

Advances in Simulations Based on the 1D-FK Deterministic Method for Earthquakes in Central Apennines

Pietro Artale Harris¹, Arben Pitarka², Aybige Akinci¹, Arianna Cuius¹, Daniele Melini¹,
Robert W. Graves³ and Houjun Tang⁴

¹Istituto Nazionale di Geofisica e Vulcanologia, Roma

²Lawrence Livermore National Laboratory, Livermore, California, USA

³United States Geological Survey, Pasadena, California, USA

⁴Lawrence Berkeley National Laboratory, Berkeley, California, USA

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SECURE

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

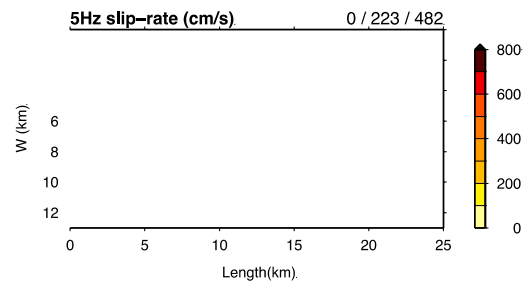
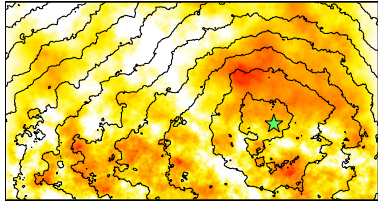
MOTIVATION AND OBJECTIVE

- The most precise simulation methods rely on 3D wave propagation modeling. However, they are more costly than methods employing 1D wave propagation.
- Employed a deterministic modeling technique that uses the Graves and Pitarka (GP16) kinematic rupture generator and 1D GFs to produce broadband ground motion time histories up to 7 Hz for three earthquakes that struck Central Italy.
 - Norcia M_w 6.5, October 30, 2016
 - Amatrice M_w 6.2, August 24, 2016
 - L'Aquila M_w 6.3, April 6, 2009
- Include site effects correction
- Validate FK 1D simulations with Goodness of Fit (GoF) analysis
- Investigate the source-related spatial variability.
- Generate flat files for each earthquake across more than 9,000 grid points (1x1 km) treated as virtual stations, and compare them with data-driven empirical ground motion predictions/models.

Physics-Based Ground Motion Simulation Method

Deterministic Approach 0-7 Hz

Kinematic Rupture Model

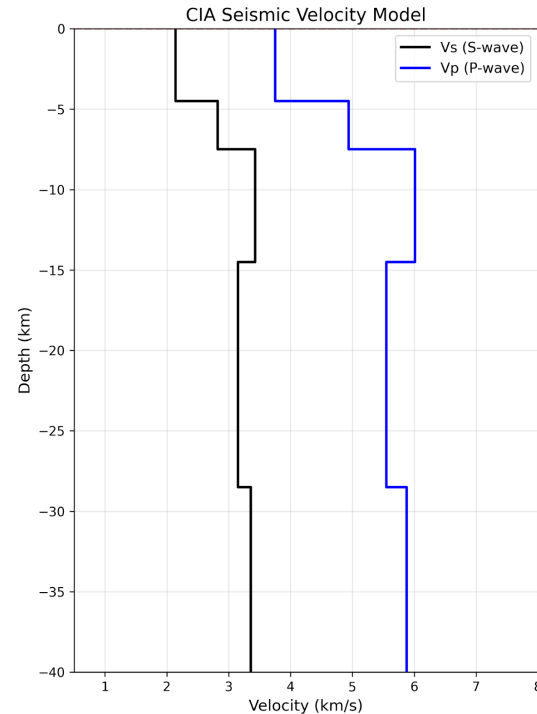


GP Method

Kinematic rupture models generated using a technique developed by Graves and Pitarka, 2016

Wave Propagation

1D Linear anelastic, constant-Q



FK Code

It solves the elastic-wave equation in the frequency domain by setting a cylindrical set of coordinates. Crustal Velocity model from Herrmann et al., (2011)

Simulations are performed using a physics-based deterministic approach, modeling the earthquake rupture and elastic wave propagation, and running a 'hand-made' parallelized CPU version of the FK code on the

Supercomputer Mercalli INGV Cluster

Model Domain covers: 102kmx88kmx31km

Min grid spacing: 25 m

Min time spacing Dt: 0.012 s

$F_{\max}$: 7Hz

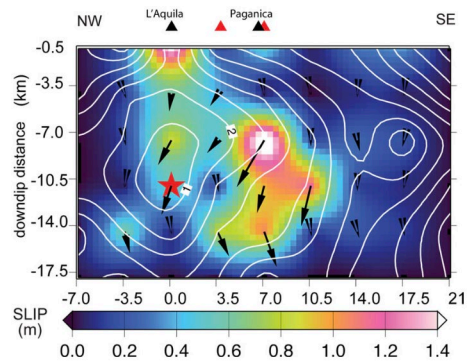
Ground motion duration: 50 s

CPUs: 1 (serial runs parallelized by hand)

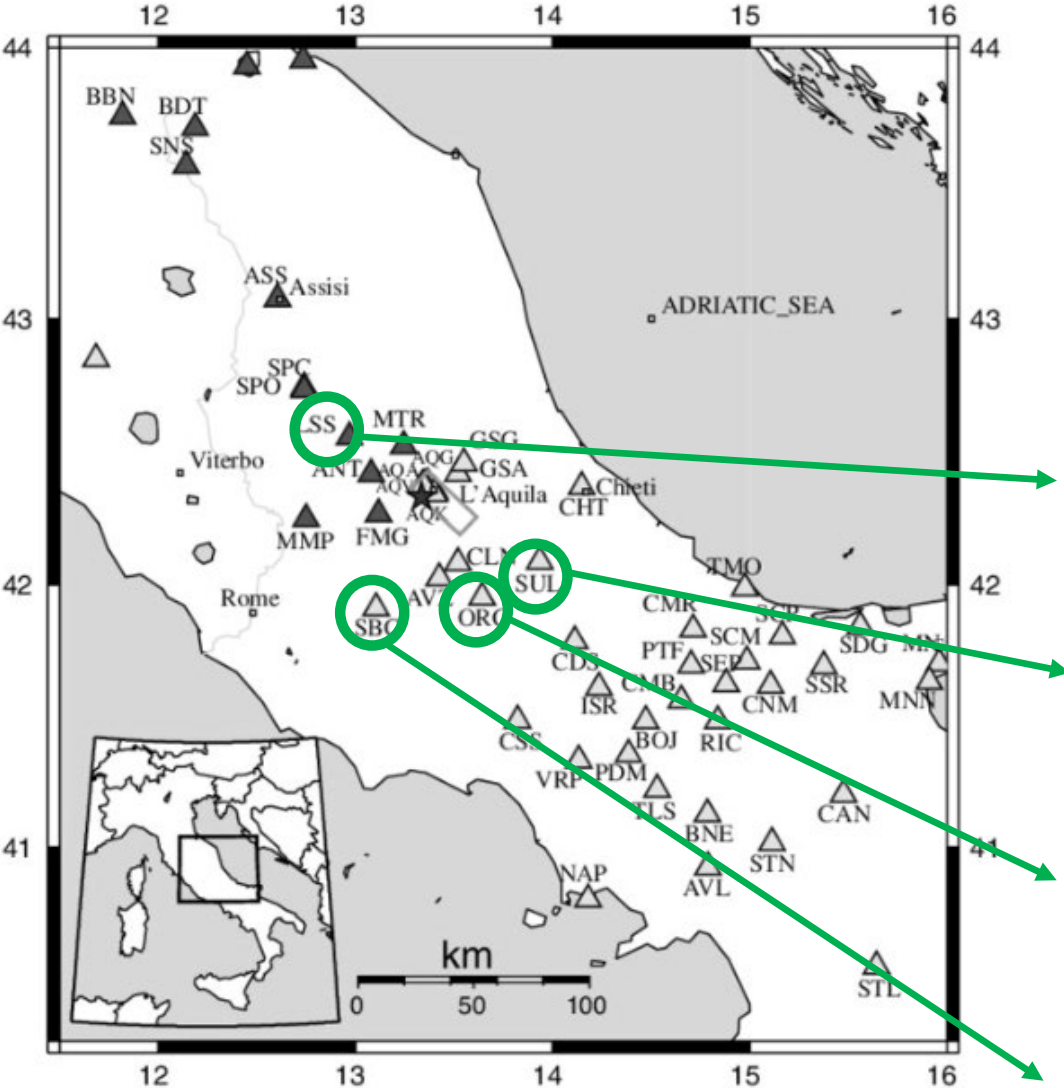
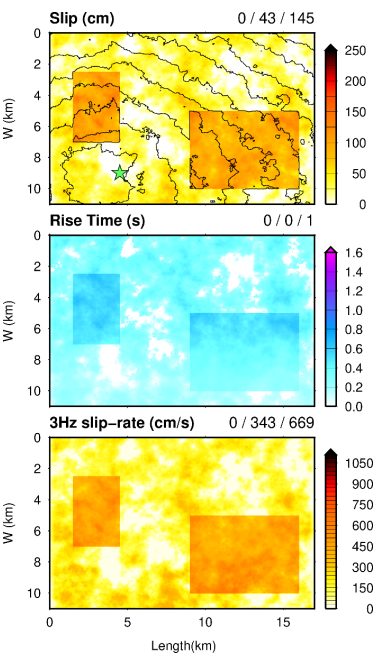
Wall time: max 10 min per station

