



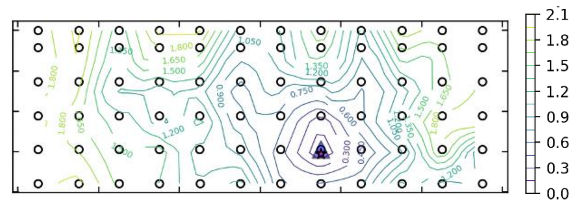
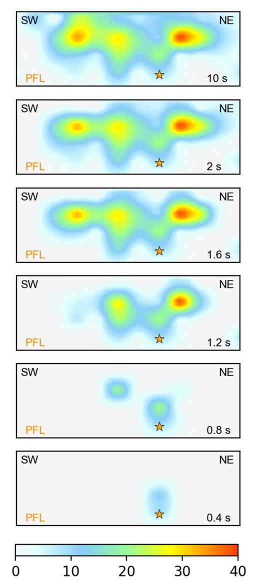


Fig.4 Rupture time (s)

Fig.5 Kinematic Slip evolution



- **Source history from a kinematic wave inversion model (Delouis et al 2020).**
- The slip-rate evolution for each subfault is estimated using a piecewise continuous function (Fig.3)
- Rupture time contours (Fig.4) and dip slip evolution (Fig.5) estimated from kinematic wave inversion.

2/ Space and time stress change estimation from kinematic rupture simulations

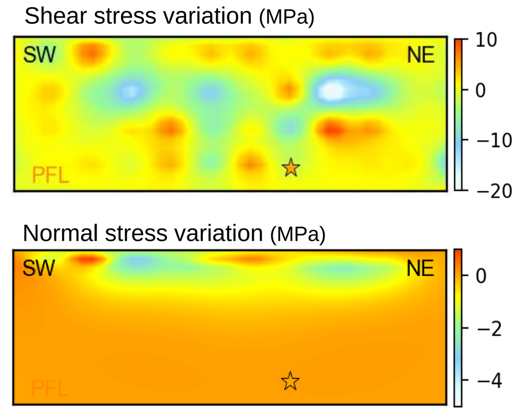


Fig.6 Stress variations

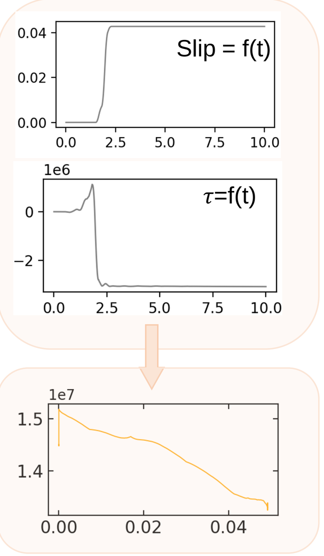


Fig.7 Example of subfault friction law estimated from kinematic simulation.

We impose the fault slip history estimated from the wave inversion data to estimate the stress variation at each position.

The evolution of traction as function of slip is used to deduce the friction law for each position of the fault model.

Results : WHAT IS IMPACTING SURFACE RUPTURE?

Changing subsurface frictional properties

- homogenizing frictional properties for the shallow layer (300 meters), keeping the heterogeneous frictional properties at depth (Fig. 8).
- Simulation of the rupture propagation under diffrenet shallow stress drops , strength excess and critical slip distance values (Fig. 9).

