Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 8: dynamic source inversion

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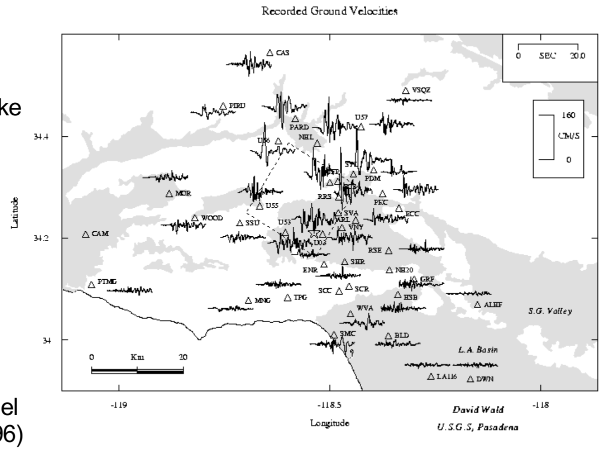
Dynamic source inversion

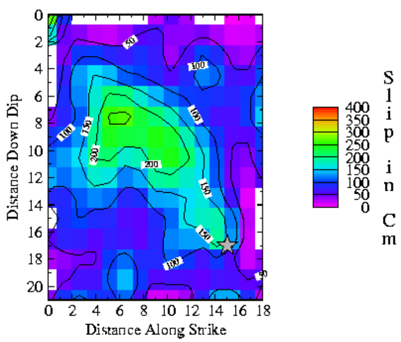
- Definition
- Early attempts
- Trade-offs
- Simplified parameterizations
- State-of-the-art
- Perspectives

Kinematics and dynamics

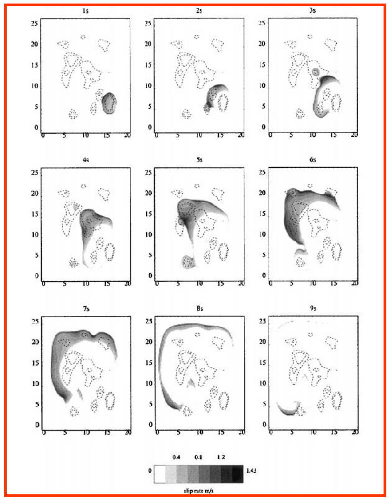
Seismograms of the Northridge earthquake 1994 M6.7



Kinematic model (Wald et al 1996)



Dynamic model (Nielsen and Olsen 2000), dashed contours = high initial stress



Ground motion observations :
Seismograms, geodesy

- Waveforms + static deformation
- Spectra
- Radiated energy
- HF envelopes

Kinematic models (how?)

→ description of the earthquake rupture history :

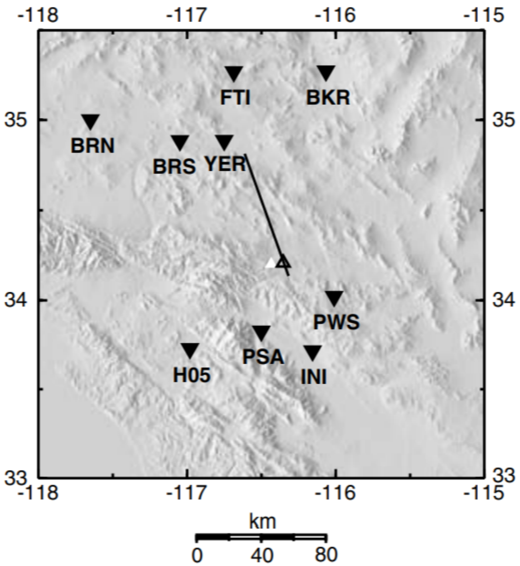
- Local final slip
- Rise time
- Rupture velocity

Dynamic models (why?)

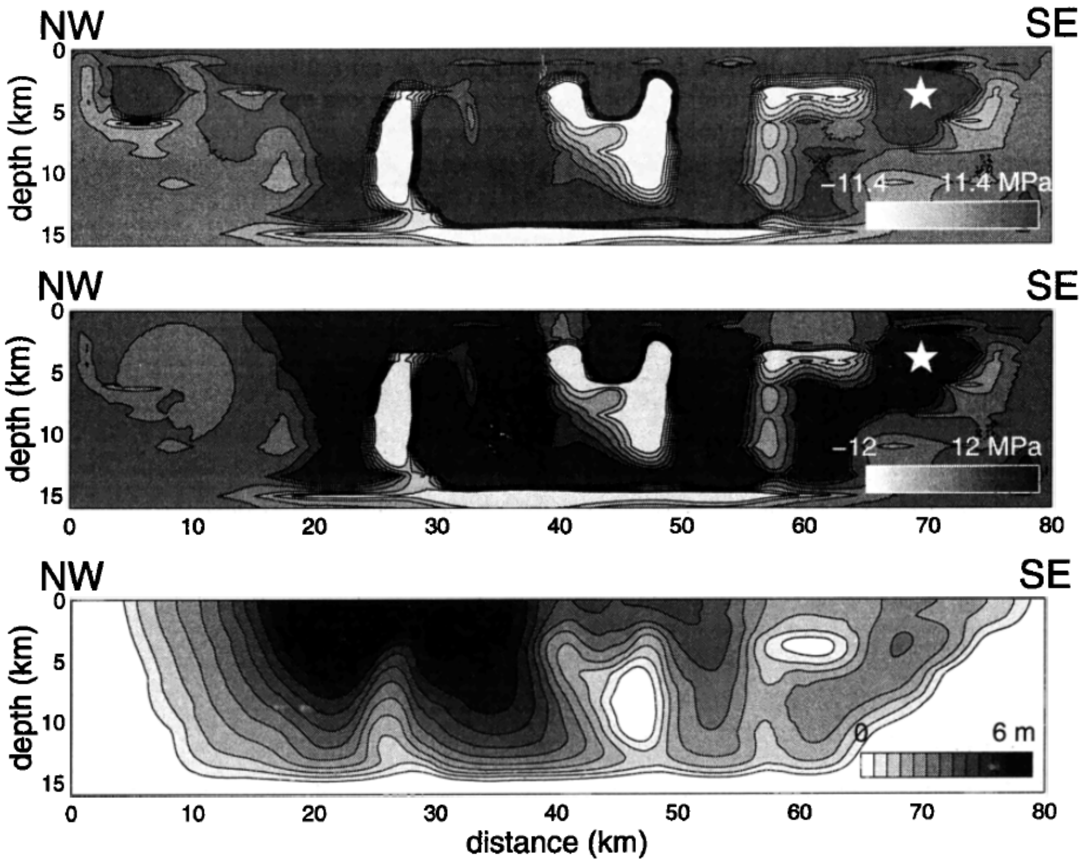
→ Physical interpretation of earthquake rupture :

- Fault constitutive law : **strength**, weakening, fracture energy, etc
- Initial conditions: **stress**, state, etc

Early attempts of dynamic source inversion



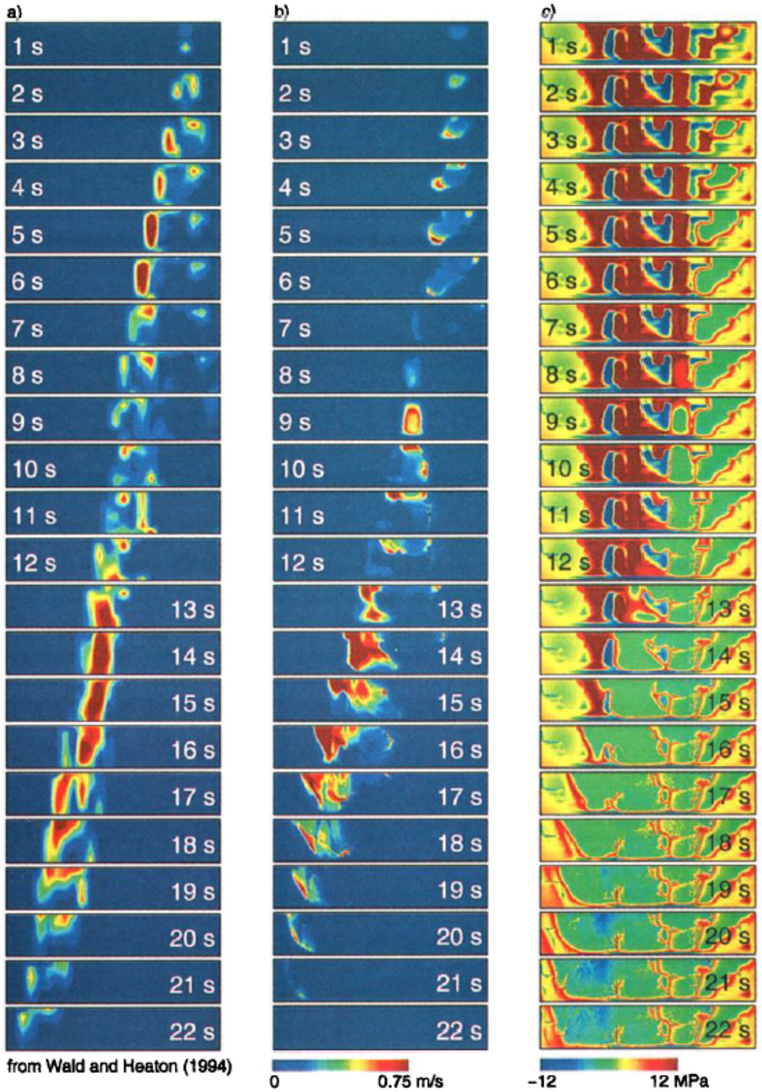
Peyrat et al (2001)
1992 Landers earthquake
Trial and error inversion.
Fixed Dc

