Linking Stress Drop and Slip Heterogeneity to Assess Source Rupture Directivity for Earthquakes in Central Italy

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WP2. Earthquake Source Characteristics and Seismic Wave Propagation in Central Apennines

MID-TERM MEETING SECURE (DYNAMIC PLANET PROJECT 2023–25)
JUNE 20, 2025 – MILAN- ITALY

Main Goal

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SECURE
REGIONAL-SCALE EARTHQUAKE **GROUND MOTION PREDICTIONS**
THROUGH PYHSICS-BASED AND EMPIRICAL APPROACHES:
A CASE STUDY CENTRAL ITALY

- ➢ to improve our knowledge of the relationship between directivity and slip source complexity;

- ➢ to investigate how kinematic/dynamic source heterogeneities affects stress drop estimates.

To pursue this goal, we have focused on:

- ✓ linking slip heterogeneity and stress drop to assess source rupture directivity effects in near-source region;

- ✓ investigating how stress drop correlates with rupture properties like velocity and asperity location, and how it varies spatially along the fault due to source directivity ;

Case Studies

Case Studies

SECURE
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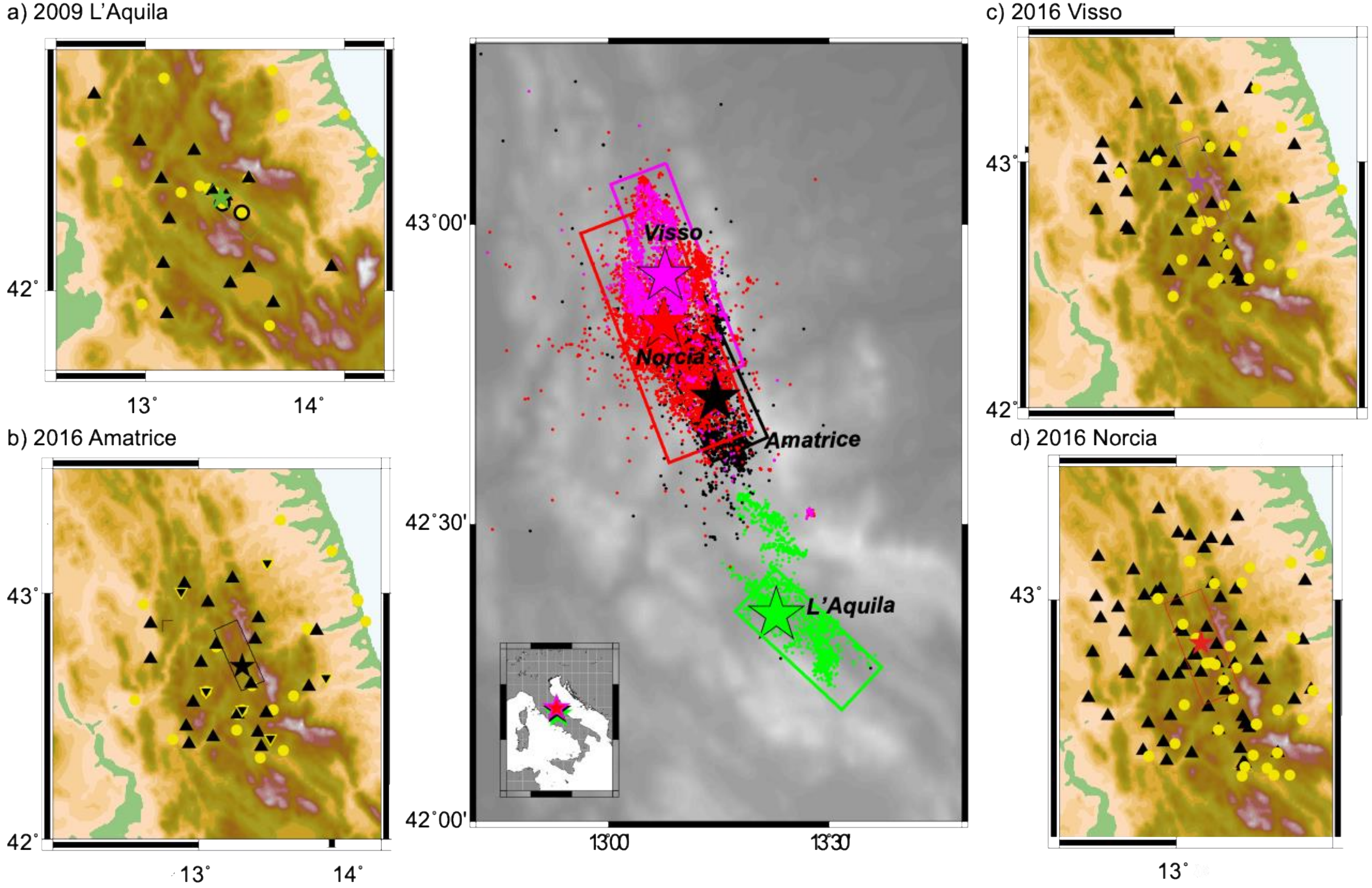


- ❖ We have analysed data from significant earthquakes like the 2009 L'Aquila, and the 2016 – 2017 Amatrice – Visso - Norcia (AVN) earthquakes, comparing rupture models and stress drop estimates;

- ❖ we have employed advanced inversion techniques, such as the finite-fault slip inversion and the Empirical Green's Function (EGF) method, which allow us to capture the complex rupture kinematics and directivity effects.