1. L'Aquila M_w 6.3, April 6th 2009 - Comparison with recorded time histories (0-7Hz)

Inverted Kinematic Slip Model
(Cirella et al., 2012)

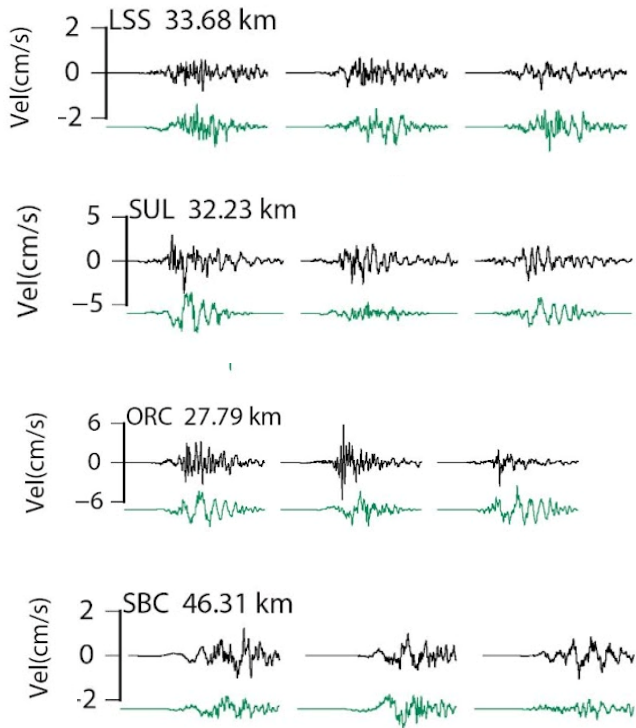


Generated with the GP Hybrid Method



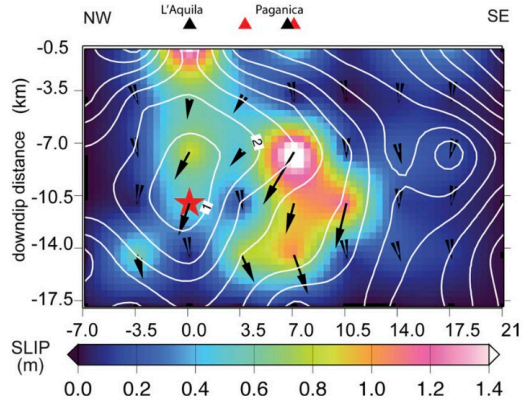
After Akinci et al. (2010)

The kinematic rupture models for the M_w 6.3 L'Aquila earthquake adopted from Cirella et al (2012) was realized using the hybrid technique of Pitarka et al. (2016) that integrates deterministic two large slip patches with the rectangular formation with random perturbations

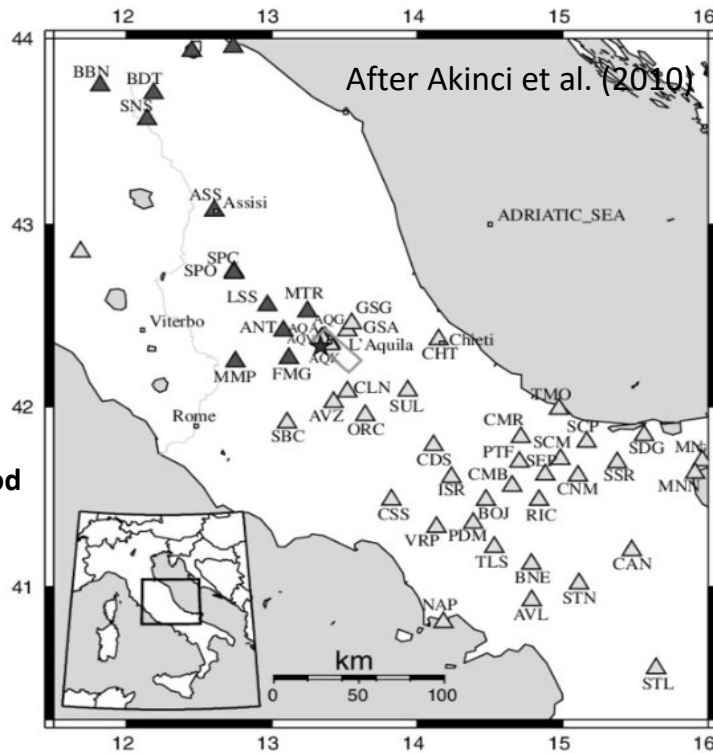
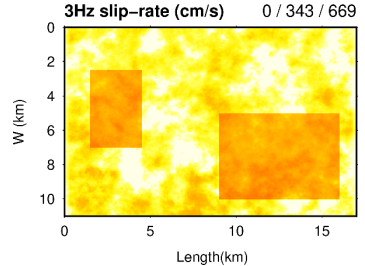
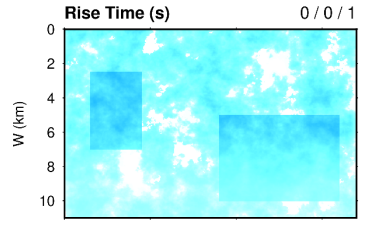
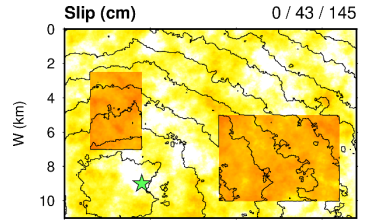