Fig.8 Shear stress distributions for the heterogeneous and homogeneous models

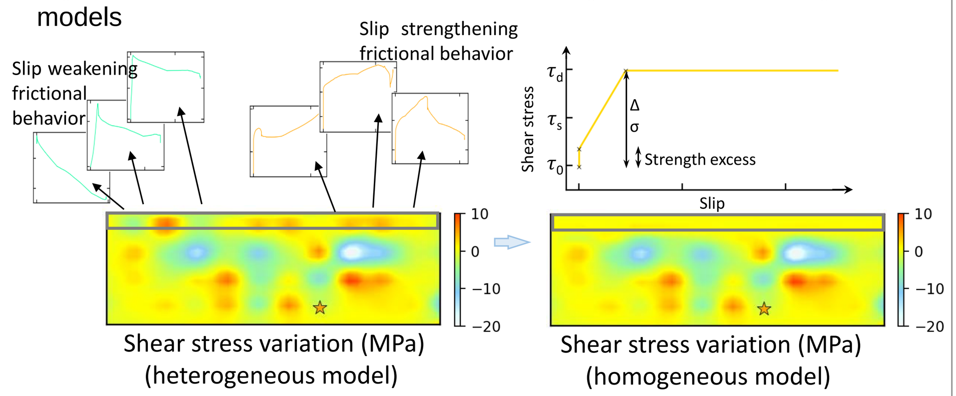
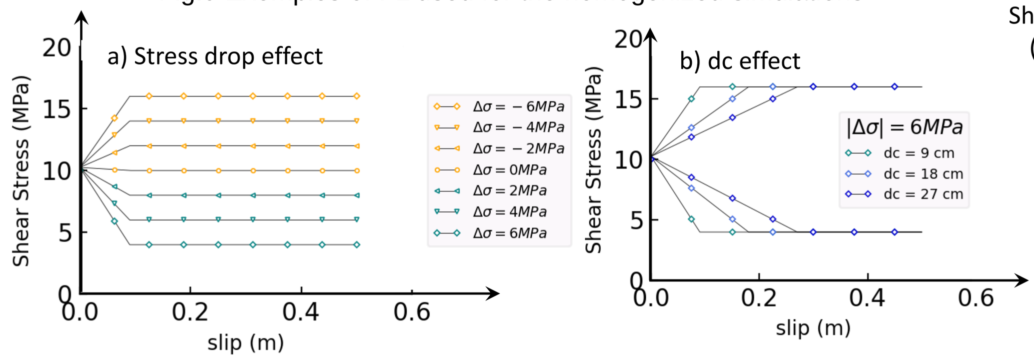


Fig.9 Exemples of FL used for the homogenized simulations



- Fig. 9a represents friction laws used for different tested **stress drop** values, for the 7 different cases tested.
- Fig. 9b represents friction laws used (6 cases) to study the **critical slip distance** impact on free surface displacement under a stress drop values of 6 MPa (circle markers) and -6 MPa (diamond markers).

SHALLOW LAYER STRESS DROP

Snapshots of dynamic rupture propagation under different shallow stress drop levels (Fig. 10) show:

- There is a strong interaction between shallow and deep rupture in terms of rupture front propagation and slip amounts.
- Rupture duration depends on shallow fault mechanical properties.
- Amplification or attenuation of the rupture velocity all over the fault plane.
- Change of the rupture history.