Methods

Methods

Kinematic Inversion & 2D Static Stress Changes Algorithms

We reconstruct the source model of each earthquake using a nonlinear inversion method that combines geodetic and seismic data, such as strong motion, high-resolution GPS, and DInSAR measurements (*Cirella et al., 2012* and reference therein). This approach assigns source parameters at the corners of subfaults and simultaneously inverts for all parameters along strike and dip, within specified variability ranges

To estimate stress changes on fault planes, we use a method by *Ripperger and Mai (2004)*, based on *Andrews (1980)*, which quickly computes static stress variations from slip distributions on a 2D fault plane.

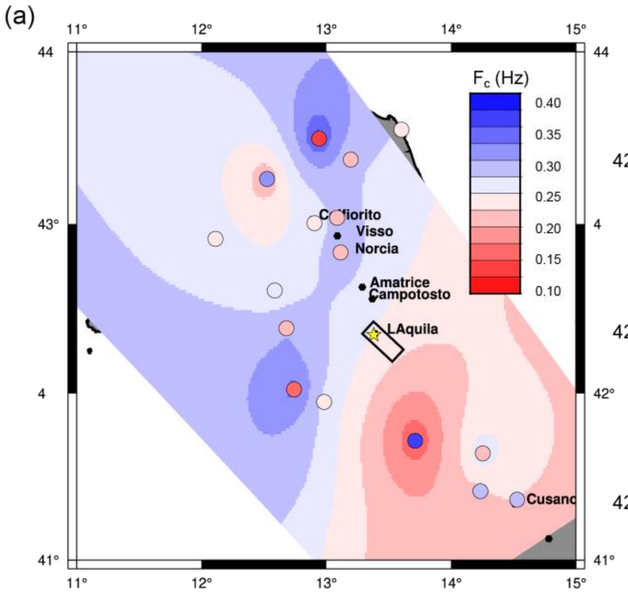
Brune Stress Drop & Directivity Computation

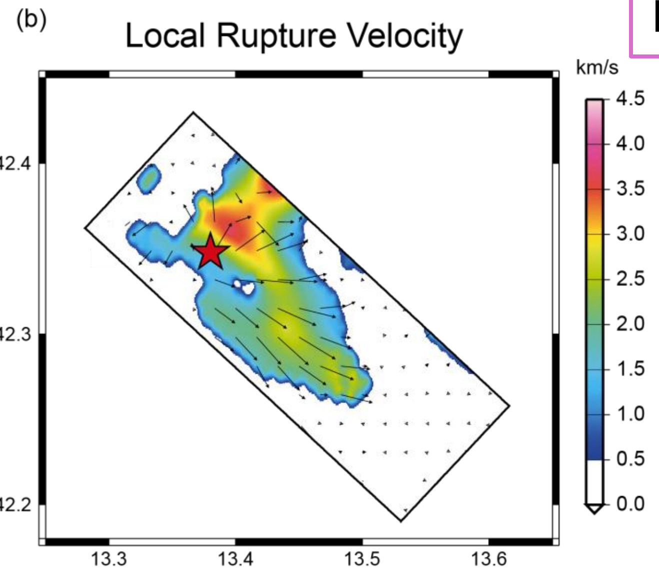
Stress drop was estimated using the Empirical Green's Function (EGF) method in the frequency domain, which isolates source effects by spectral division *(Calderoni et al., 2013, Calderoni & Abercrombie, 2023)*. Rupture directivity for AQU was assessed via a directivity index (0–1) quantifying spectral asymmetry above the corner frequency (*Calderoni et al., 2015*). For AVN, a statistical framework based on EGF and a t-test criterion was applied to evaluate spectral ratio differences across station groups oriented forward, backward, and transverse to rupture propagation *(Calderoni et al., 2023)*.