1. L'Aquila M_w 6.3, April 6th 2009 – comparison of recorded and Simulated Spectral Accelerations

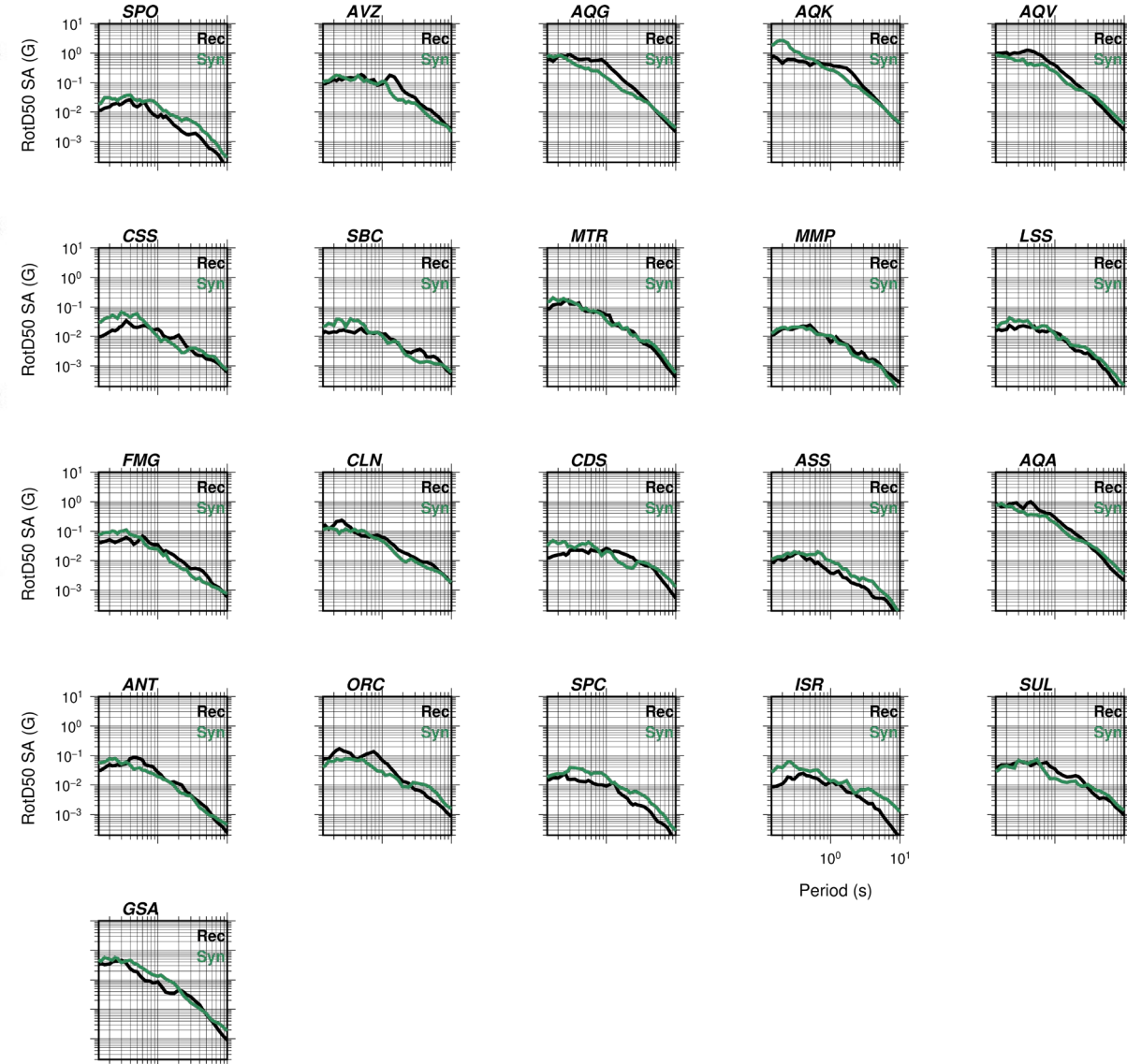
Inverted Kinematic Slip Model (Cirella et al., 2012)



Generated with the GP Hybrid Method

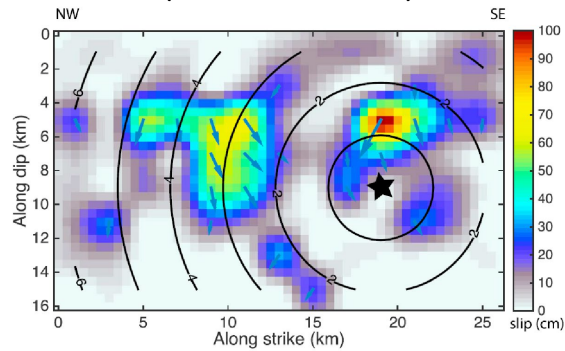


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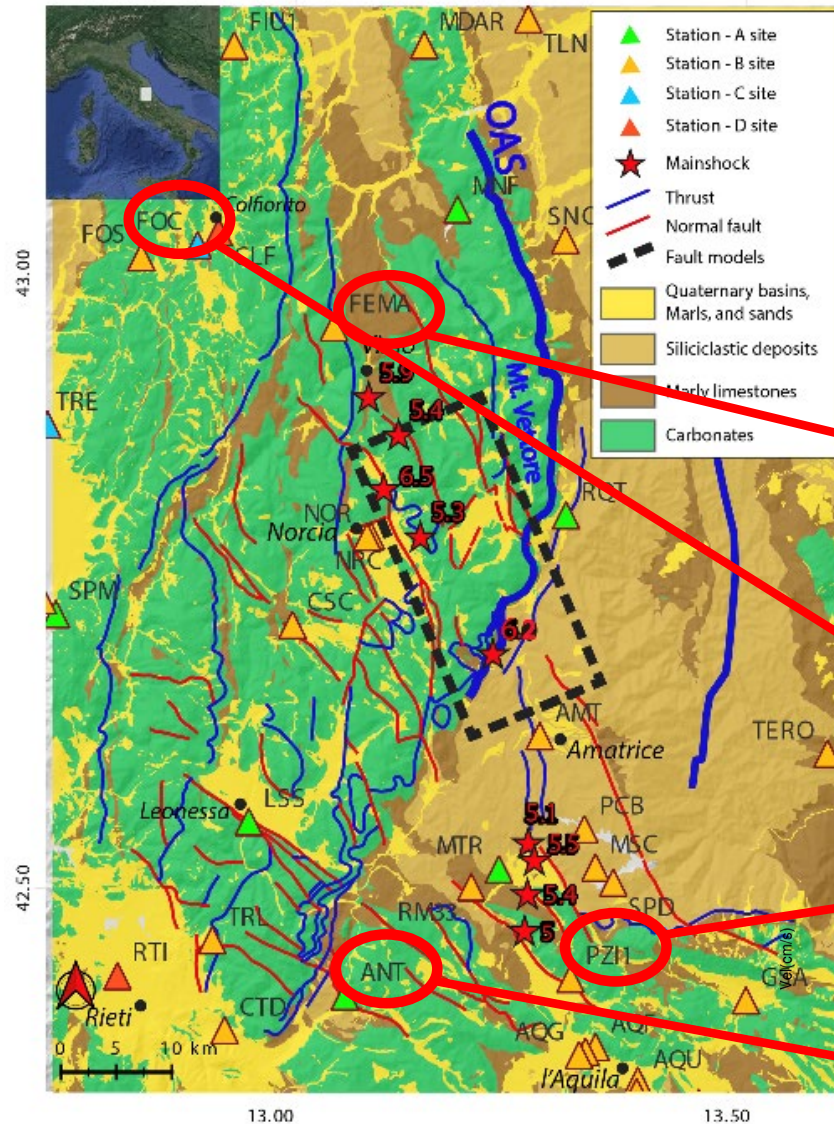
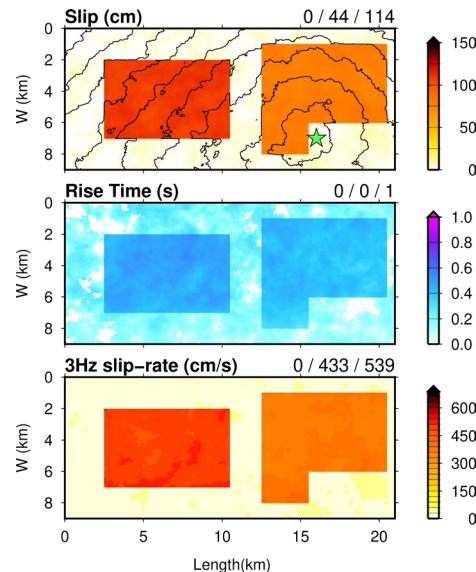


2. Amatrice M_w 6.2, August 24th 2016 - Comparison with recorded time histories (0-7Hz)

Inverted Kinematic Slip Model
(Tinti et al., 2016)

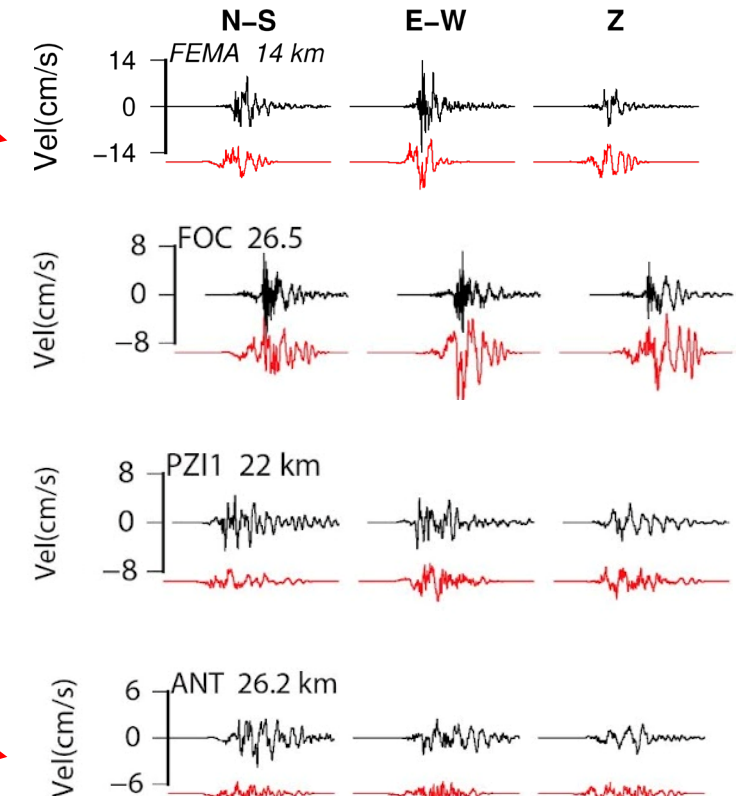


Generated with the GP Hybrid Method



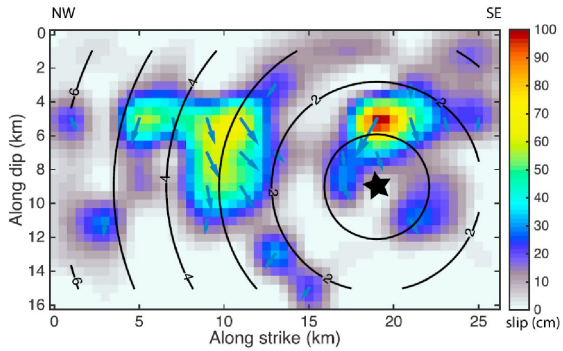
After Akinci et al. (2024)