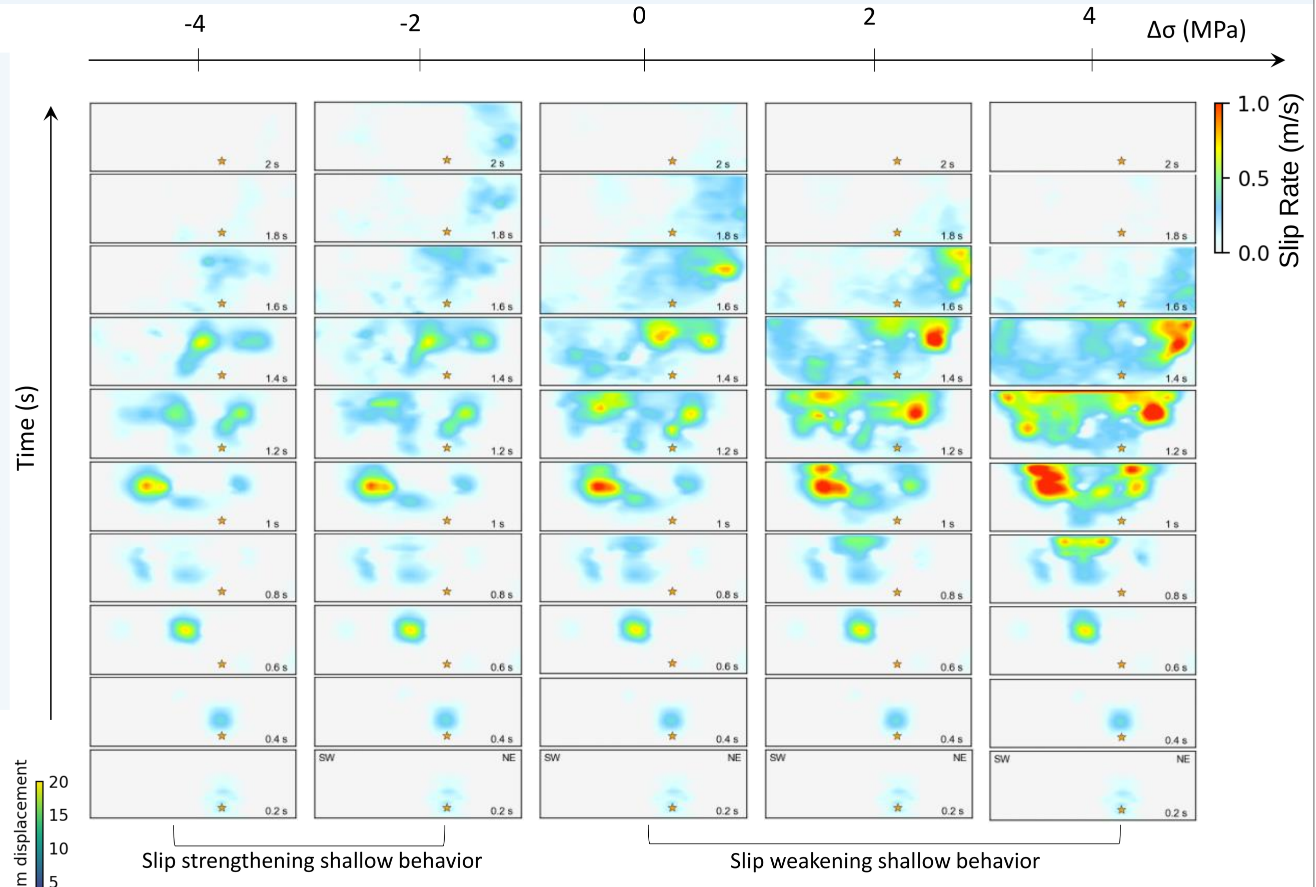


Fig.10 Snapshots of dynamic rupture propagation under different shallow stress drop levels

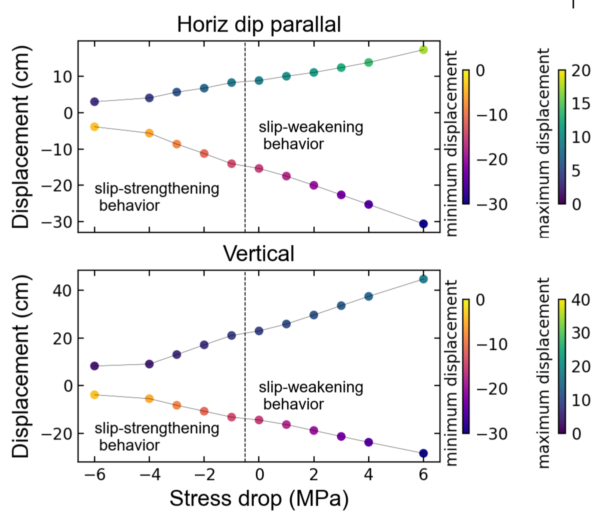


Fig.11 Maximum and minimum surface displacement

Maximum ground surface offset components across the different shallow stress drop levels (Fig. 11).

- The sensitivity of permanent surface displacement to the shallow stress drop level is more important in the slip-weakening behaviour than slip-strengthening behaviour cases.
- Considering a single fault geometry, the surface vertical offset (~20 cm) observed during the 2019 Mw 4.9 Le Teil EQ is conditioned by a slip-strengthening shallow frictional behaviour and a stress drop amount of about -3 MPa.

SHALLOW LAYER dc (and FRICTION LAW SLOPE)

Final slip distribution under different shallow stress drop and dc levels for slip-weakening and slip-strengthening behaviours in shown on Figs. 12a and 12c. Each panel represents a single simulation.

SLIP WEAKENING (Unstable)