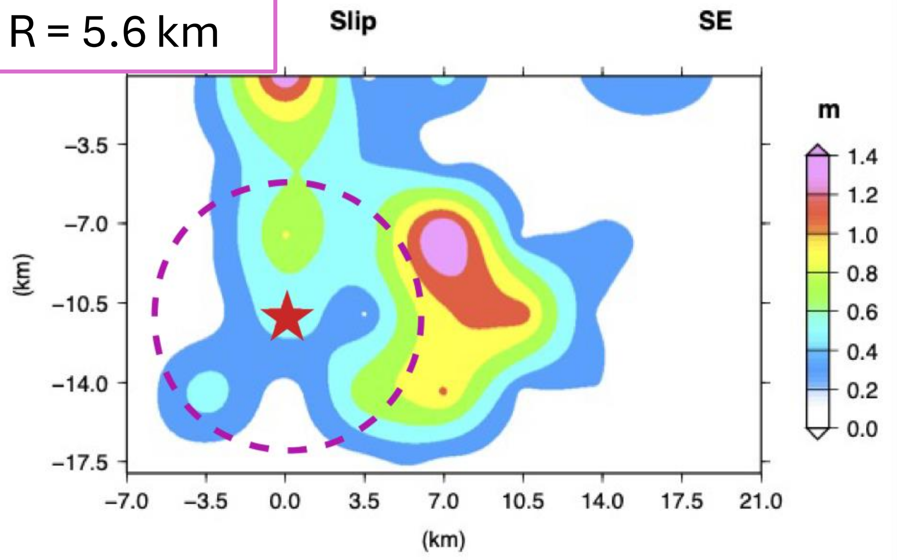
Results: 2009 L'Aquila EarthQuake

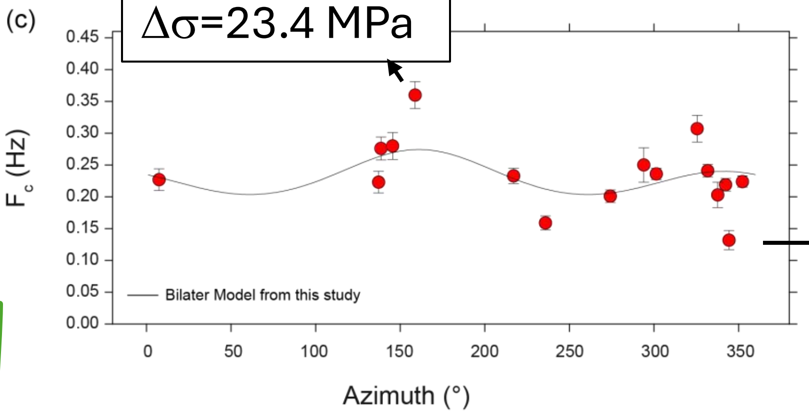
Results

SR: 8.68 (8.07–9.34)
R = 5.6 km
DIR - SE R = 5.6 km



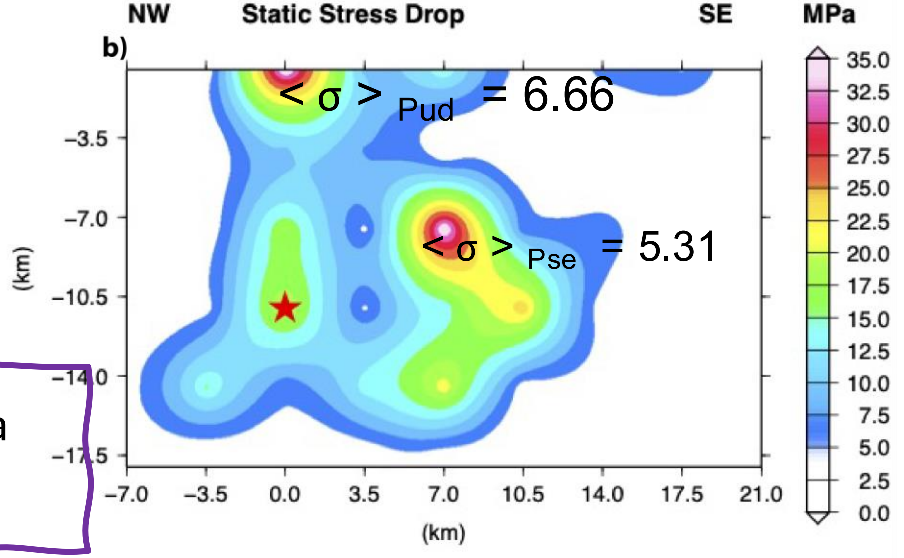






$\Delta\sigma$=23.4 MPa

$\Delta\sigma$=1.5 MPa



$< \sigma >_{Pud}$ = 6.66

$< \sigma >_{Pse}$ = 5.31