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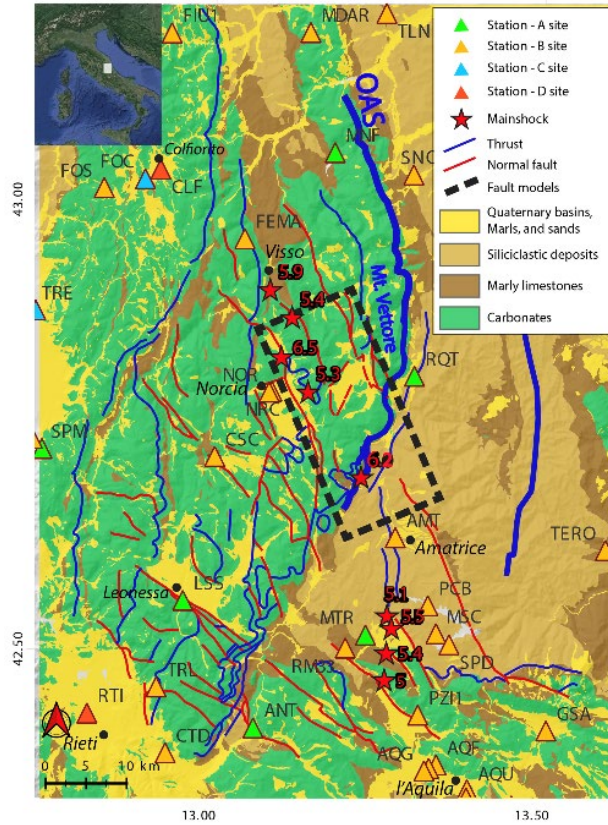
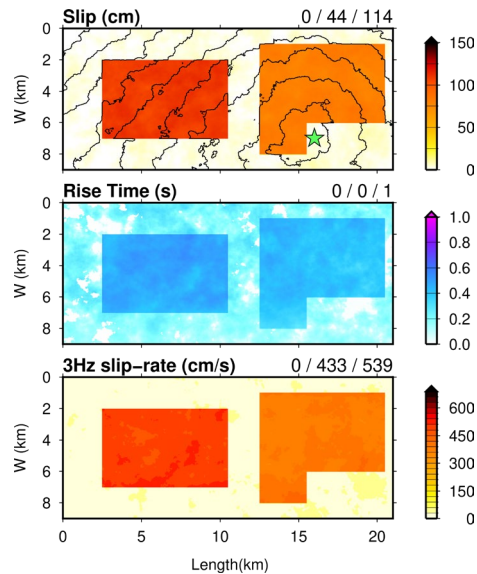


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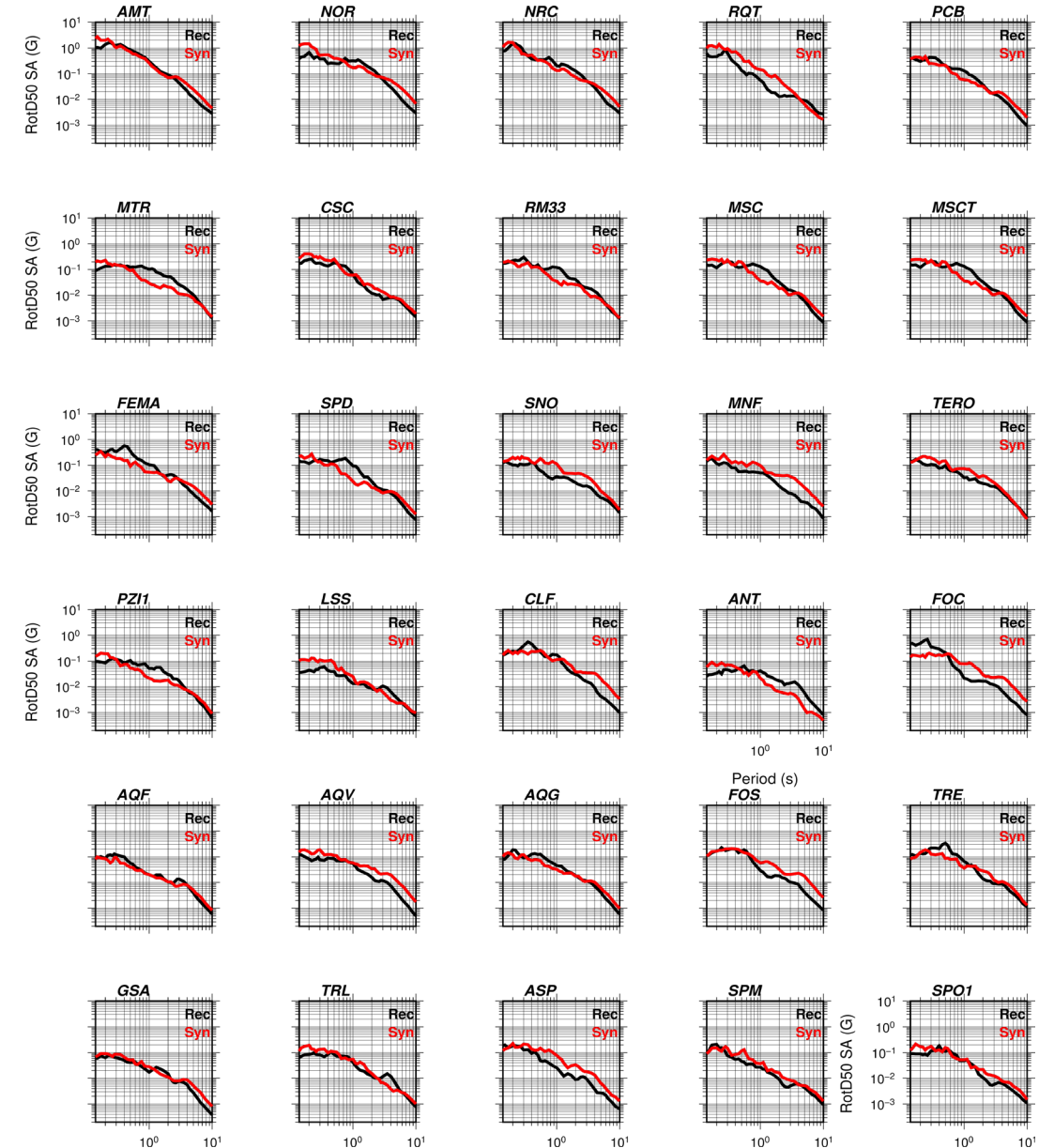


Generated with the GP16 Hybrid Method



After Akinci et al. (2024)

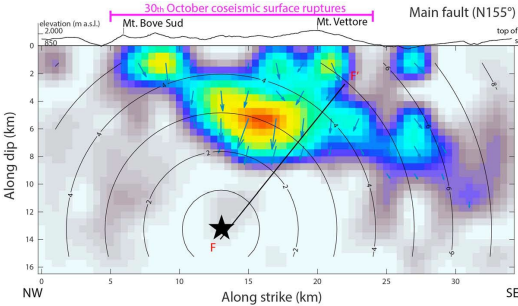
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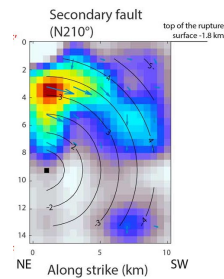
3. Norcia M_w 6.5, October 30th 2016 - Comparison with recorded time histories (0-7Hz)