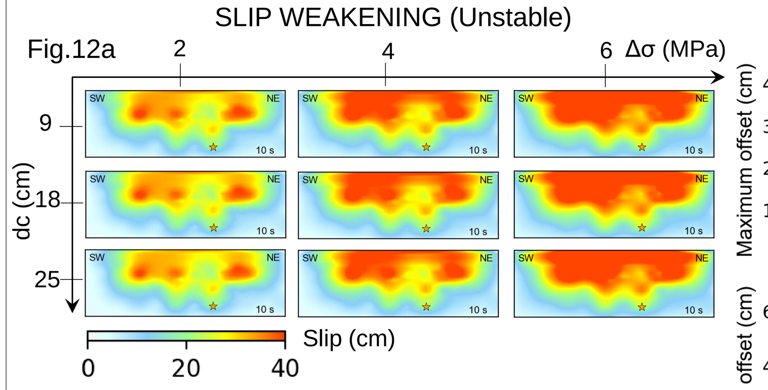
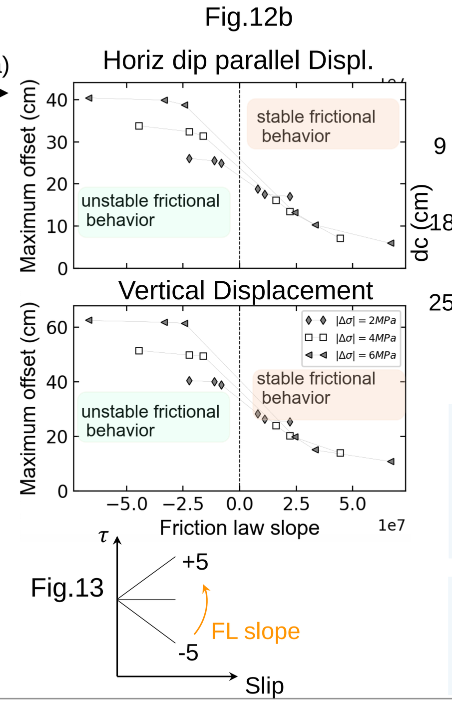
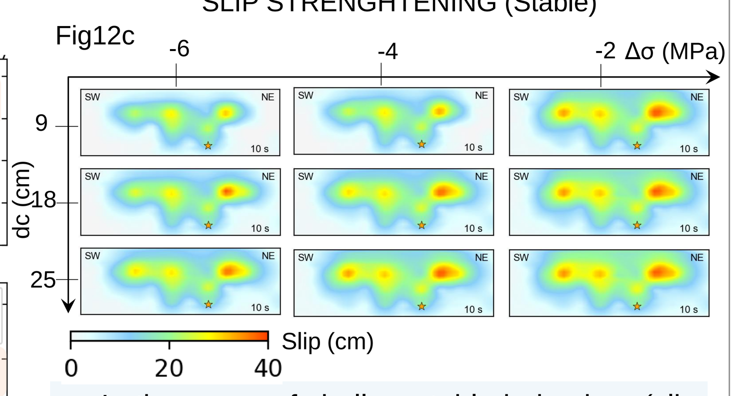


Fig.12b



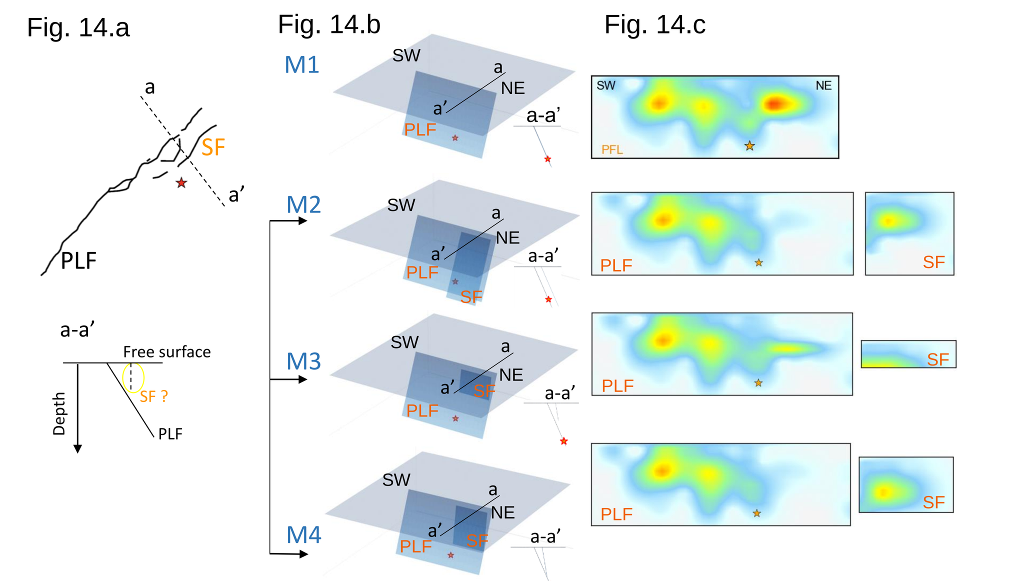
SLIP STRENGHTENING (Stable)



- In the cases of shallow unstable behaviour, (slip weakening) the maximum ground surface displacement is only controlled by the stress drop (Figs. 12ab) ; the sensitivity to dc does not show off. We interpret this as a consequence of final slip being significantly larger than dc.
- In the cases of shallow stable behaviour (slip strengthening), the maximum surface displacement is sensitive to both dc and stress drop (Figs. 12bc).
- There is a correlation between the amount of slip at surface and the slope of the slip friction law (Figs. 12b &13).