$fact_{Fc}$= 3
$fact_{\Delta\sigma}$ = 20

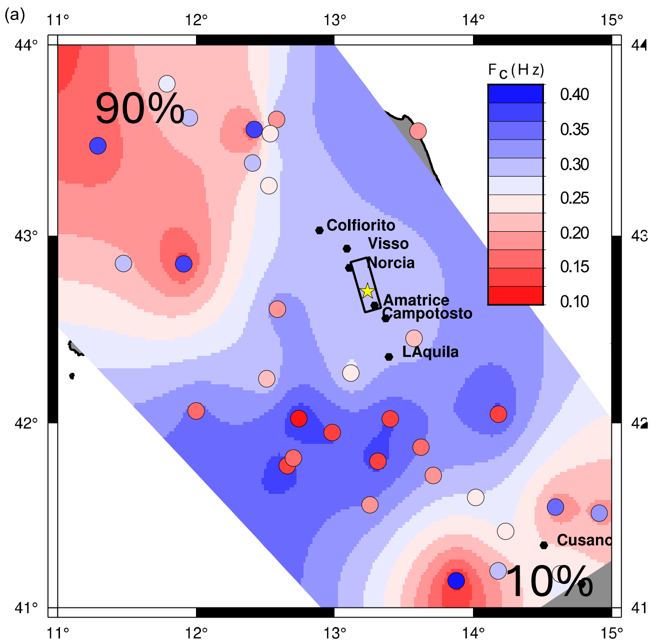
$< \sigma >$ 20% = 9.79 MPa

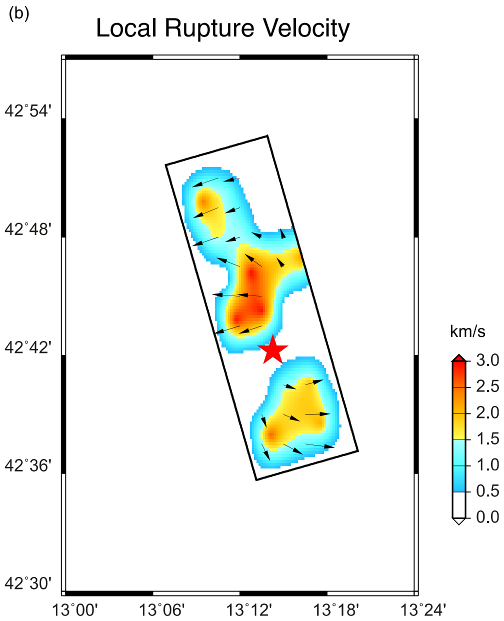
$< \sigma >$of = 8.92 MPa

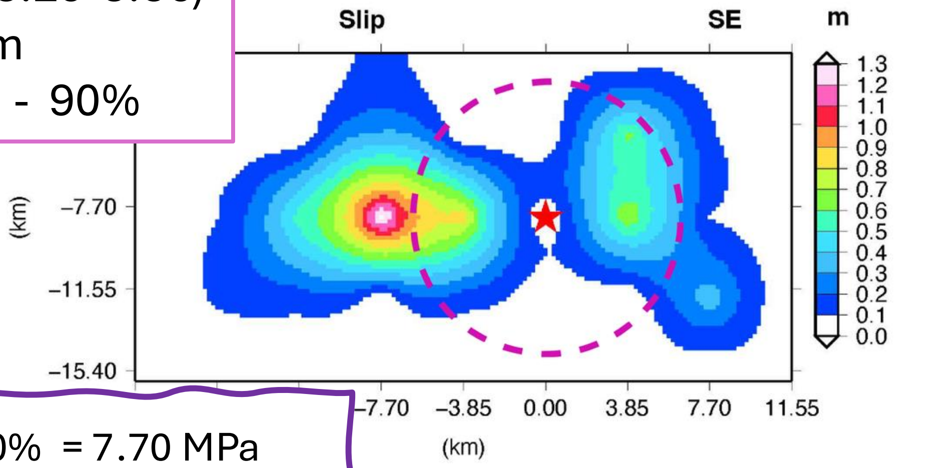
Results: 2016 Amatrice EarthQuake

Results

SR: 3.45 (3.18-3.74)
R = 6.2 km
SP: 3.43 (3.29-3.56)
R = 6.2 km
DIR: 325° - 90%