Inverted Kinematic Slip Model (Scognamiglio et al., 2018)

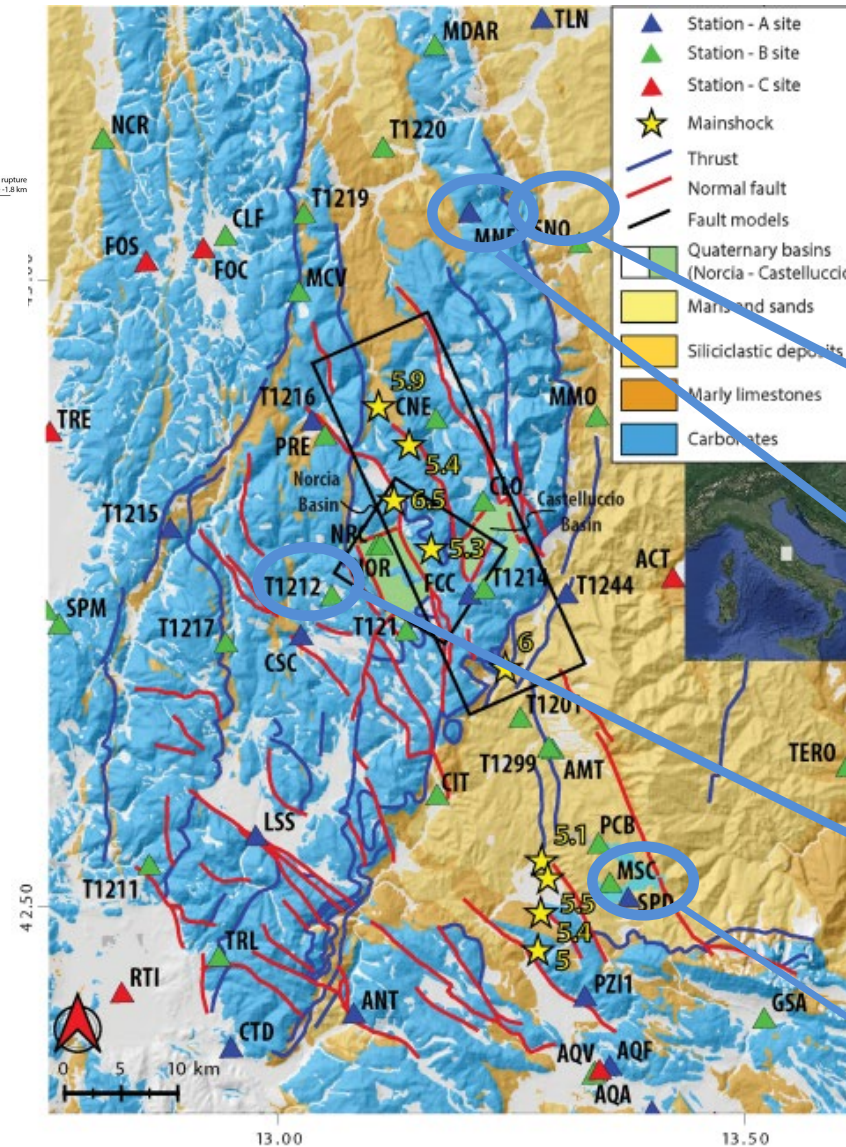
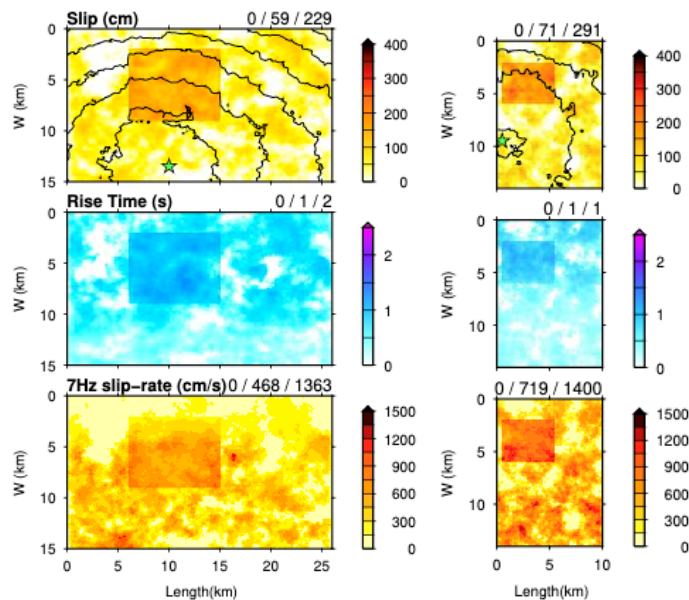
Segment 1



Segment 2

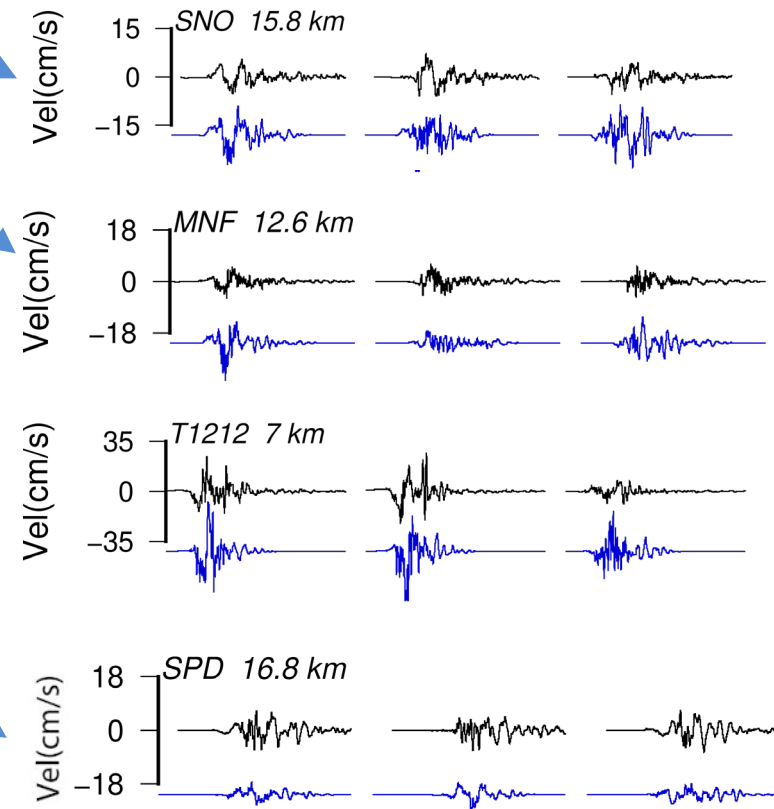


Generated with the GP16 Hybrid Method



After Pitarka et al. (2021)

The Kinematic rupture model for the M_w 6.5 Norcia earthquake adopted from Scognamiglio et al. (2018) using a hybrid approach (Pitarka et al., 2016) that combines deterministic large slip patches with rectangular shape, with random perturbations.

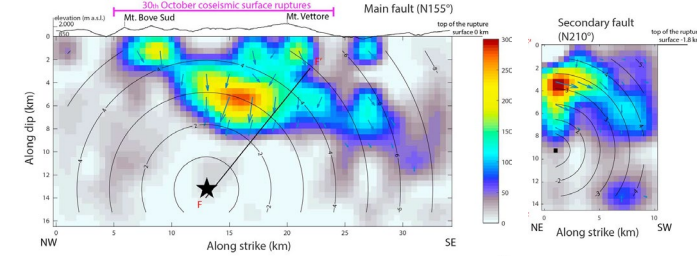


3. Norcia M_w 6.5, October 30 2016 - Comparison of recorded and Simulated Spectral Accelerations

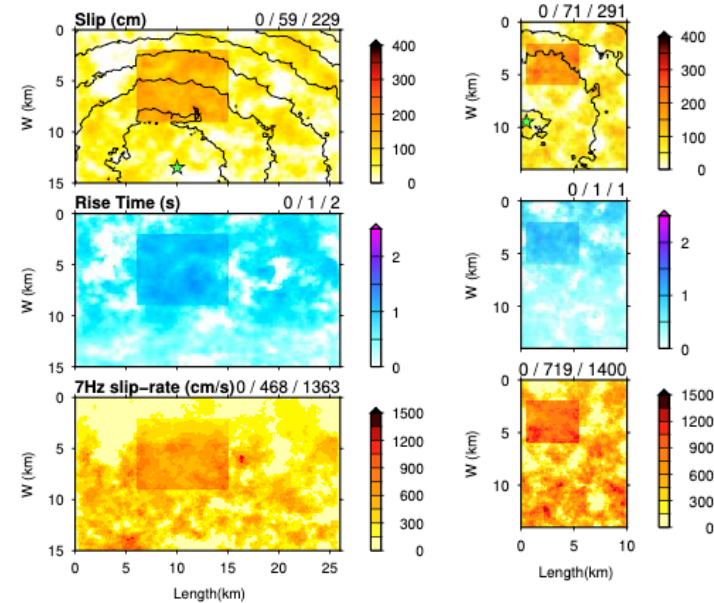
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Segment 1