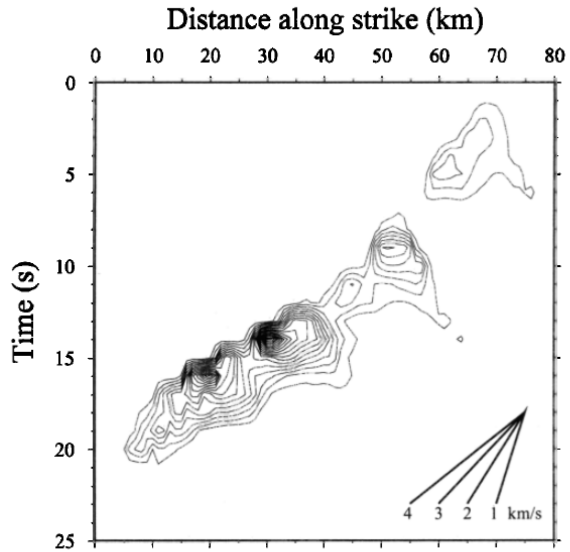


$\tau_0(x)$
Prior
model

$\tau_0(x)$
Preferred
model

Final slip
Preferred
model





Peyrat et al (2001)
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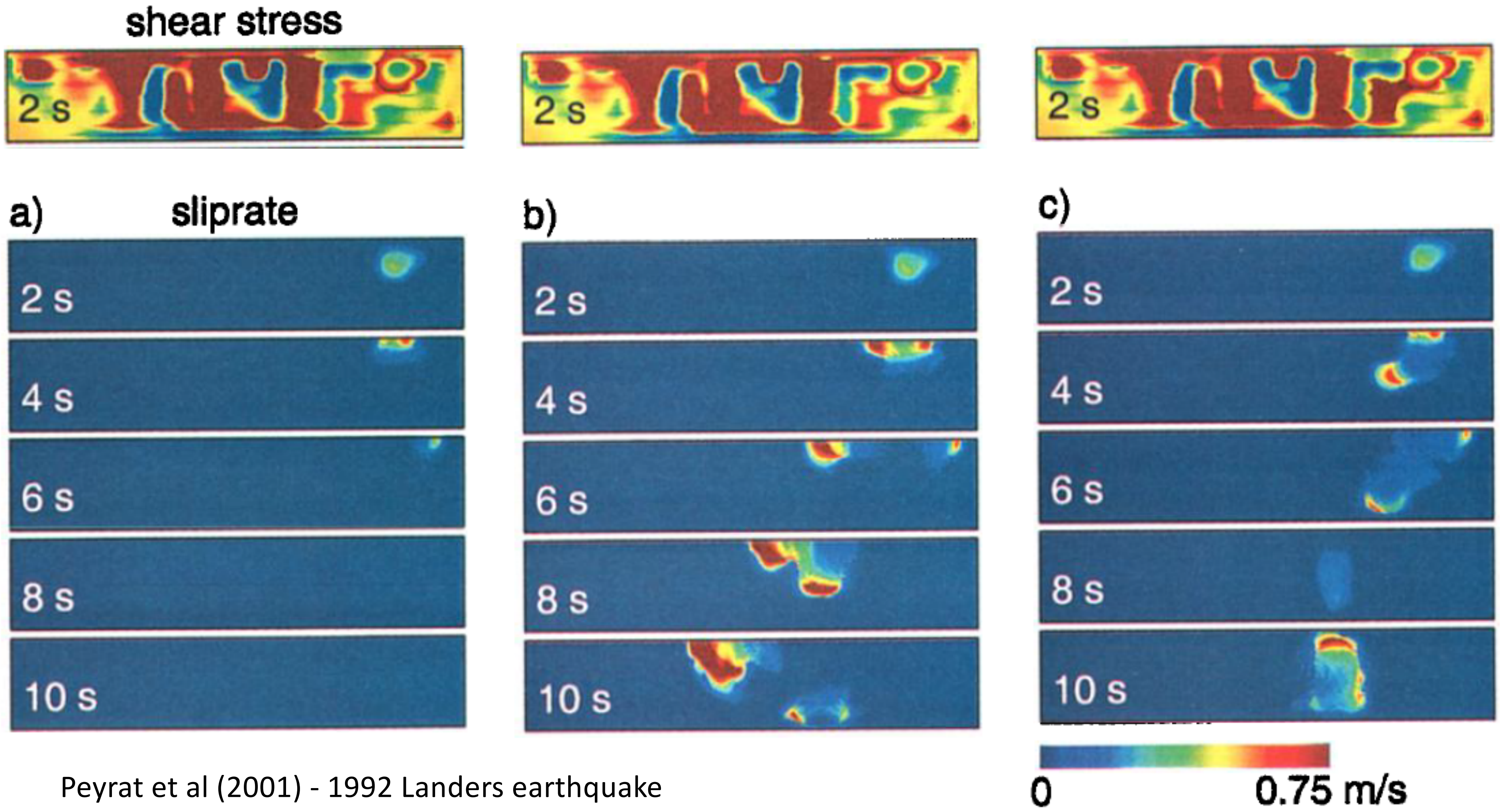
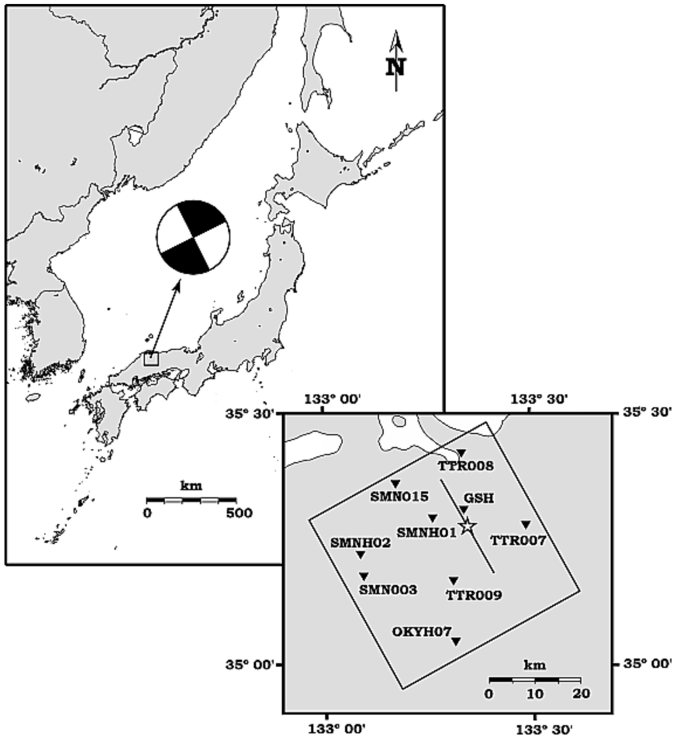
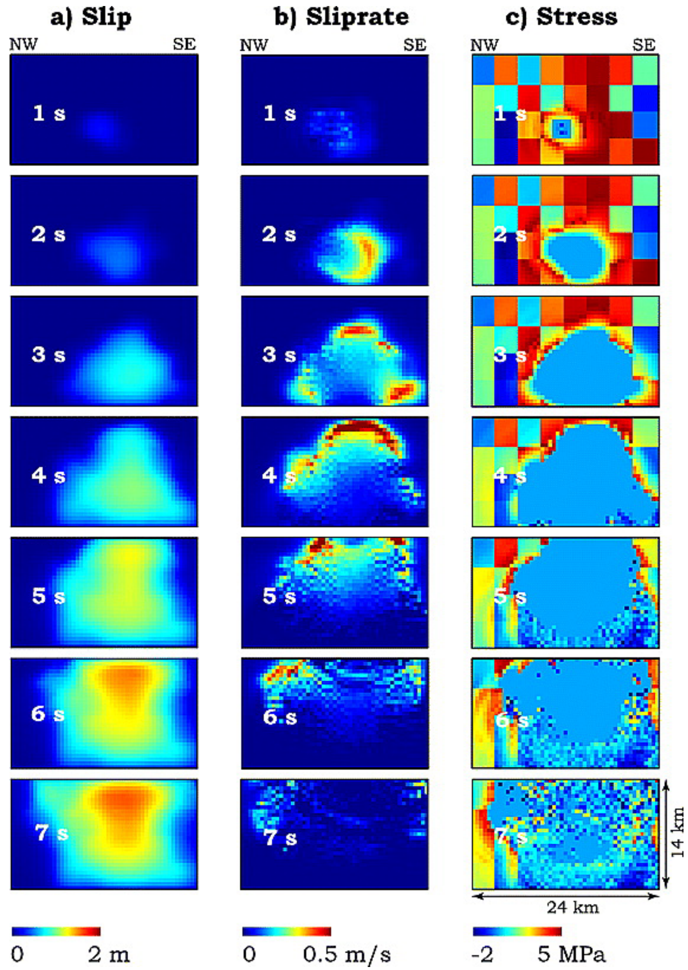
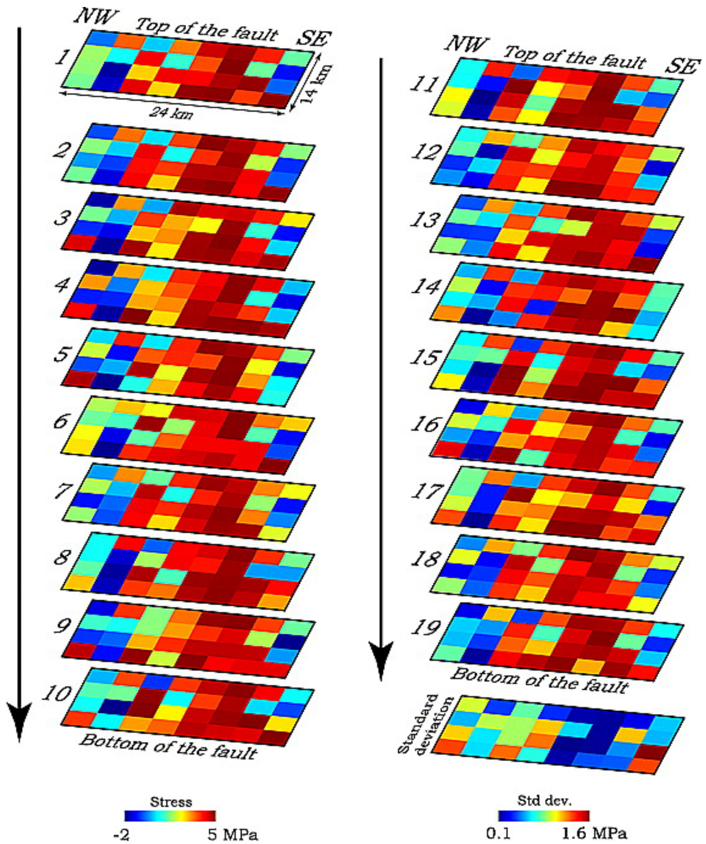


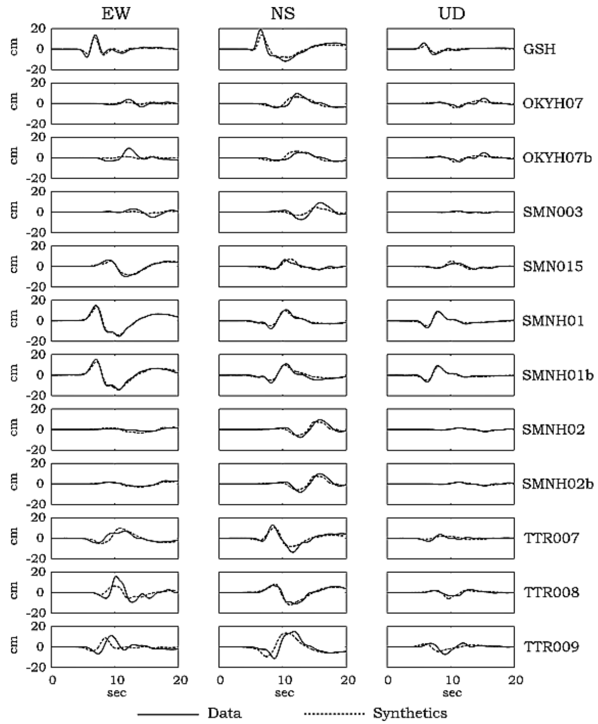
Peyrat et al (2001) - 1992 Landers earthquake