FAULT GEOMETRY : A SECONDARY STRUCTURE ACTIVATION?

According to mapped surface ruptures (Fig. 14a) and InSAR unwrapped deformation (Fig. 15), in the northern part of the rupture a secondary fault accommodates more displacement than the main fault.



To test the propagation of the rupture on 2 faults, we first distribute the slip on secondary fault (Fig. 14c), use the kinematics to determine the friction evolution in each model, then compute the spontaneous rupture propagation

We assume a principal fault (PLF) geometry based on geological studies (ritz et al 2020)

We test three different geometries for the unknown secondary fault (SF): M2, M3, M4 (Fig. 14b)

Free surface displacement of the Le Teil EQ from spontaneous rupture propagation

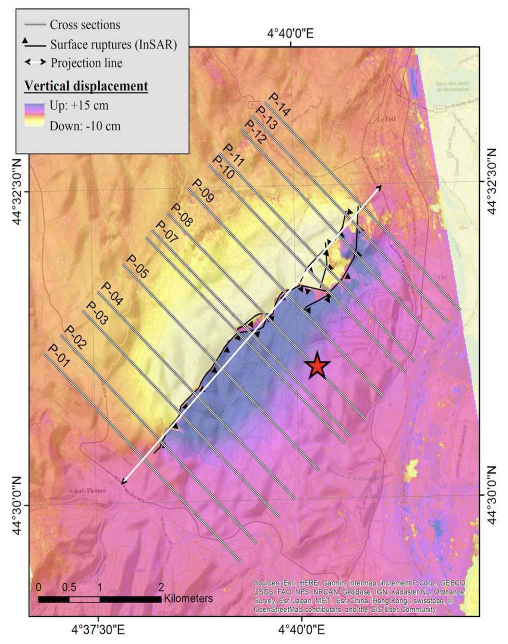


Fig.15 Permanent vertical surface displacement from InSAR (from Ritz et al 2020).

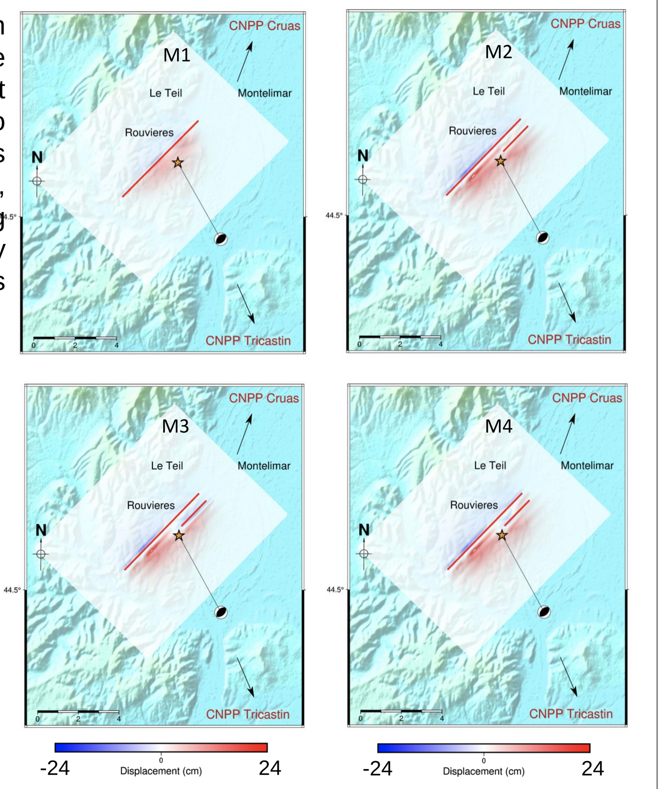


Fig.16 Comparison of synthetic surface vertical displacement associated to different fault models M1 (single fault), M2, M3 and M4 having different secondary fault geometries

Introducing the secondary fault leads to a better qualitative agreement between InSAR and synthetic surface vertical deformation, especially in the northern part of the rupture, where a single fault does not match the observations, for all models. Based on profiles P10 and 12, M4 model seems to show best agreement.