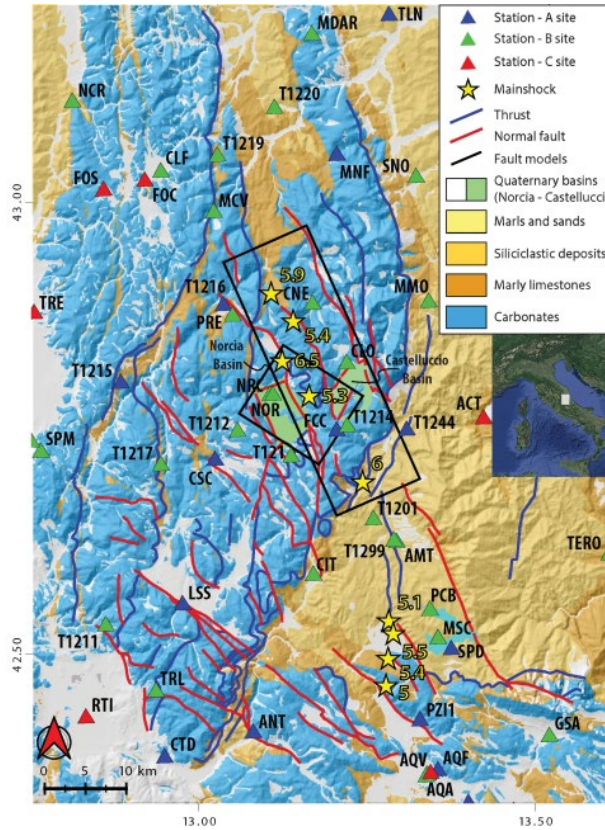
Segment 2



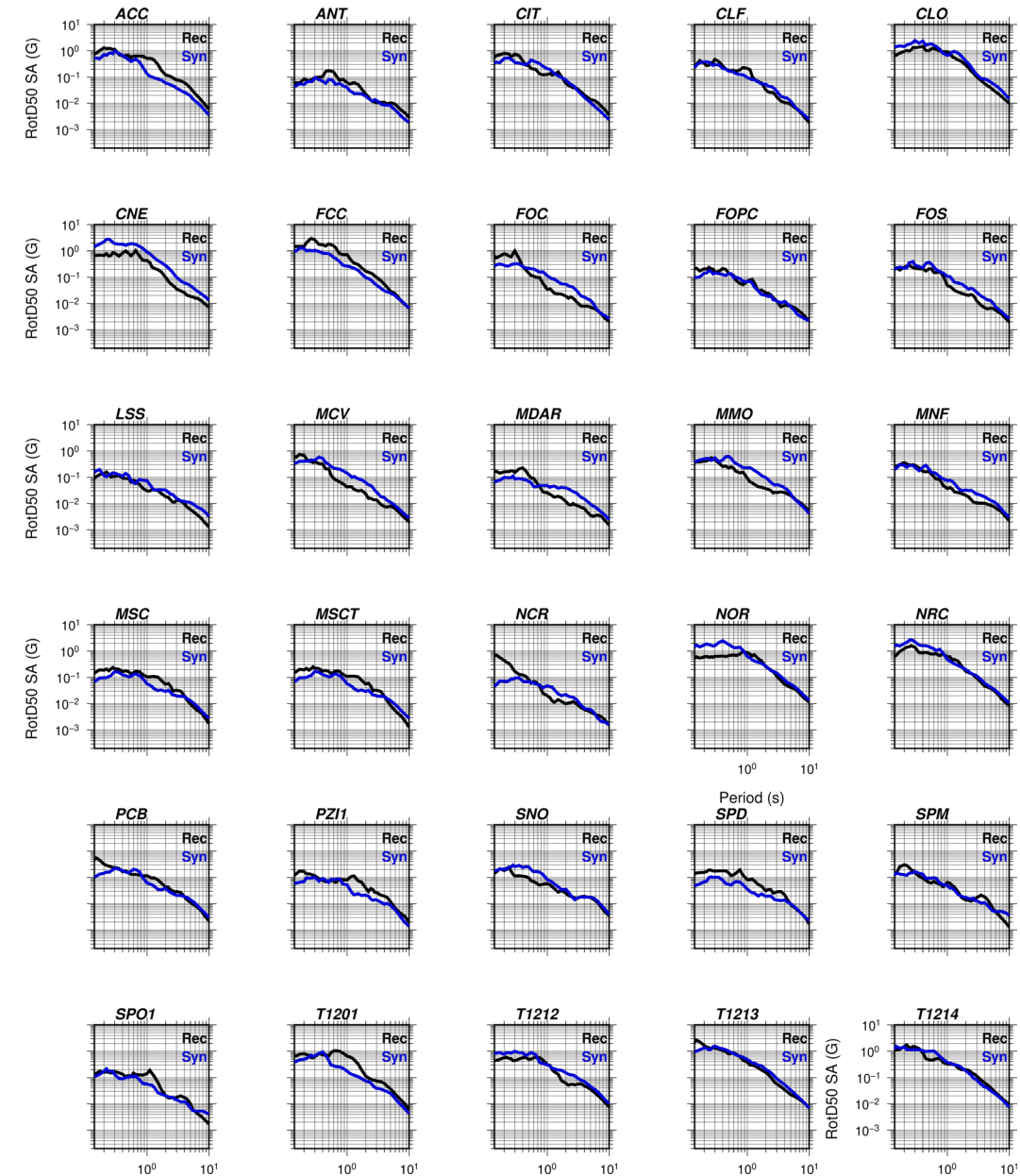
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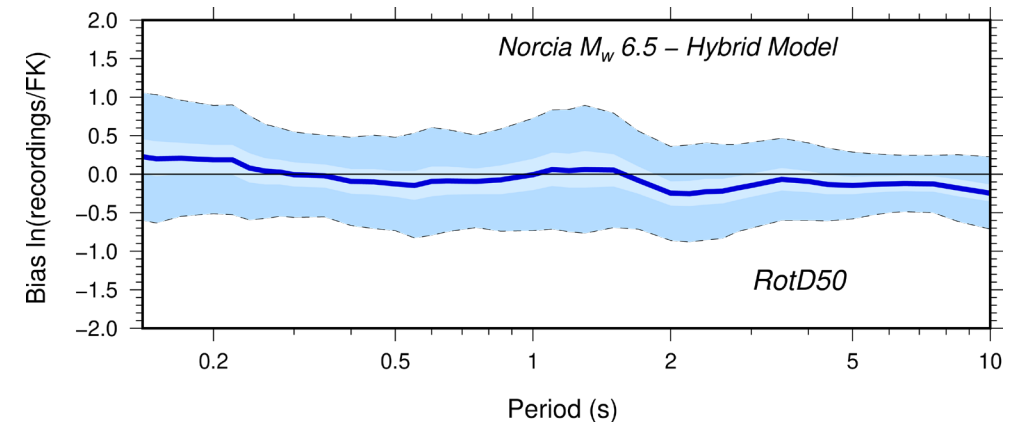
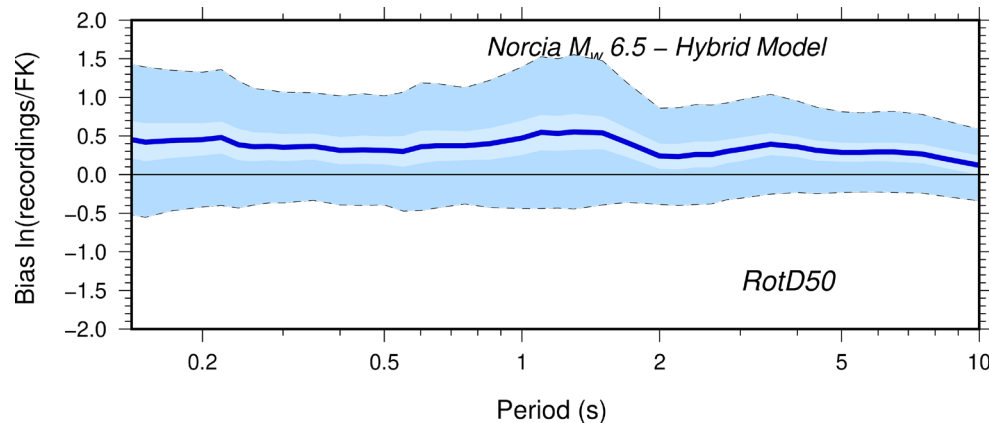


