Unveiling Seismic Hazard Merging Geophysical and Catalog-based Data into a 3D Seismic Rate Model: a Case Study from the Adriatic Thrust Zone (Italy)

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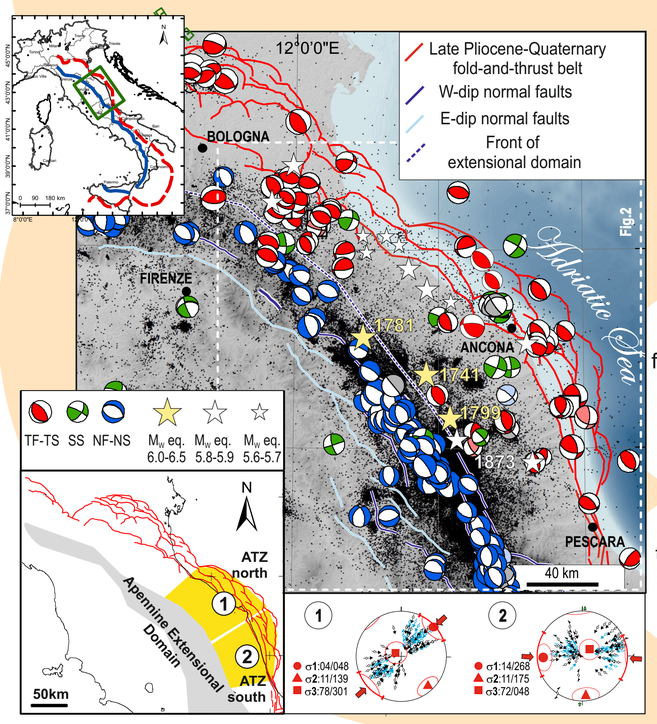
The Study Area



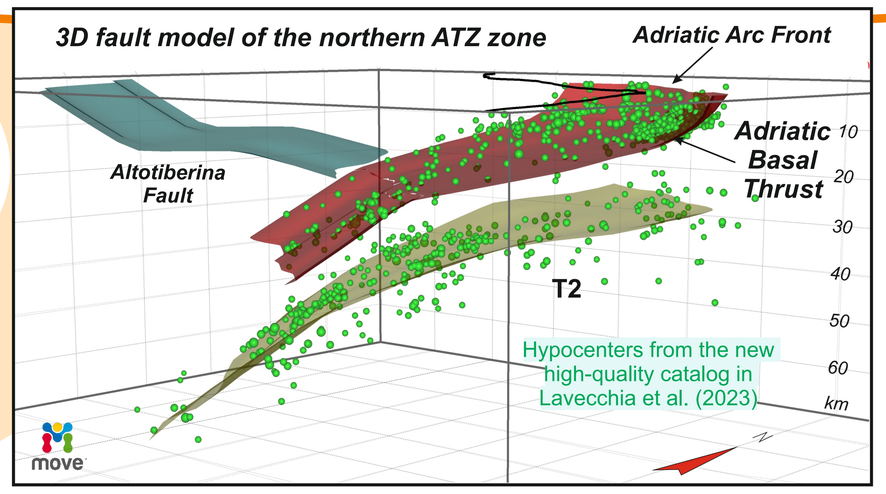
Eqs and focal mechanisms from Pondrelli et al. (2006), de Nardis et al. (2022), Rovida et al. (2022)

Stress tensors from de Nardis et al. (2022)

The present study performs a **comprehensive PSHA** of the Adriatic Thrust Zone (ATZ) of eastern Central Italy, investigating the combined effect of the **Adriatic Basal Thrust (ABT)** and a recently outlined underlying lithospheric thrust, referred to as **T2 thrust** in de Nardis et al. (2022).

Both thrusts deep at low-angle SW-ward with an average distance of 12.5 km between them. The ABT extends from the near-surface Adriatic Thrust front to depths of about 40 km, while T2 ranges from 20 to 60 km.

This peculiar regional configuration, characterized by the **coexistence of well-defined and overlapping seismogenic compressional volumes** within the Marche Adriatic lithosphere, makes it relevant to differentiate and quantify their contributions to ground shaking



How to model the ATZ zone for PSHA?

Lack of detailed geological and geodetic data
Off-shore or buried structures

Difficulties in segmentation along-dip
Extensive structures along dip

Complex multi-layered seismotectonic framework
Overlapping structures

Difficulties in segmentation along-strike
Regional structures whose just one segment is re-activated

Uncertainties to model the magnitude recurrence relations for earthquakes
Few historical earthquakes and seismic sequences related to this domain

New 3D seismotectonic and catalog-based approach

Step 1
Catalog Selection and Analysis
to identify the activity associated with the ABT and the T2 thrusts

Step 2
Seismogenic Volume Characterization
The ABT and T2 are parametrized within a 3D grid with rupture parameters

Step 3
New 3D Adaptive Smoothed Seismicity
to compute ABT and T2 earthquake rates