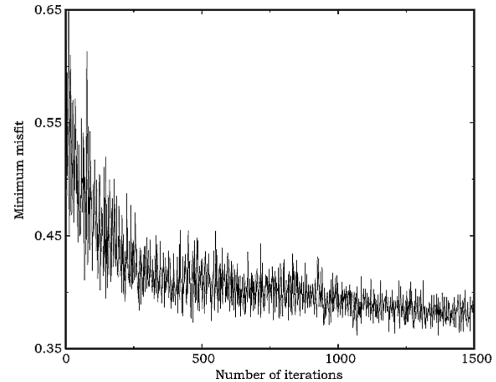


Peyrat and Olsen (2004)
2000 Mw 6.6 Tottori, Japan earthquake
Non-linear inversion by Neighborhoood Algorithm



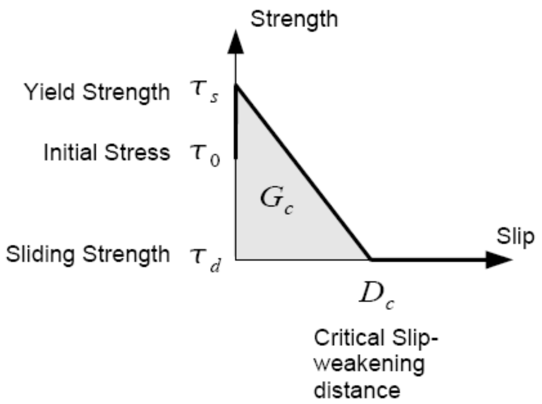


Non-linear inversion required 60,000 computations of forward problem



Peyrat and Olsen (2004) - 2000 Mw 6.6 Tottori, Japan earthquake

Trade-off between dynamic rupture parameters



Spudich & Guatteri: trade-off between $(\tau_s - \tau_d)$ and D_c when the inversion is based on low frequency data

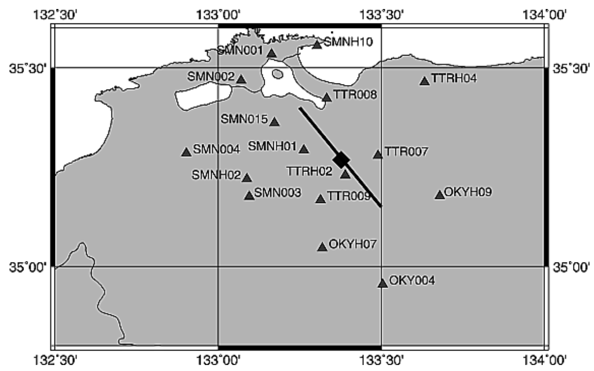
Physical explanation:

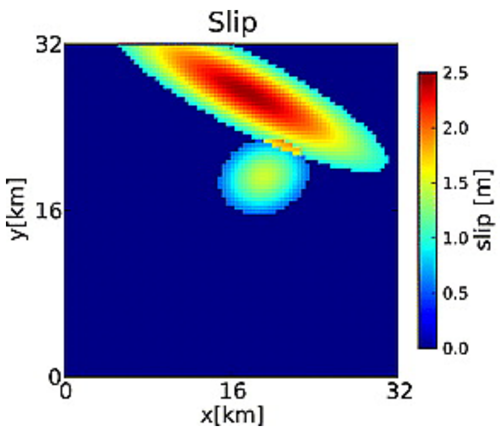
- Static elasticity → final slip $D(x)$ depends linearly on stress drop $\Delta\tau(x) = \tau_0(x) - \tau_d(x)$
- Fracture mechanics → First-order aspects of dynamic rupture depend on the non-dimensional number

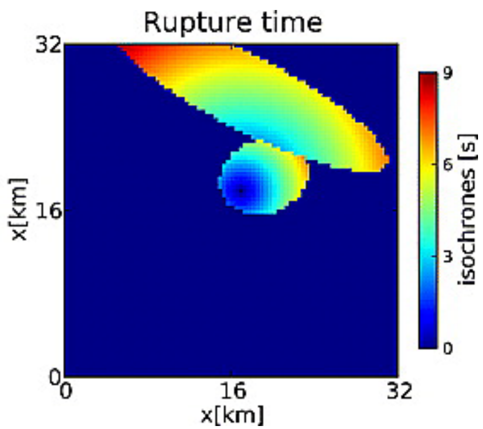
$$\kappa = G_0/G_c \sim \frac{(\tau_0 - \tau_d)W^2}{\mu(\tau_s - \tau_d)D_c}$$

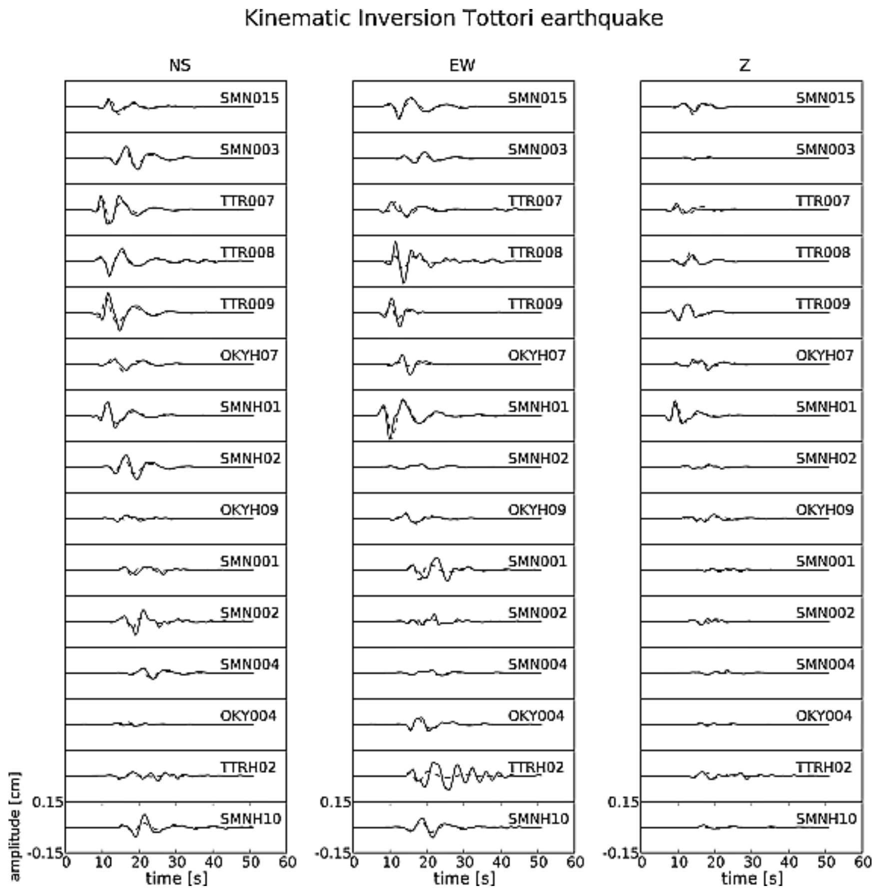
Di Carli et al (2010) - Tottori earthquake

Dynamic source inversion based on elliptical patches







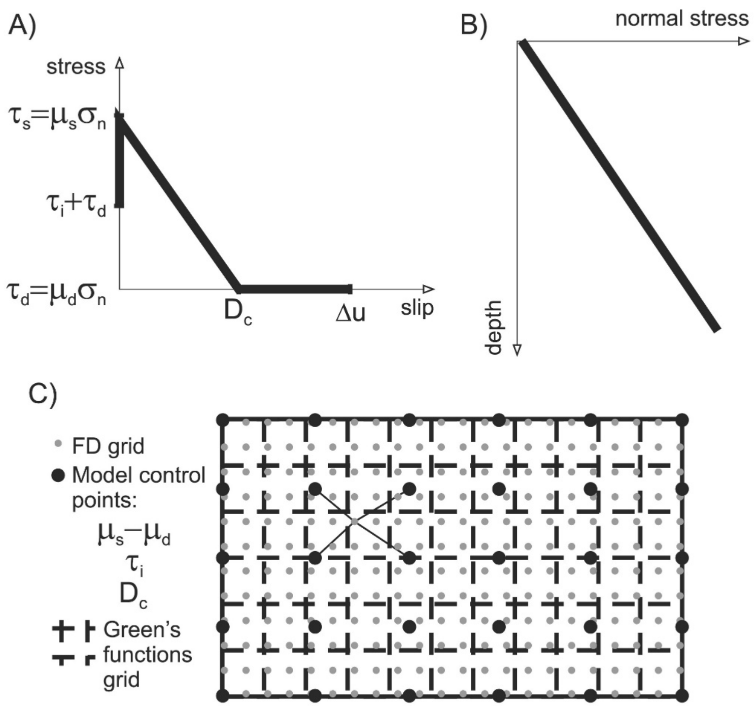


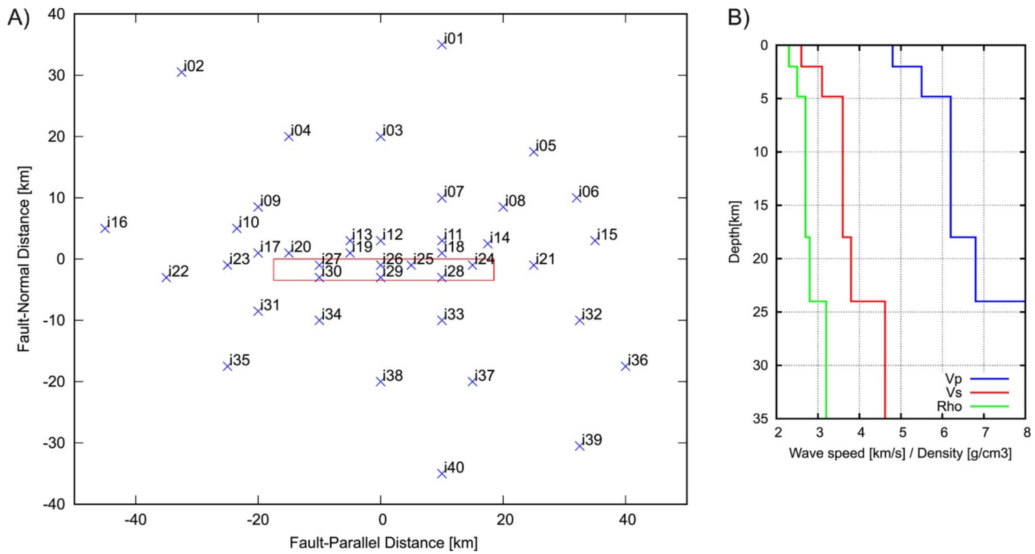
Dynamic source inversion

Gallovic et al (JGR 2019)

Forward problem is computationally expensive
→ optimized FD code, simple geometry

Uncertainty quantification
→ Bayesian sampling with Parallel Tempering Monte Carlo