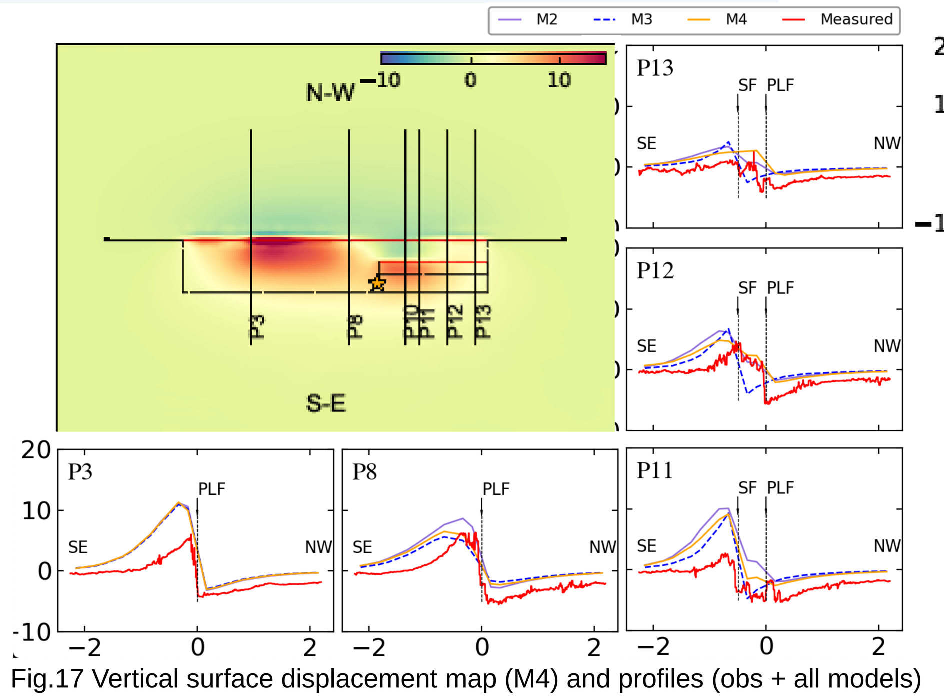


Fig.17 Vertical surface displacement map (M4) and profiles (obs + all models)

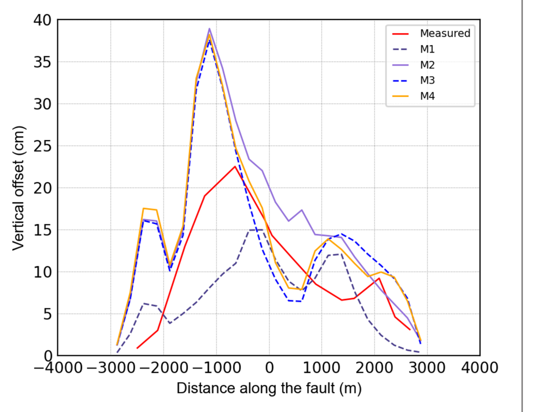


Fig.18 Along strike rupture offset (PLF)

Conclusions & Discussions

- The shallow layer frictional behaviour (stress drop, slip weakening or slip strengthening distance) directly modulates the amount of surface rupture. The slope of the friction law seems to be the scaling parameter. In turns, the rupture history and the slip amount at depth depends on shallow slip amount.
- Based on the amount of slip observed during Le Teil EQ, it seems that the shallow layer behaviour of the fault was slightly slip strengthening.
- Dynamic rupture models show a great sensitivity to initial stress, shallow surface parameters and secondary fault rupture, and although governed by kinematic-derived FL, have propagations histories different than kinematics. Dynamic rupture needs large initial stresses to propagate ; this questions the initial kinematic model, or the physics of rupture that was used in our study (rate-dependent friction, fluids)
- Adding the northern secondary structure improves qualitatively the agreement of surface deformation and the rupture propagation (bilateral like kinematics). Dynamic branching on the secondary fault is very sensitive to the fault orientation and occurs for connected branch close to the hypocenter.