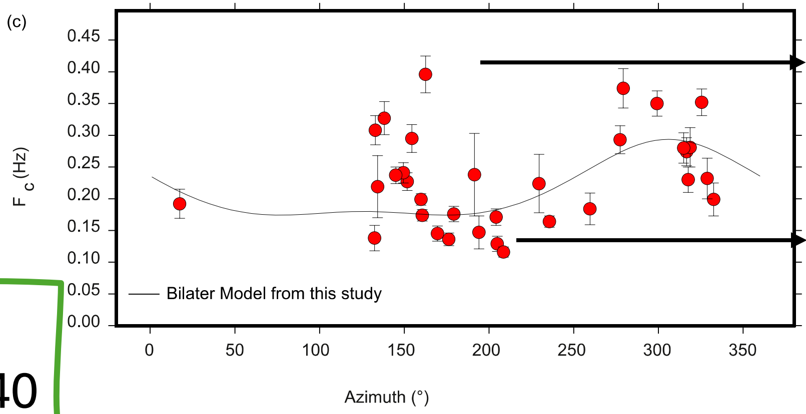






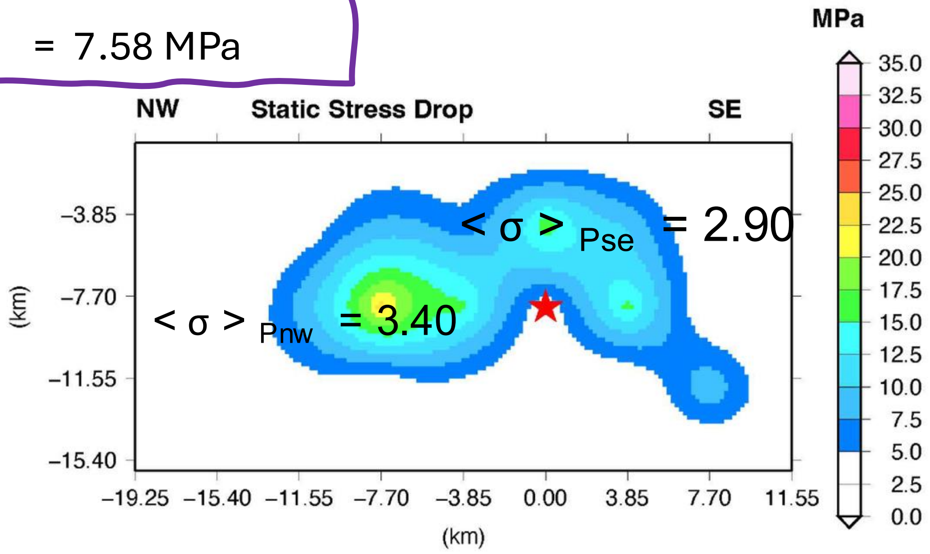
$< \sigma >_{20\%} = 7.70$ MPa

$< \sigma >_{of} = 7.58$ MPa



$\Delta\sigma$=19.9 MPa

$\Delta\sigma$=0.5 MPa

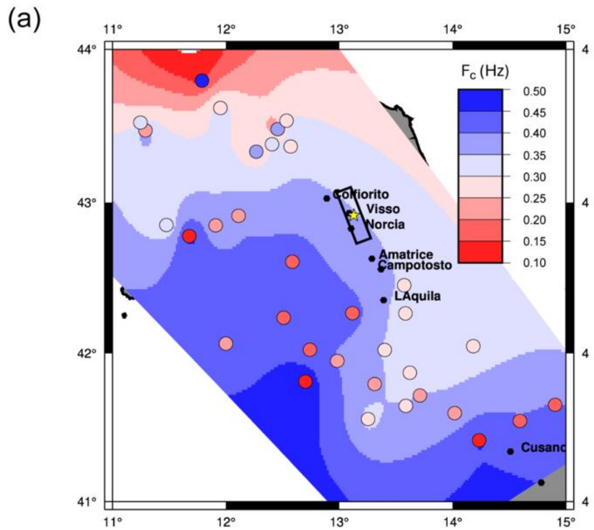


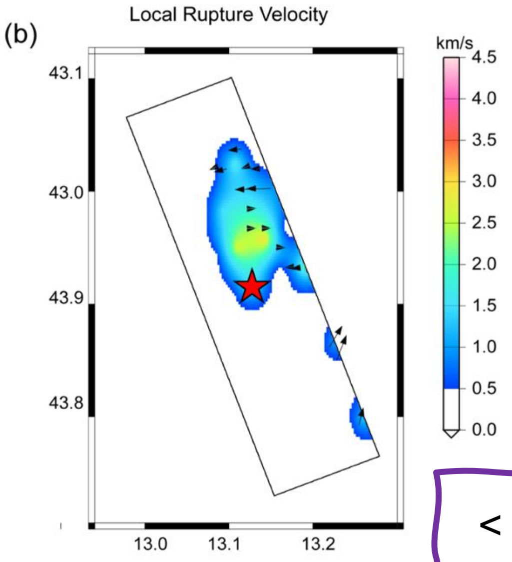
$fact_{Fc} = 3$
$fact_{\Delta\sigma} = 40$