Site Effect & Impact on GoF

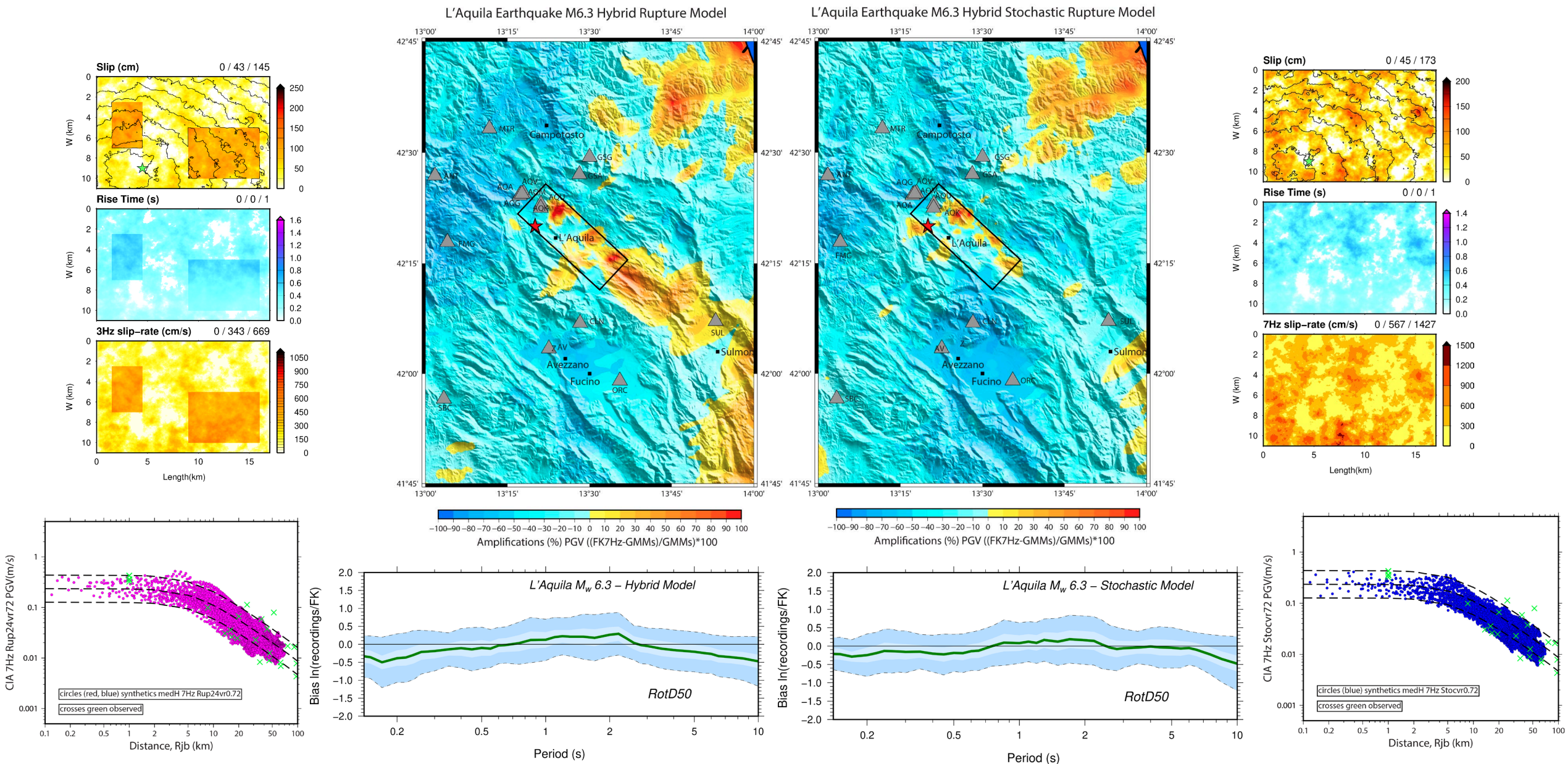
- CIA 1D velocity model with site-specific amplification
- Borchardt (1994) method for site corrections: applied to real stations using ITACA Vs30 values

$$F_x = \left(\frac{v_{site}}{v_{ref}} \right)^{m_x}$$

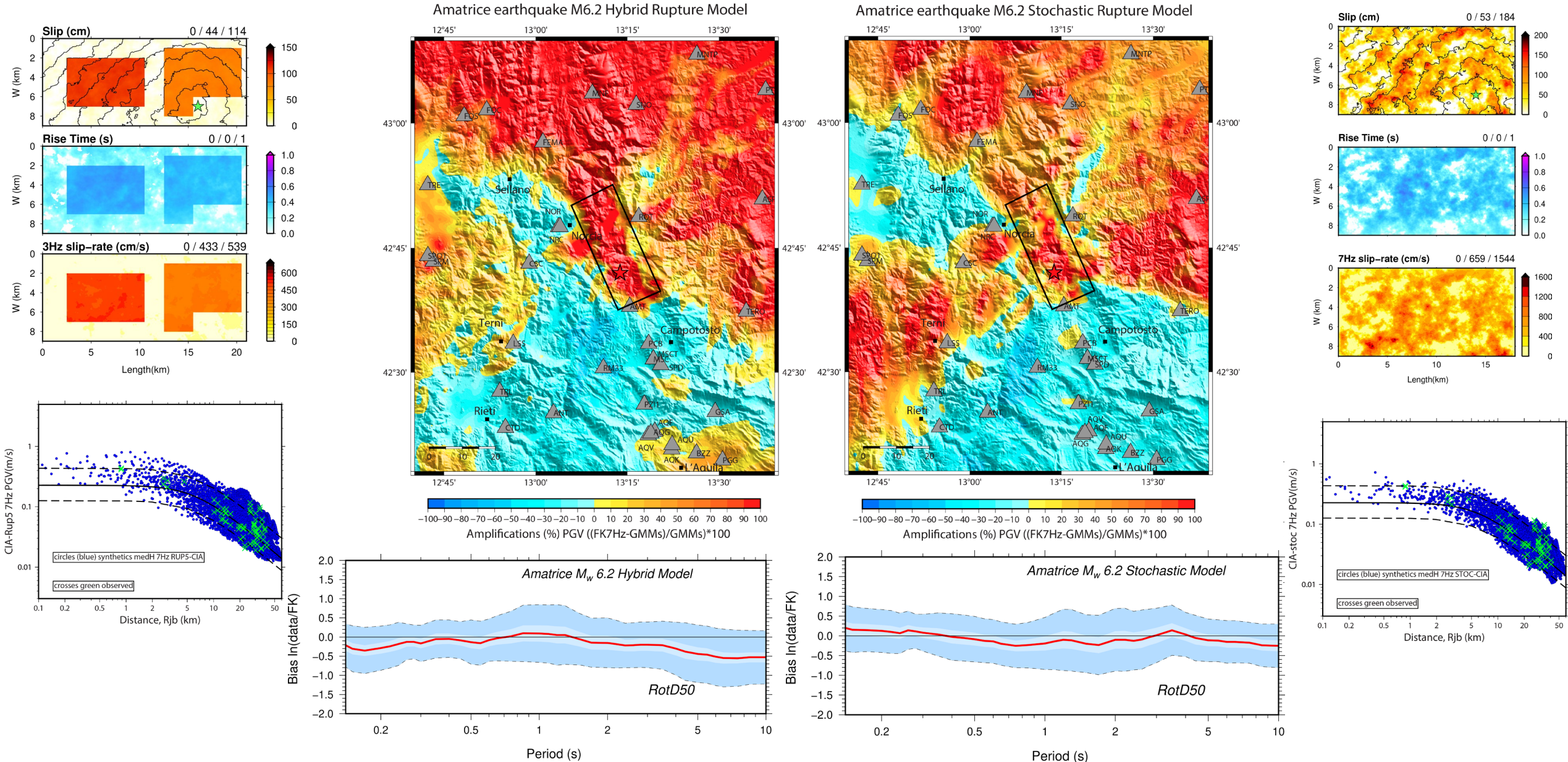
- Frequency-dependent with non-linear effects
- Stronger impact at short periods and high intensities
- Improved RotD50 SA goodness-of-fit after site correction
- Better agreement at short periods