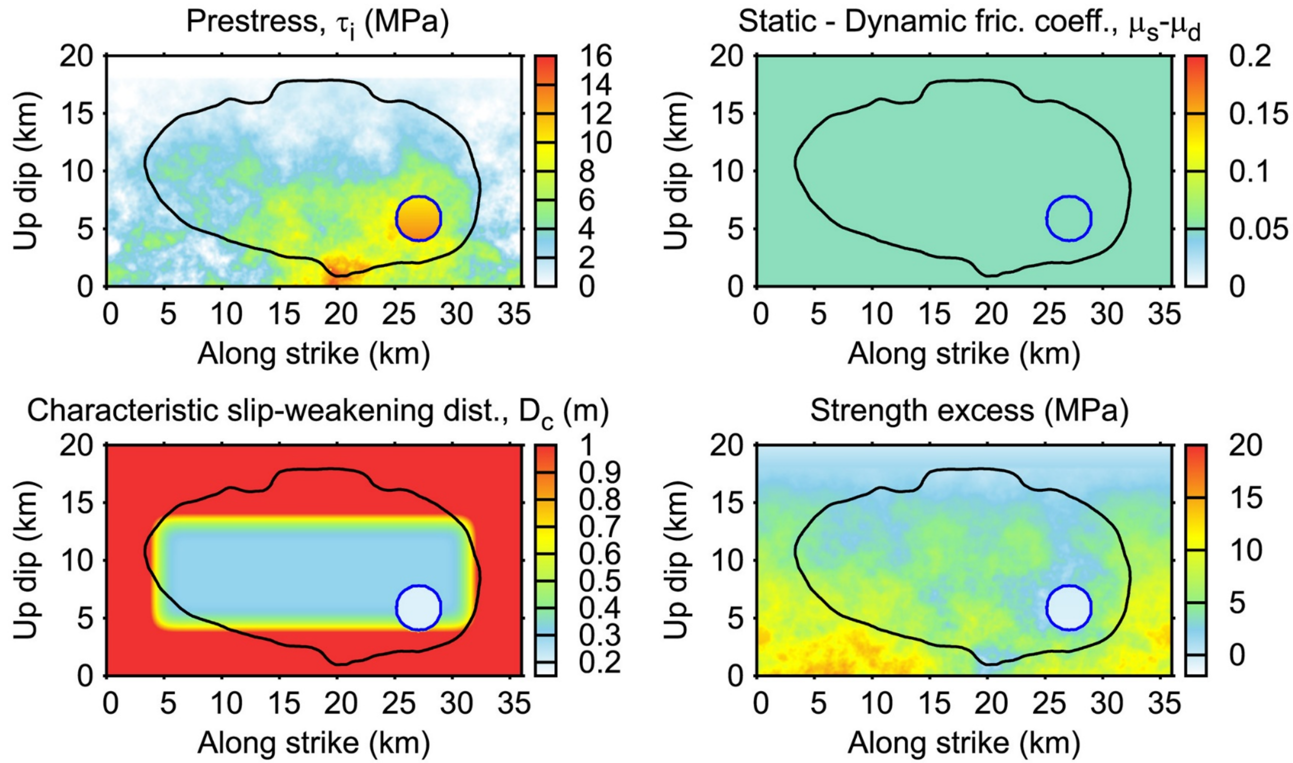


Dynamic source inversion

Gallovic et al (JGR 2019)

Synthetic test

Input dynamic parameters of the target model (SIV Inv1 test problem)

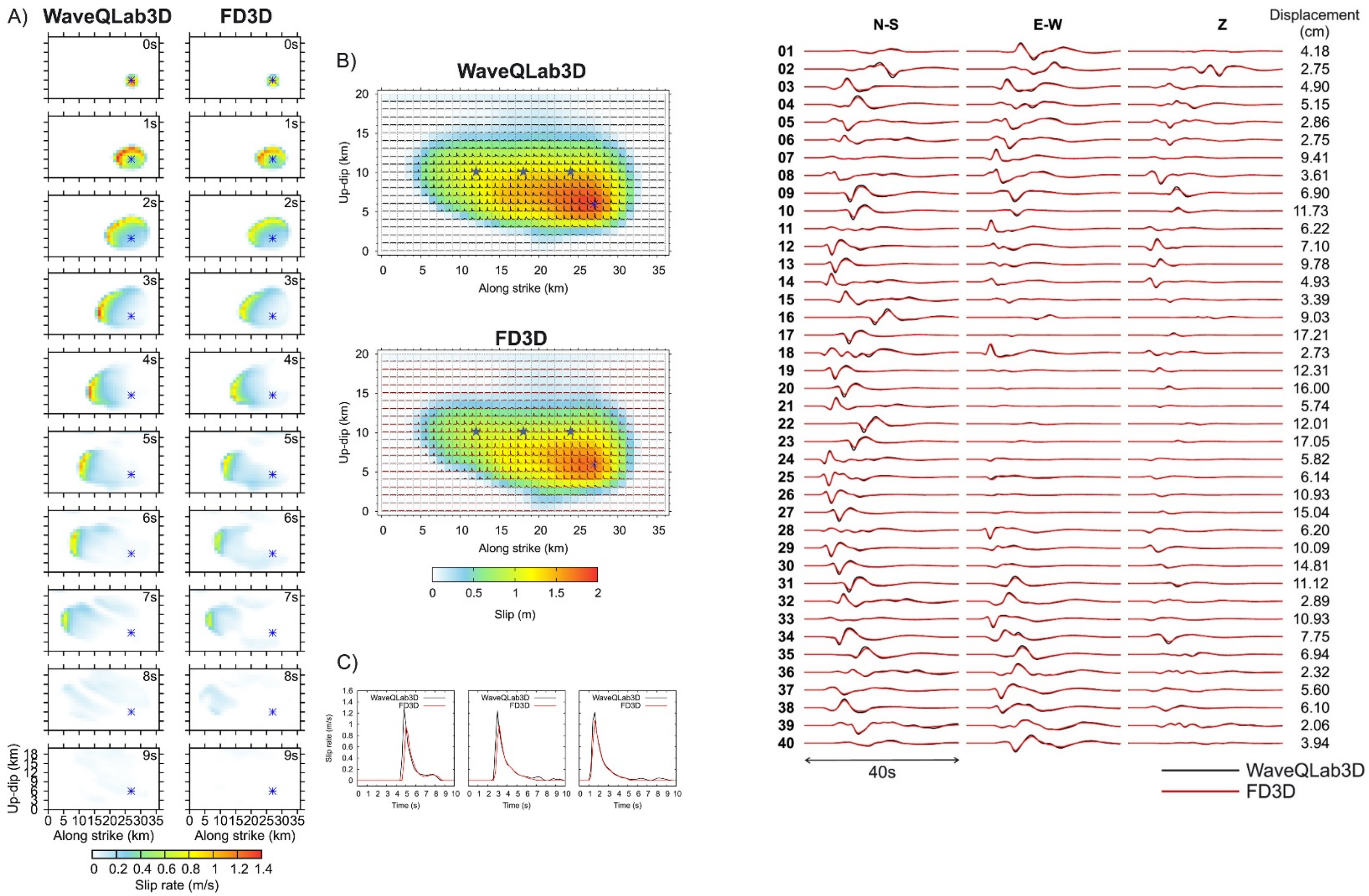


Dynamic source inversion

Gallovic et al (JGR 2019)

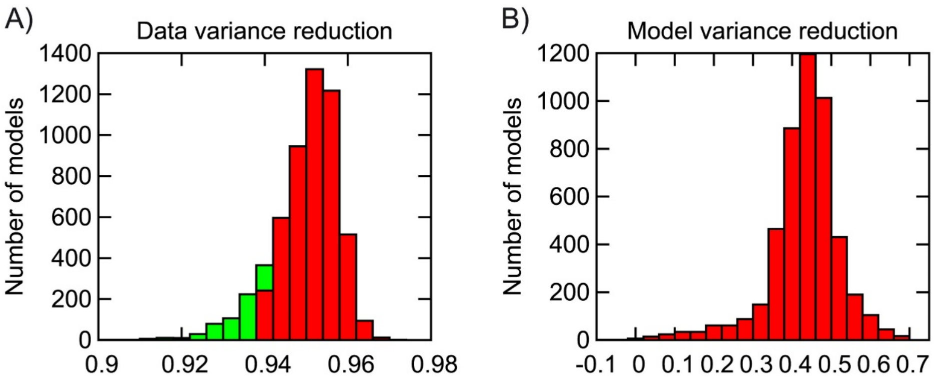
Synthetic test

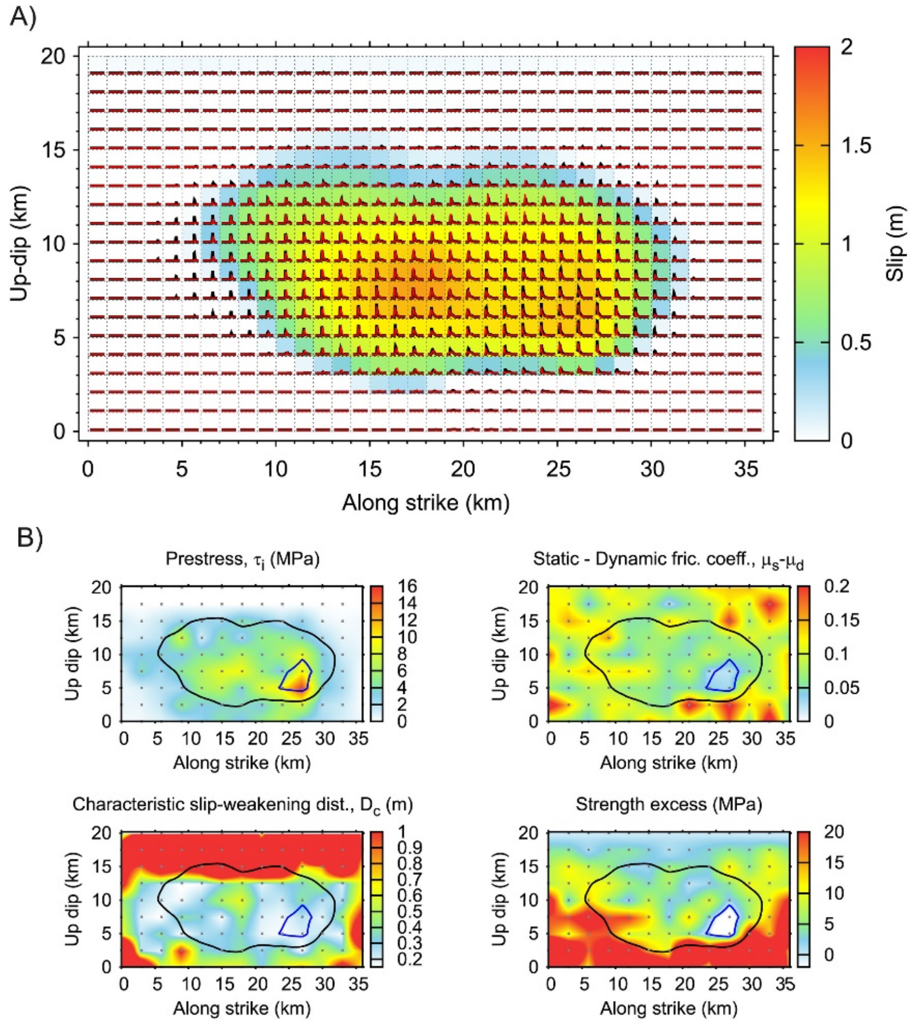
Verify the simplified FD code by comparison to a more complete but more expensive code, WaveQLab3D



Dynamic source inversion

Gallovic et al (JGR 2019)