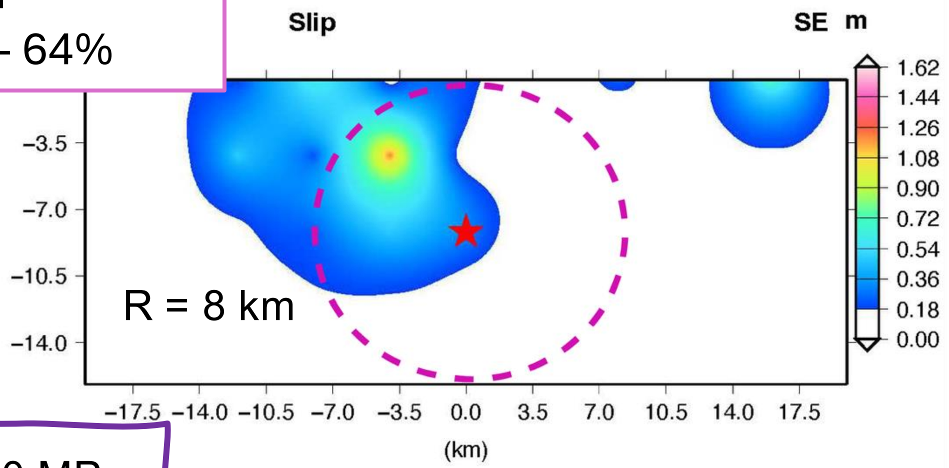
Results: 2016 Visso EarthQuake

Results

SR: 1.46 (1.42-1.51)
R = 8 km
SP: 2.17 (2.08-2.26)
R = 6.9 km
DIR: 243° - 64%

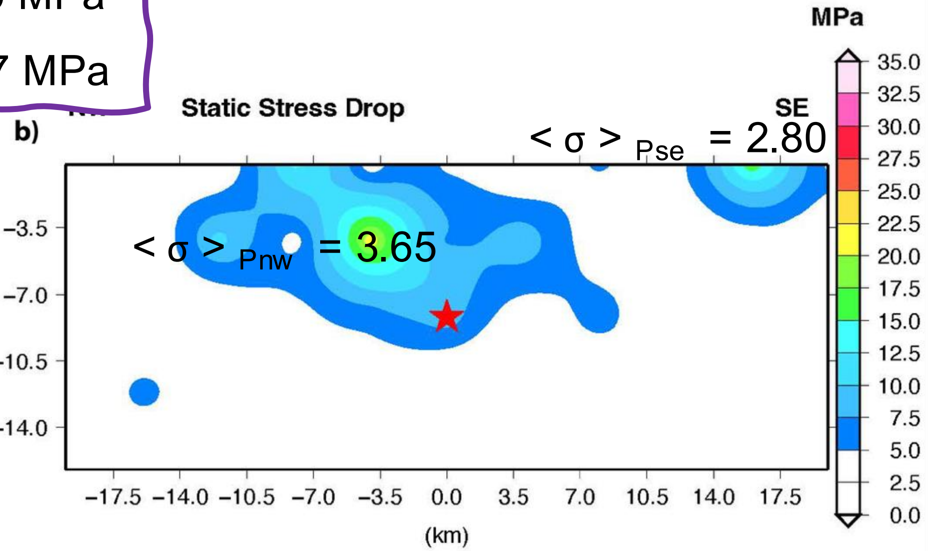


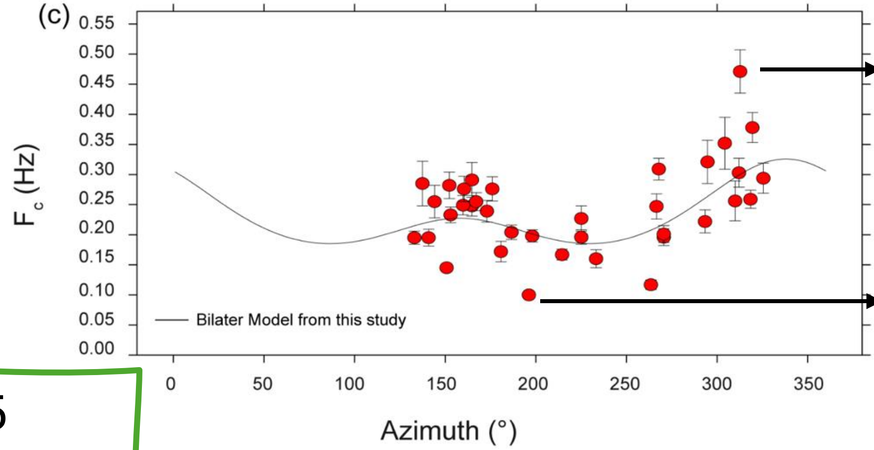




$< \sigma >_{of} = 4.70$ MPa

$< \sigma >_{20\%} = 5.57$ MPa





$\Delta\sigma$=23.7 MPa

$\Delta\sigma$=0.2 MPa

$fact_{Fc} = 5$