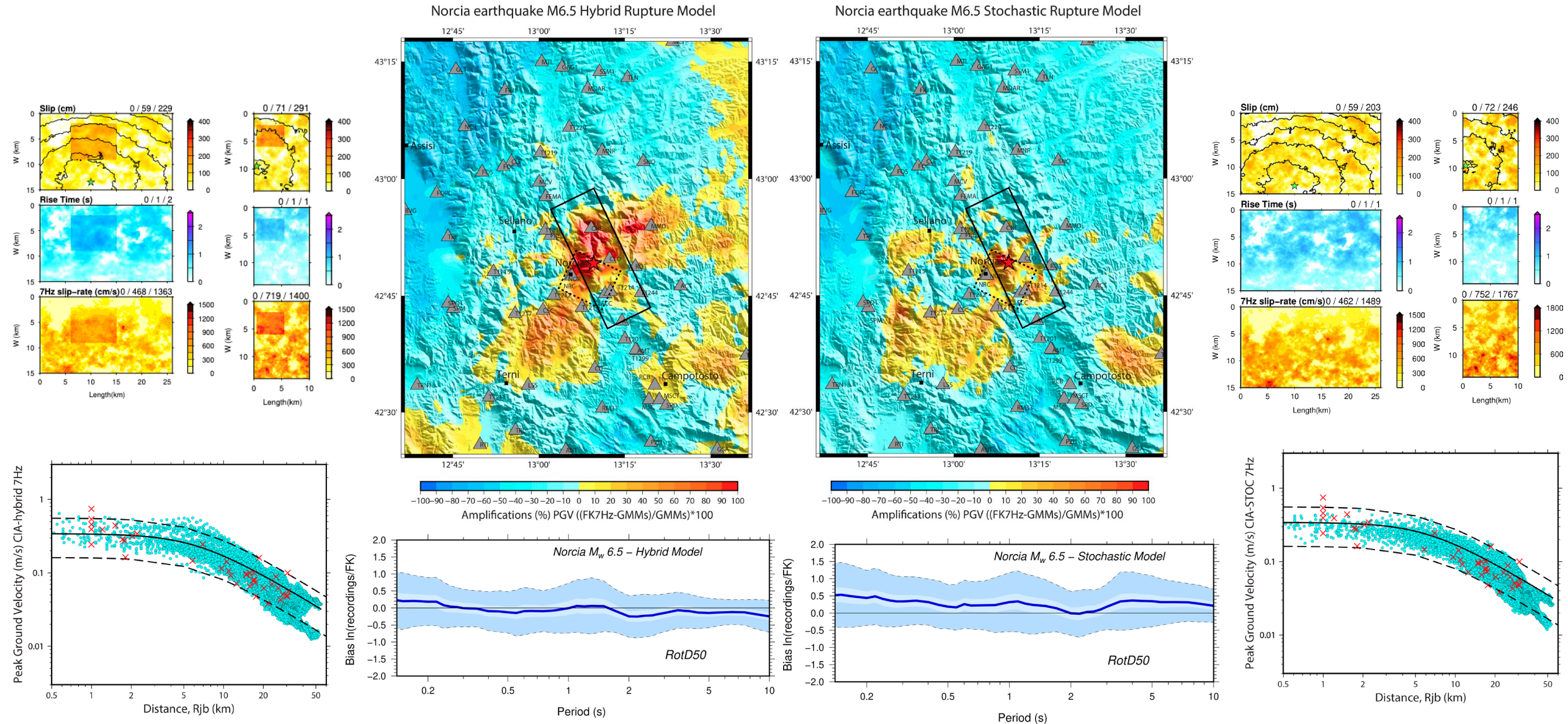
Stochastic vs Hybrid Rupture Models: 1 – L'Aquila earthquake



Stochastic vs Hybrid Rupture Models: 2 – Amatrice earthquake



Stochastic vs Hybrid Rupture Models: 3 – Norcia earthquake



Wave Propagation Visualization: example of L'Aquila

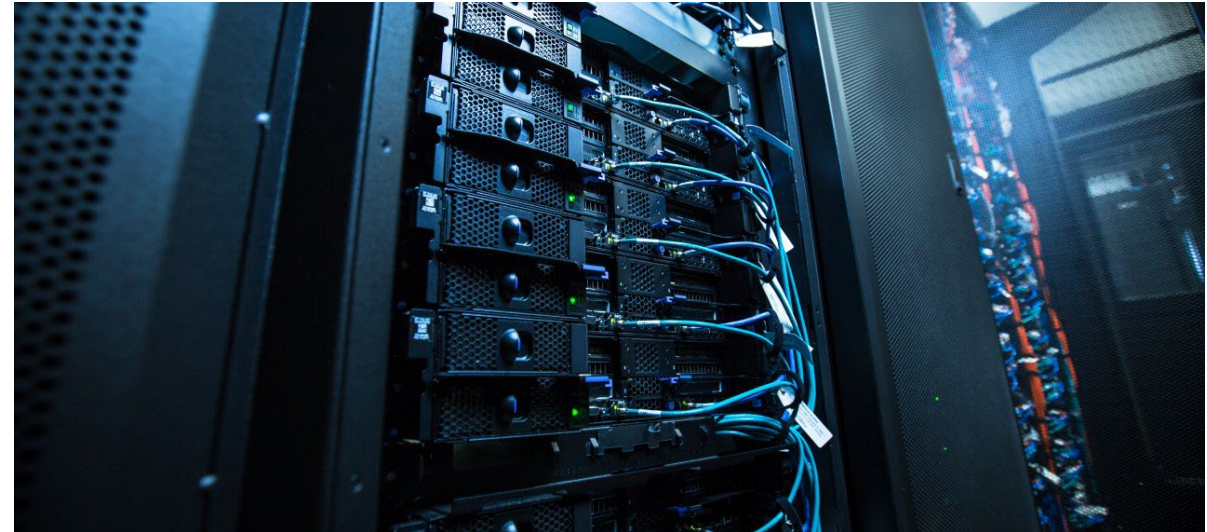
Movie of PGV propagation on virtual station grid (1 km spacing): FK 7hz



Comparison with SW4 3D Simulations

- 3D simulations with SW4 were performed on the Quartz supercomputer at Lawrence Livermore National Laboratory using the parallelized CPU version of the code.

- **With surface topography:**
 - 10,800 CPUs
 - Wall-clock time: 17-21 hours (3-5hz)
- **With flat free surface:**
 - 3,200-3,600 CPUs (3-5hz)
 - Wall-clock time: 4-4.5 hours



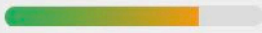
- We are currently testing the GPU version of SW4 (**ISCRA C CINECA PROJECT - GSIM-accepted**)
- First tests with **8 GPU**
 - 16 hours (2hz)
 - 46 hours (3hz)

CINECA

CONCLUSIONS

- We demonstrated the reliability of 1D deterministic simulations in reproducing observed ground motions (0–7 Hz) and capturing source-related spatial variability.
- Site effects were accounted for to ensure consistency with recorded ground motions.
- Our method achieves high-frequency accuracy comparable to 3D simulations, but with significantly lower computational cost.
- The rupture model is a key factor in accurately simulating near-source ground motion.
- Hybrid models offer a more realistic representation of rupture complexity than purely stochastic approaches.
- Directivity effects are clearly observed in the Amatrice and L'Aquila events.
- The 1D deterministic method is efficient and well-suited for regional seismic hazard analysis.

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CPU1: 

CPU2: 

CPU3: 

CPU4: 

NODES: 10,800

WALL TIME: 17H

> QUARTZ SUPERCOMPUTER
> CPU: 10,800 CORES
> RUNNING
> SCHEDULING ACTIVE
> STATE ANALYSIS...
> 3D MODEL
> 10,800

Thank you for your attention!
Grazie per l'attenzione!
İlginiz için teşekkürler!