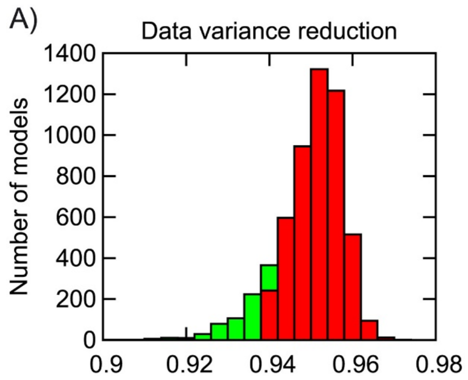


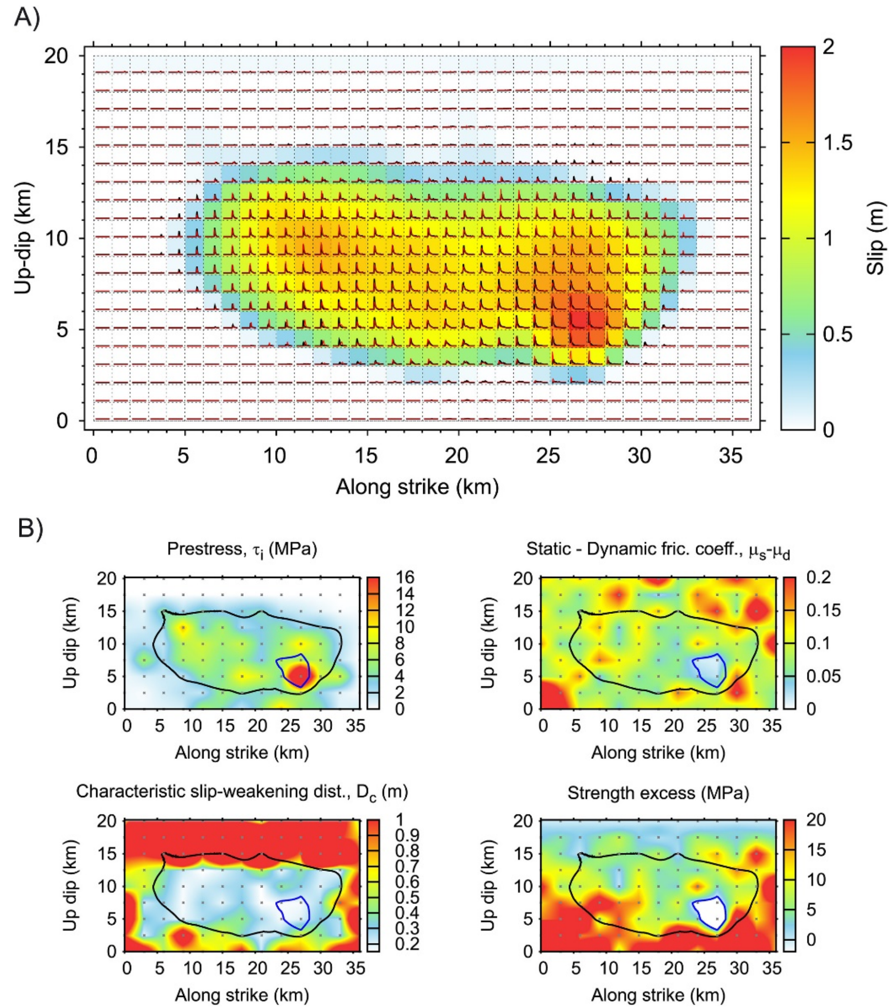


Properties of the inverted rupture model with
the largest Model VR = 0.71
(its Data VR is 0.94)

Dynamic source inversion

Gallovic et al (JGR 2019)

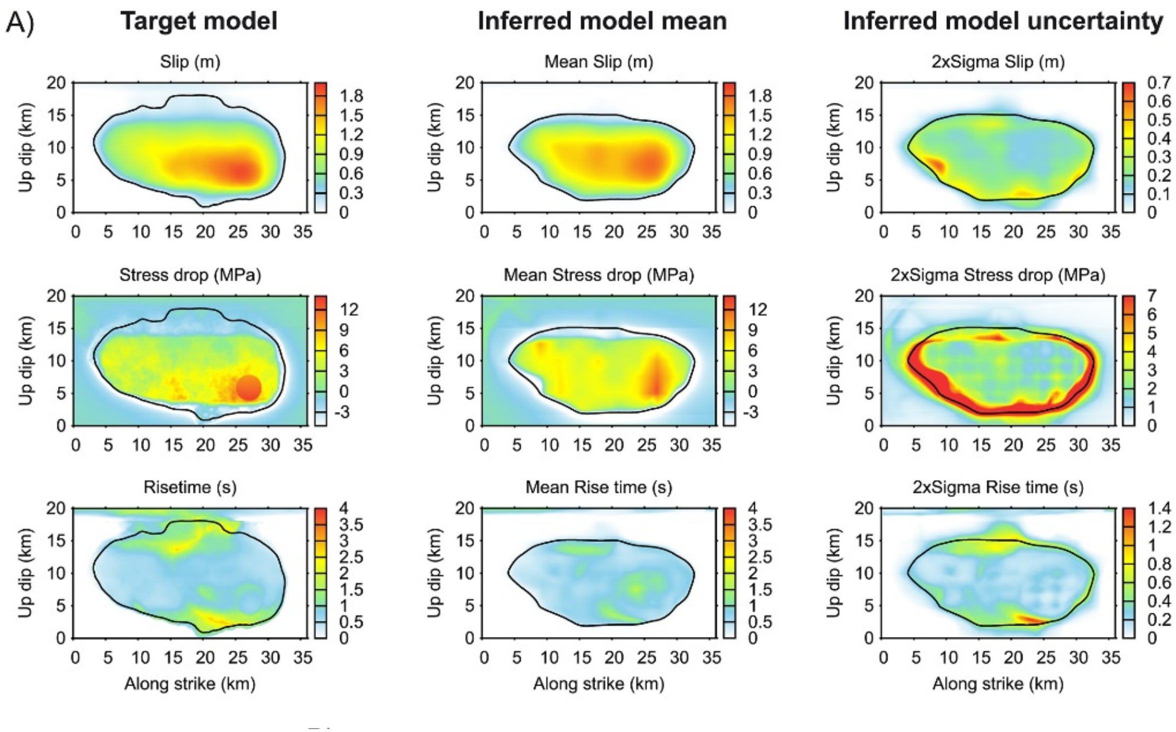




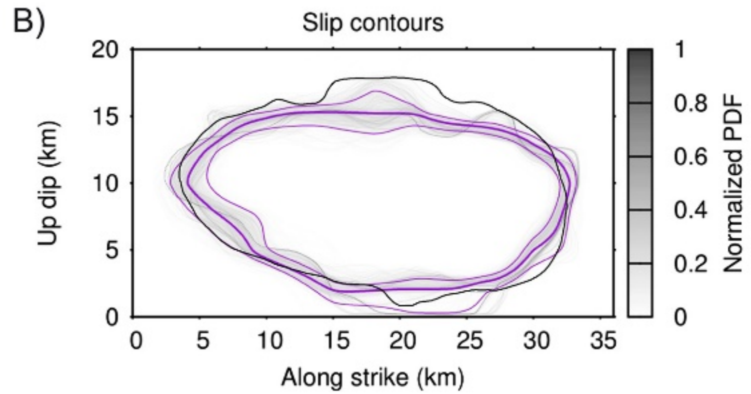
Properties of the inverted rupture model with the largest Data VR = 0.97

Dynamic source inversion

Gallovic et al (JGR 2019)