$fact_{\Delta\sigma} = 100$

Results: 2016 Norcia EarthQuake

Results

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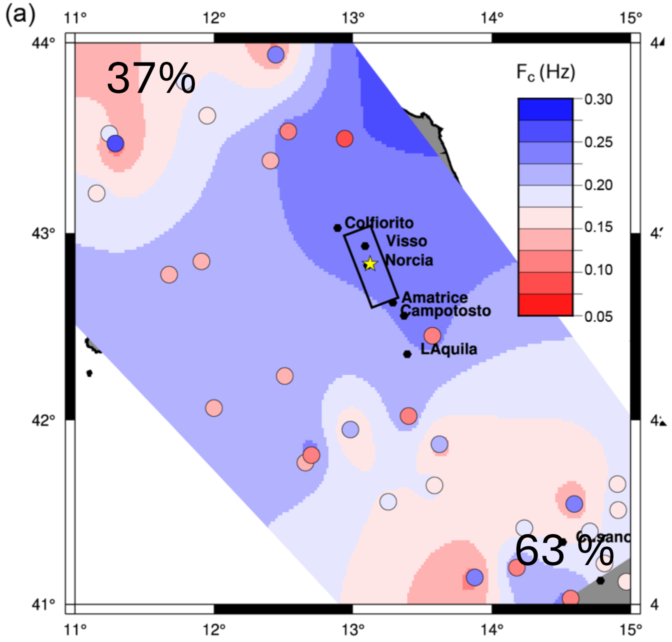
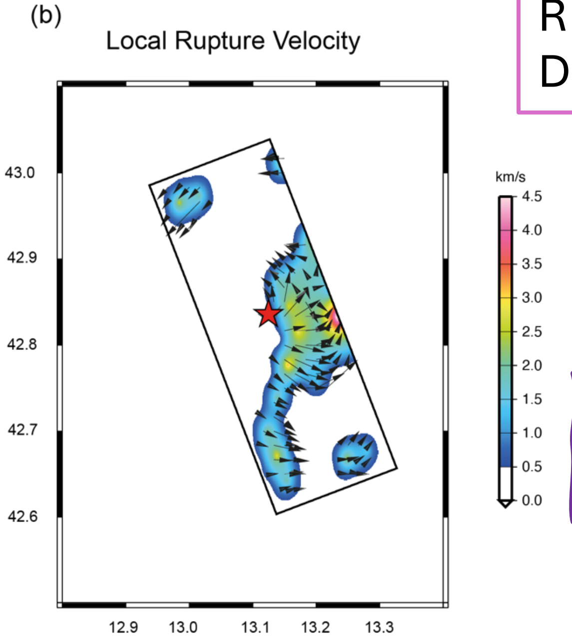
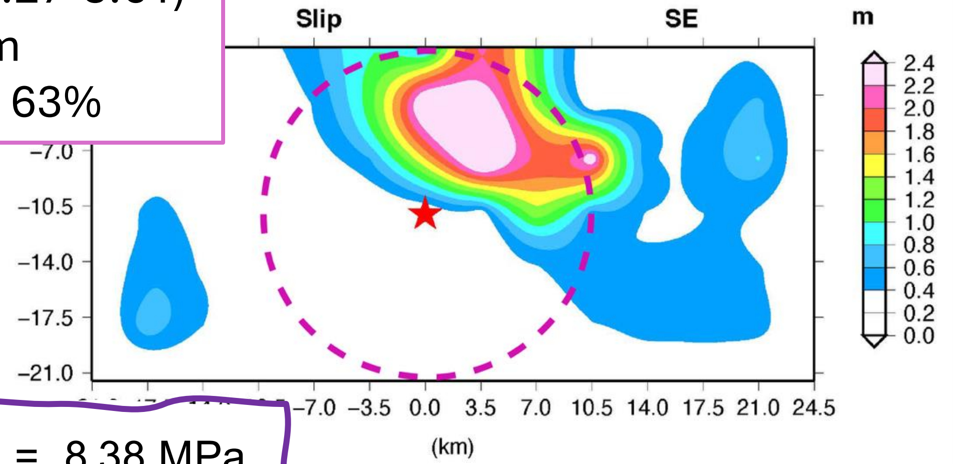
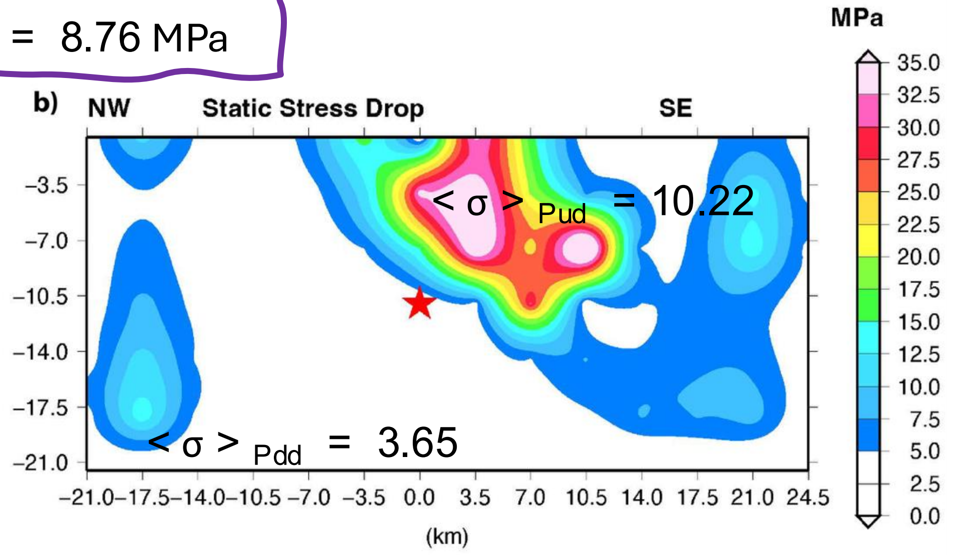
SR: 3.97 (3.70-4.26)
R = 11.4 km
SP: 3.43 (3.27-3.61)
R = 11.3 km
DIR: 196° - 63%