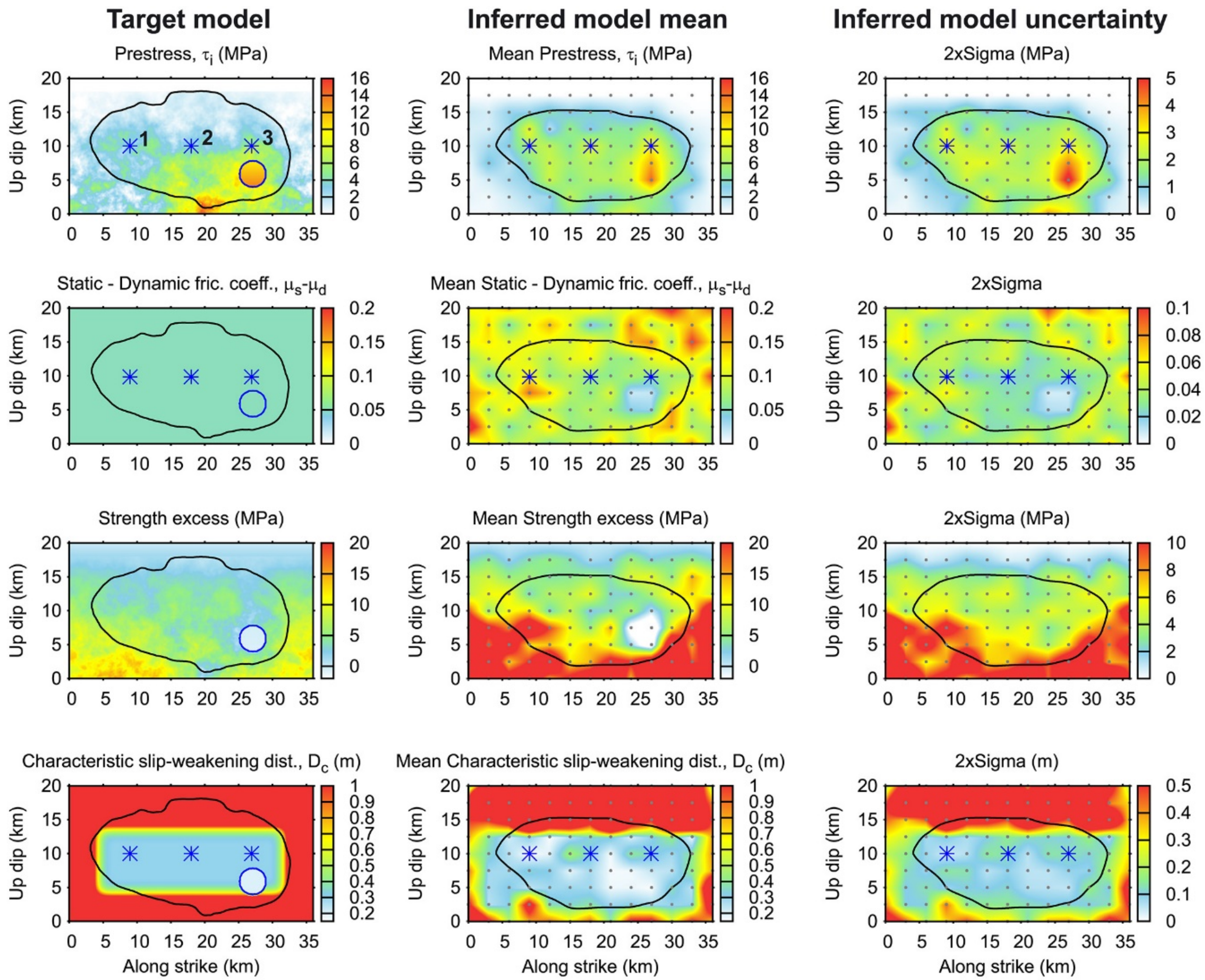
Kinematic source properties



Dynamic source inversion

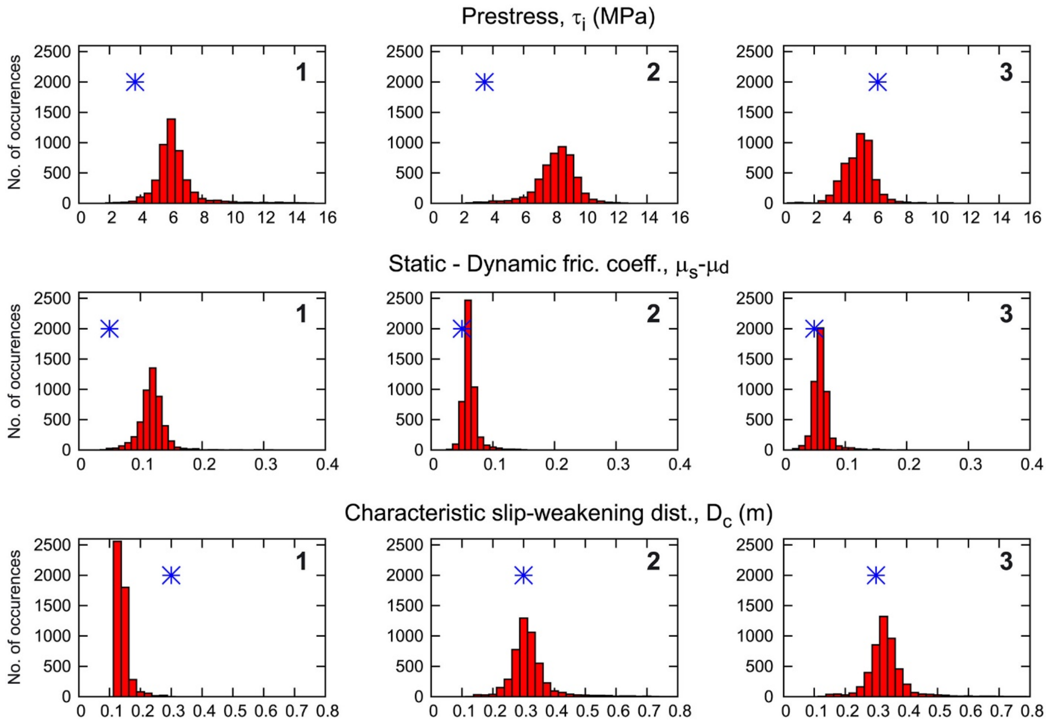
Gallovic et al (JGR 2019)

Dynamic source parameters

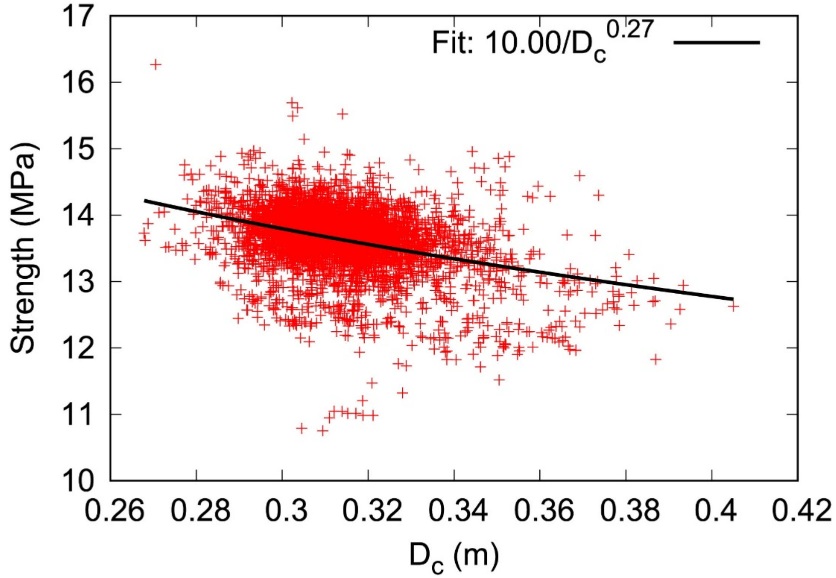


Dynamic source inversion

Gallovic et al (JGR 2019)



Histograms of model parameters at three selected points



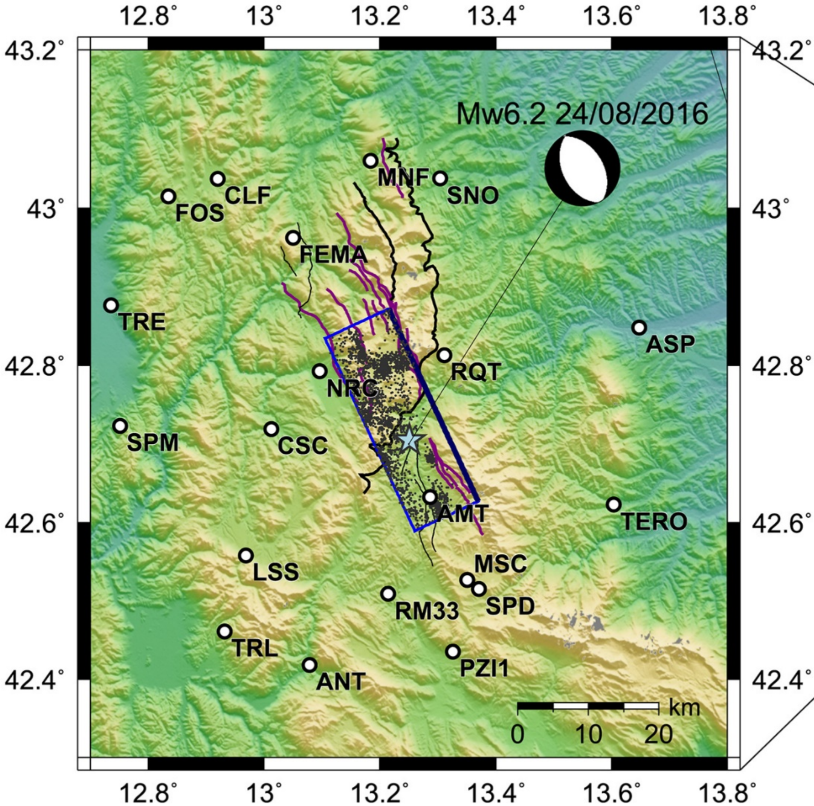
Mean strength τ_s versus mean D_c for all accepted model samples

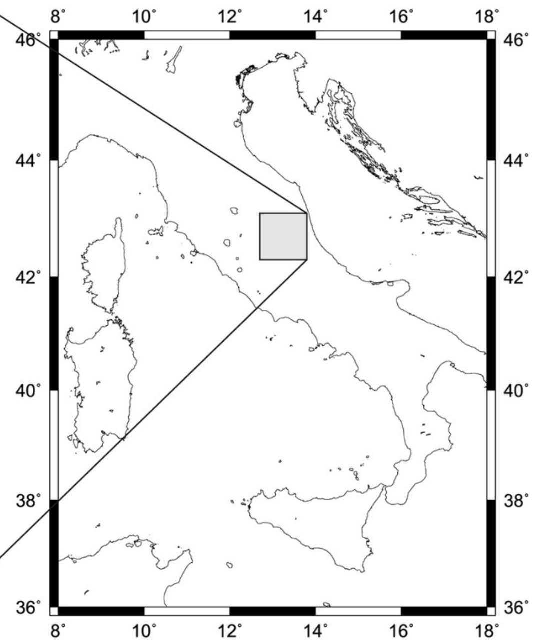
Trade-off is weak

Dynamic source inversion

Application to the 2016 Amatrice earthquake

Gallovic et al (JGR 2019)



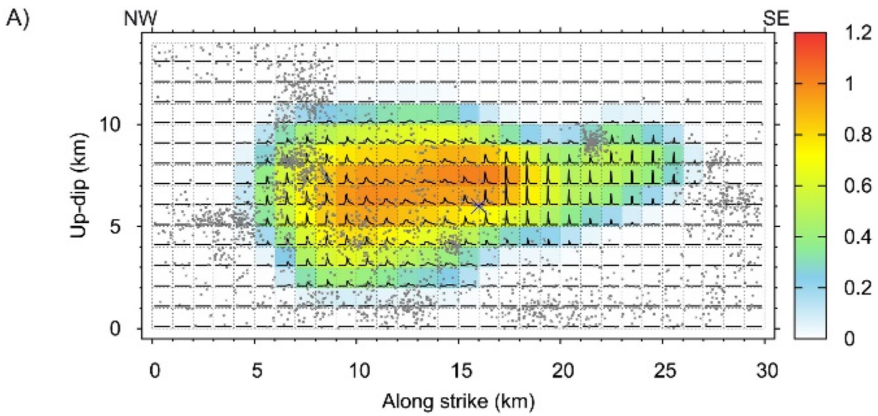


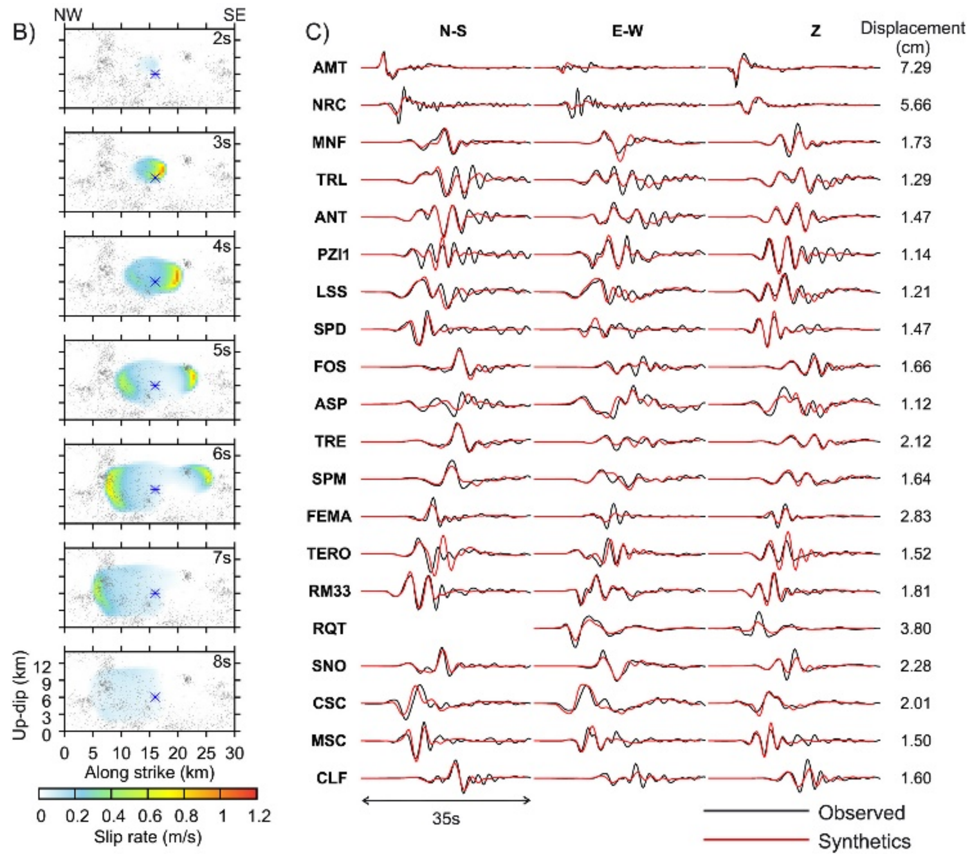
Dynamic source inversion

Application to the 2016 Amatrice earthquake

Gallovic et al (JGR 2019)