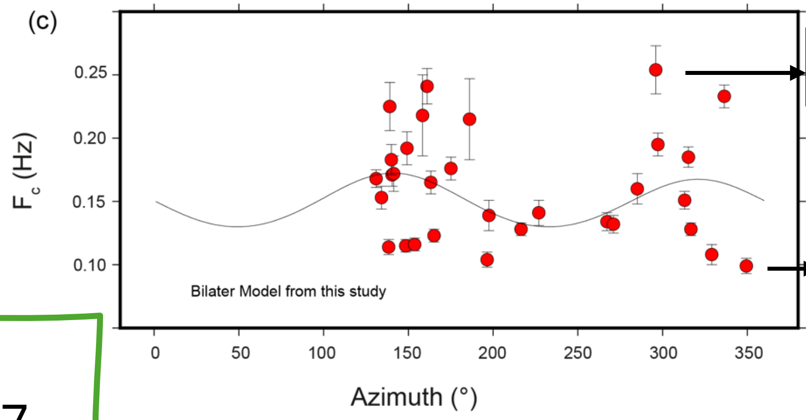






$< \sigma >_{of} = 8.38$ MPa
$< \sigma >_{20\%} = 8.76$ MPa





$\Delta\sigma$=18.2 MPa

$\Delta\sigma$=1.1 MPa

$fact_{Fc}$= 3
$fact_{\Delta\sigma}$ = 17

Brune Stress Drop Comparison & On-Fault Stress Drop Estimate (this Study)

SECURE
REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

Mainshock	*Δσ (MPa) Calderoni et al.,*	*2D Static Stress Changes (MPa)*	*Δσ (MPa) Other studies*
M_w6.1 L'Aquila	SR: 8.68 (8.07–9.34) R = 5.6 km DIR - SE	$<\sigma>_{of}$ = 8.92 $<\sigma>_{Pse}$ = 5.31 $<\sigma>_{Pud}$ = 6.66 $<\sigma>_{20\%}$ = 9.79	Bindi, D., et al. (2009–2011): 9.2 Ameri et al., (2012): 10 Picozzi et al. (2012): 10 Pacor et al. (2015): 10
M_w6.1 Amatrice	SR: 3.45 (3.18-3.74) R = 6.2 km SP: 3.43 (3.29-3.56) R = 6.2 km DIR: 325° - 90%	$<\sigma>_{of}$ = 7.58 $<\sigma>_{Pse}$ = 2.90 $<\sigma>_{Pnw}$ = 3.40 $<\sigma>_{20\%}$ = 7.70	Kemna et al., (2021): 2 Morasca et al., (2022) Tab CCT: 3.96 Tab GIT: 4.67
M_w 5.9 Visso	SR: 1.46 (1.42-1.51) R = 8 km SP: 2.17 (2.08-2.26) R = 6.9 km DIR: 243° - 64%	$<\sigma>_{of}$ = 4.70 $<\sigma>_{Pse}$ = 2.80 $<\sigma>_{Pnw}$ = 3.65 $<\sigma>_{20\%}$ = 5.57	Morasca et al., (2022) Tab CCT: 3.78 Tab GIT: 3.57
M_w 6.3 Norcia	SR: 3.97 (3.70-4.26) R = 11.4 km SP: 3.43 (3.27-3.61) R = 11.3 km DIR: 196° - 63%	$<\sigma>_{of}$ = 8.38 $<\sigma>_{Pdd}$ = 3.65 $<\sigma>_{Pud}$ = 10.22 $<\sigma>_{20\%}$ = 8.76	Kemna et al., (2021): 2 Morasca et al., (2022) Tab CCT: 3.88 Tab GIT: 5.52

SR: Spectral Ratio
SP: Spectral Fitting
*$<\sigma>_{20\%}$: mean stress changes (> 20% average slip).
*$<\sigma>_{of}$: mean stress changes over all fault distribution.
*$<\sigma>_{P}$: mean stress changes computed on a single patch.

Conclusion

Key Take Aways

- We further explore the correlation between stress drop and key rupture properties, including rupture velocity, asperity and hypocentral location, and the strength (i.e., amount of slip) of slip patches;
- We assess how these factors influence the spatial characteristics of rupture directivity along the fault.

Key Findings:

- all the static stress drop patterns computed from the inverted earthquake slip distribution highlight strong heterogeneity in the stress redistribution due to the source rupture complexity;
- Large-slip patches are associated with higher stress drop in near-source regions;
- Source directivity strongly affects stress-drop estimates at different azimuths (as previously reported by *Calderoni et al., 2013, 2015,2023*).

Implications

Take Home Message

Implications:

- ✓ Estimating a single stress drop value is neither straightforward nor reliable; worthy of noting that it is essential to treat stress drop as a parameter that varies in both space and time.

- ✓ Our results may help improve ground motion prediction in near-fault zones, where complex source effects play a major role.

Such insights are crucial for improving seismic hazard assessments and informing future risk mitigation strategies in seismically active region, as the Central Italy.

Thank For Your Attention

Thank For Your Suggestion

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