Best-fitting dynamic source model
Frequency band 0.05–1.0 Hz (AMT and NRC) and 0.05–0.5 Hz (others)
Variance reduction = 0.62





Dynamic source inversion

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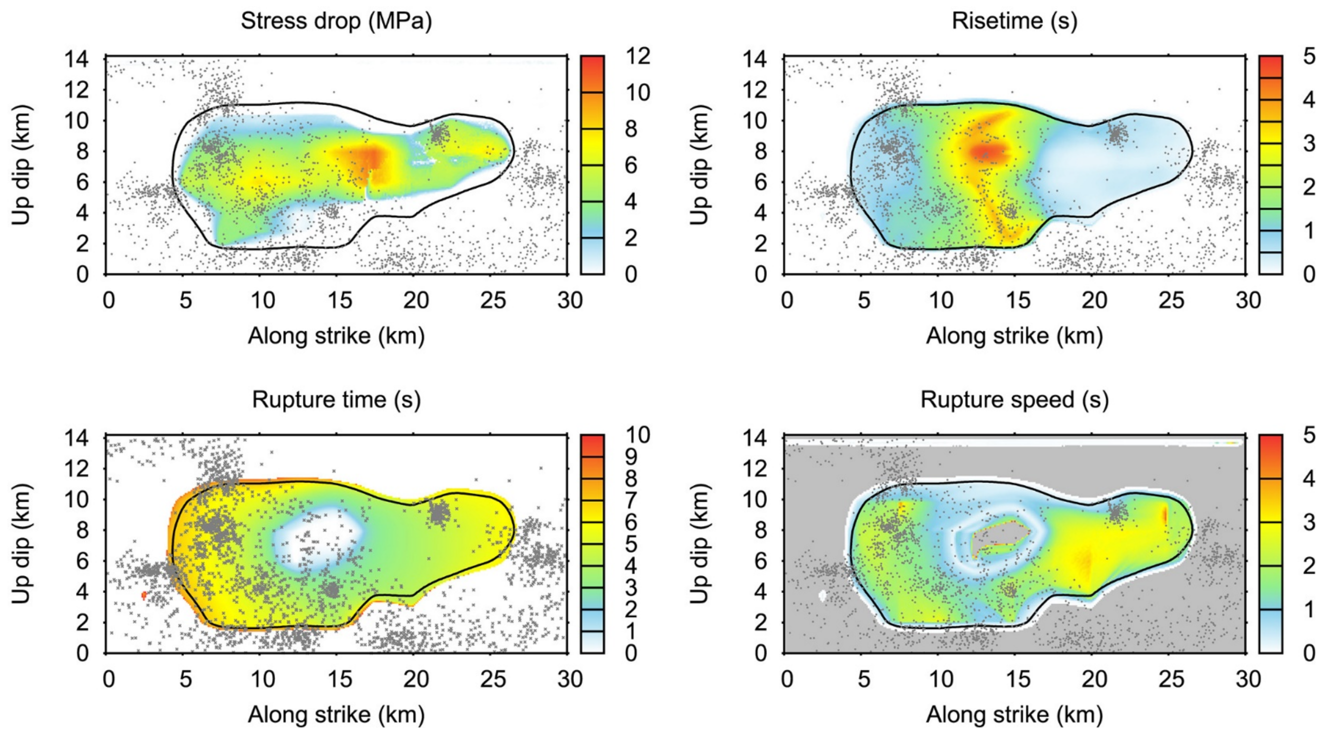
Gallovic et al (JGR 2019)

Kinematic parameters of the best-fitting model



Dynamic source inversion

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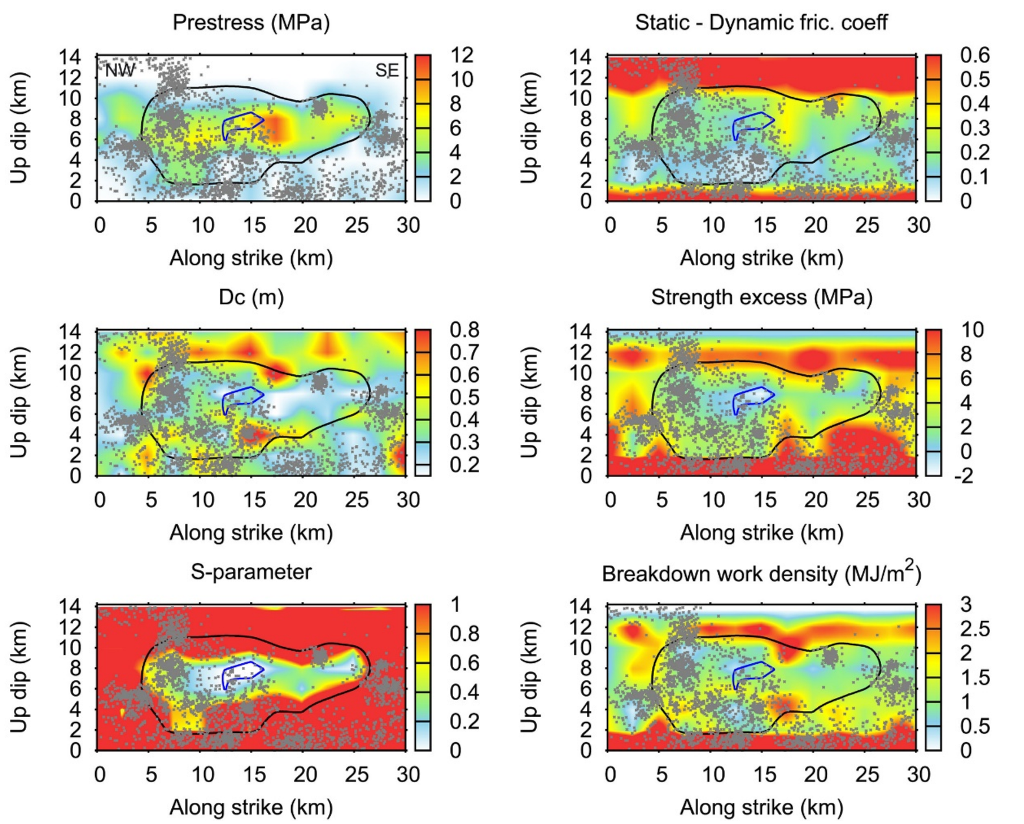


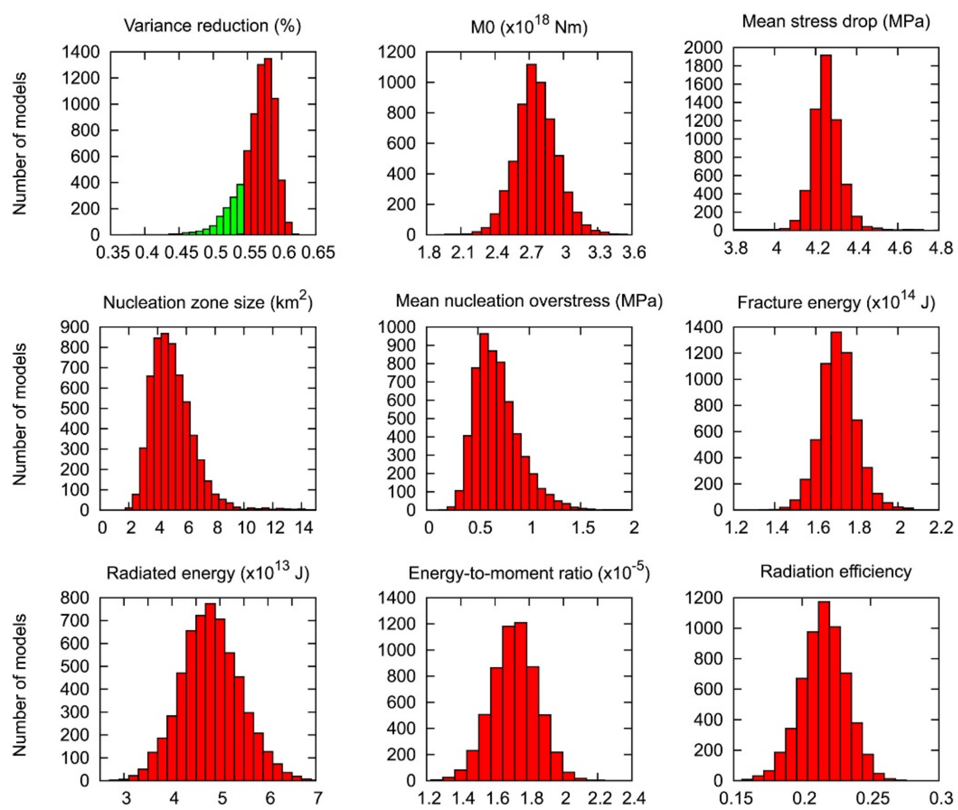
Dynamic source inversion

Application to the 2016 Amatrice earthquake

Gallovic et al (JGR 2019)

Ensemble properties:

Histograms of rupture parameters



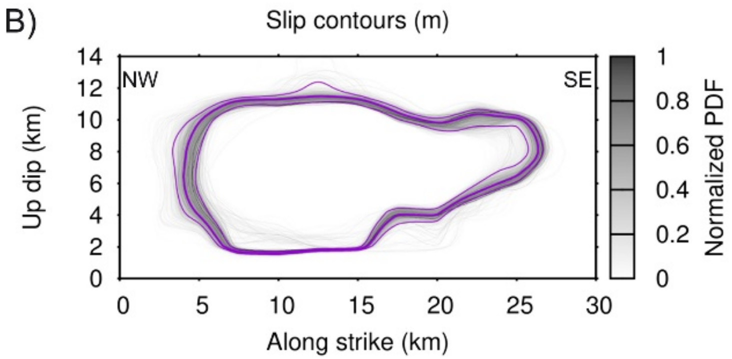
Dynamic source inversion

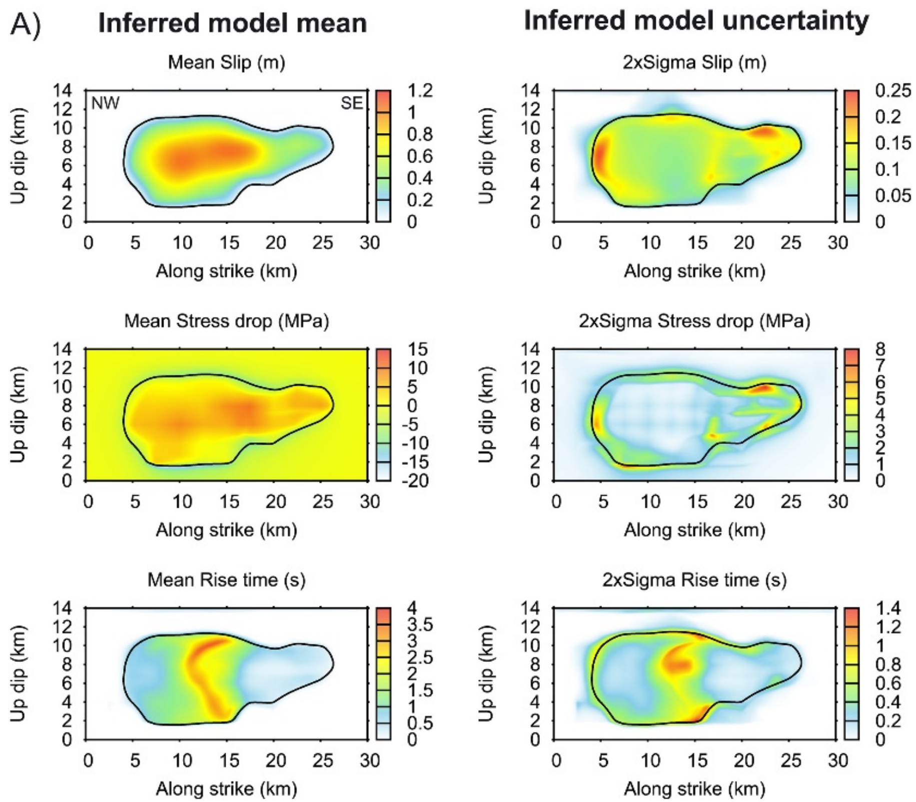
Application to the 2016 Amatrice earthquake

Gallovic et al (JGR 2019)

Ensemble properties:

Mean and variance of rupture parameters





Dynamic source inversion

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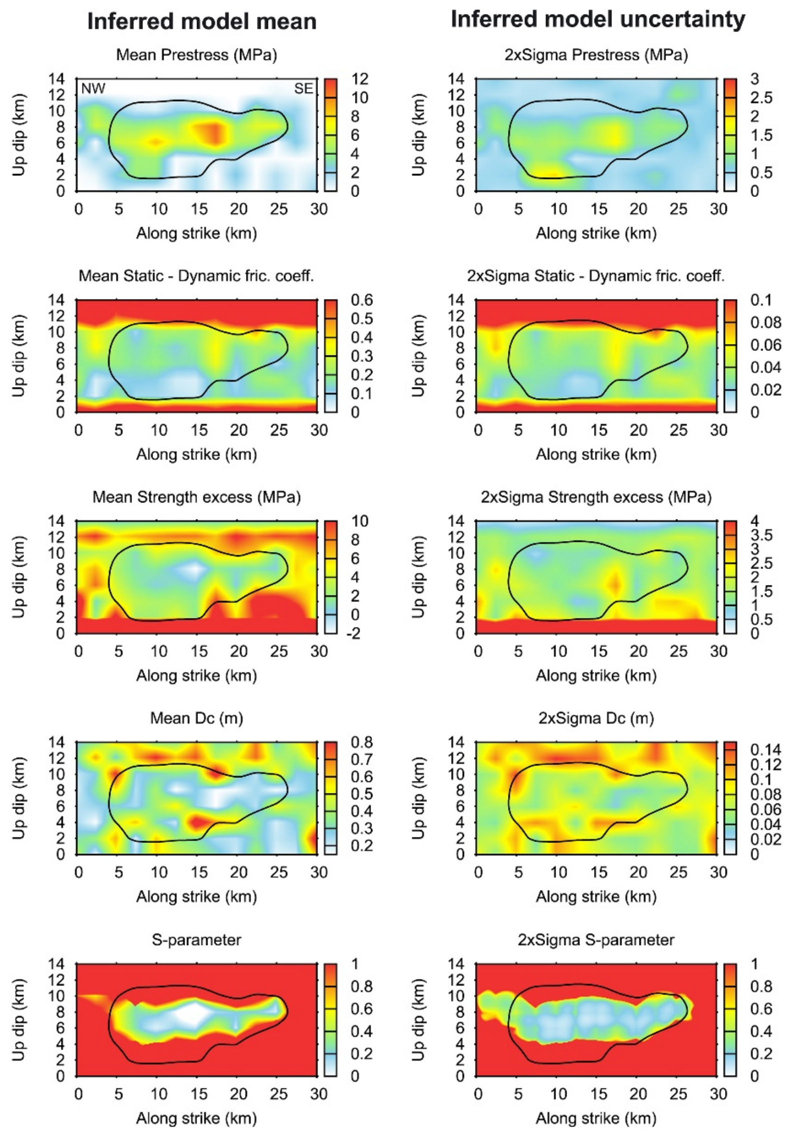

Dynamic source inversion

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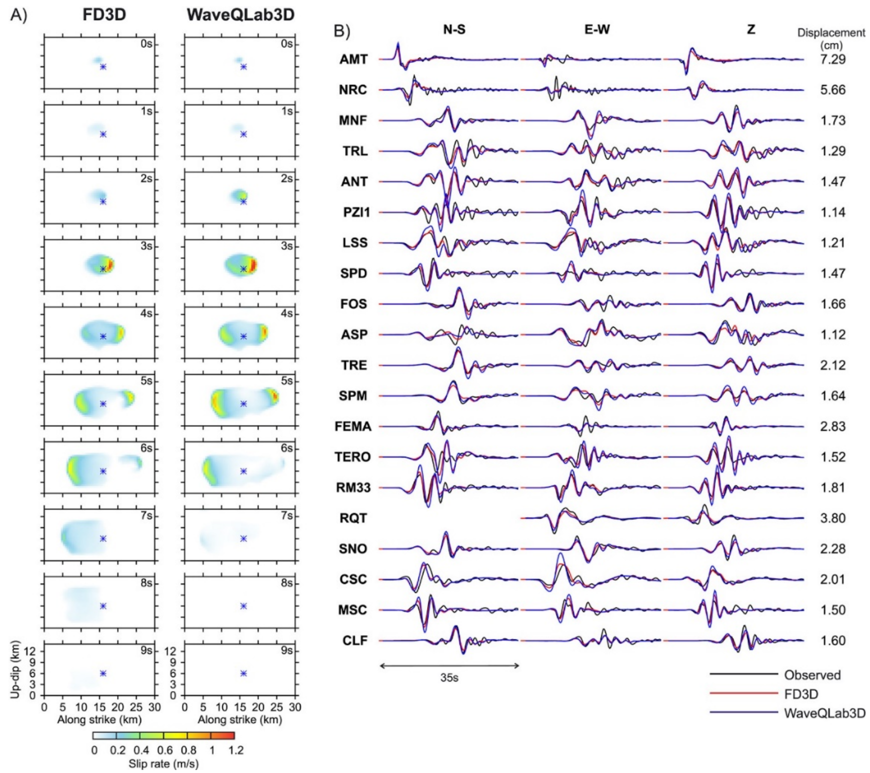
Verify the simplified FD code by comparison to a more complete but more expensive code, WaveQLab3D

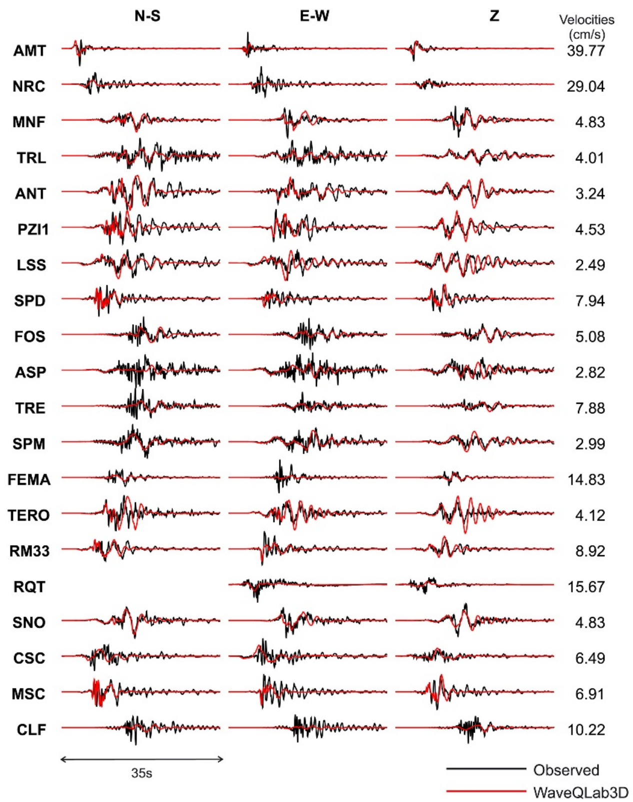


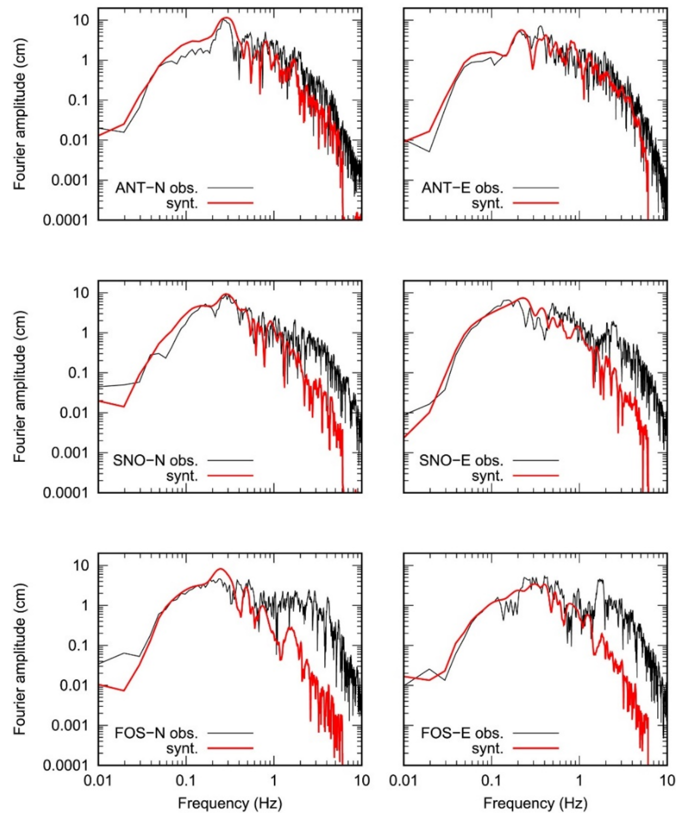
Dynamic source inversion

Application to the 2016 Amatrice earthquake

Gallovic et al (JGR 2019)

Velocity waveforms for the best-fitting model, 0.05–**5.0** Hz





Dynamic source inversion

Continued development of dynamic source inversion
enabled by advances in computational power and sampling algorithms
Provides physics-based regularization of the inverse problem

Challenges ahead:

- Finer scale resolution of dynamic parameters
- More realistic friction laws + off-fault dissipation
- Include uncertainties in crustal structure (model covariance Cp)