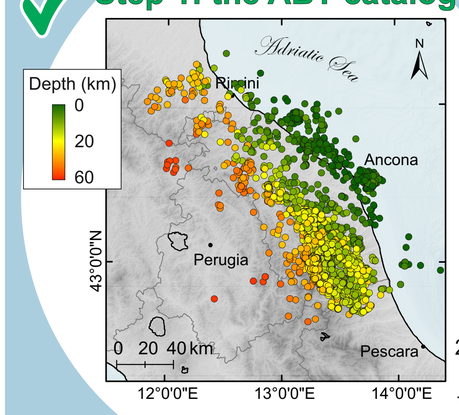
The **3D grids** reflect the geometrical complexity of structures

3D Gaussian kernel

$$K_j = \frac{1}{2\sqrt{2\pi^{3/2}\sigma^3}} \exp\left(\frac{-R3_{ij}^{\,2}}{2\sigma^2}\right)$$

The ABT thrust

Step 1: the ABT catalog



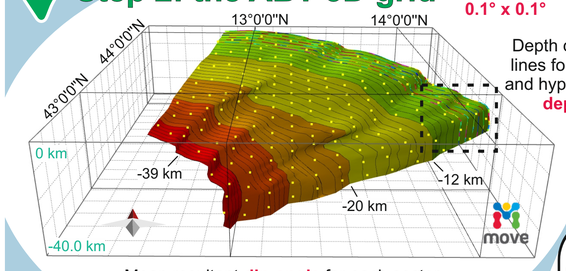
Relocated high-quality seismic catalog from Lavecchia et al. (2023) selected to identify ABT activity

6939 earthquakes recorded between 2010 and 2021

Magnitude from 0.0 to 4.8 ML

Step 2: the ABT 3D grid

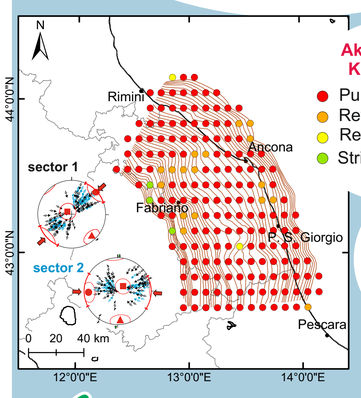
Regular grid **0.1° x 0.1°**



Depth contour lines for **strike** and hypocentral **depth**

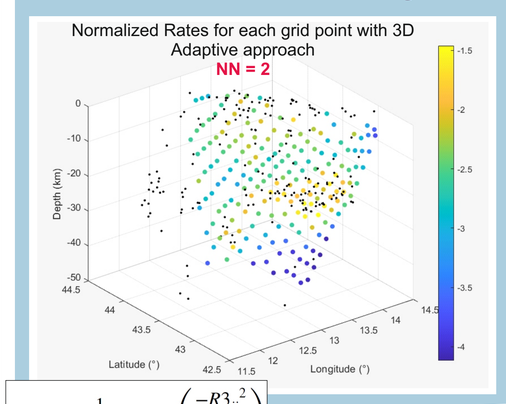
Mean resultant **dip-angle** for each sector by Move statistics

37° 25° 24° 18° 15°



Rake computed with the method developed by Xu et al. (2017)

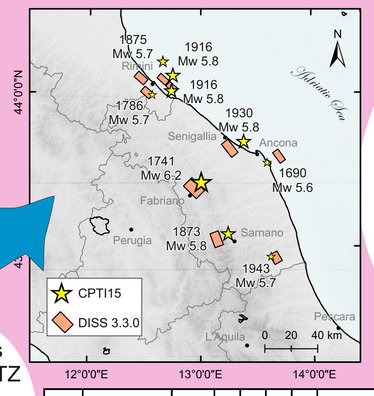
Step 3: 3D Adaptive Smoothed Seismicity



$$K_j = \frac{1}{2\sqrt{2\pi^{3/2}\sigma^3}} \exp\left(\frac{-R3_{ij}^{\,2}}{2\sigma^2}\right)$$

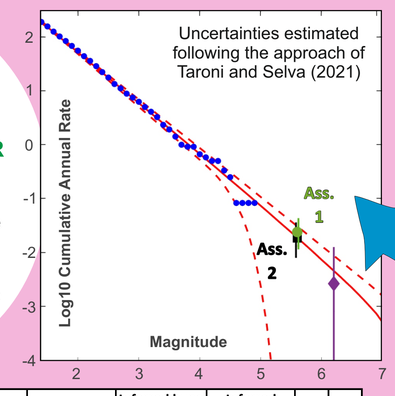
σ represents the model parameter that governs the smoothing amplitude based on the number of **nearest neighbors (NN)**

Can a microseismicity catalog be rapresentative for strong earthquakes?



Large Eqs related to ATZ identified through a detailed comparison of **literature**

Comparison between the earthquake rates computed with the **overall tapered GR of the unified ABT + T2 catalog** and the earthquake rates of the **large earthquakes** associated with the ATZ



ID	Locality	Y	M	D	H	M	Latitude CPTI15	Longitude CPTI15	Mw CPTI15	Depth range Lavecchia et al. 2007	Depth range DISS 3.3.0	Inferred hypo depth Sbarra et al. 2023	Inferred hypo depth Gironelli et al. 2023	Ass. 1	Ass. 2
1	Anconetano	1690	12	23	0	20	43.5500	13.5940	5.58	≤ 10 km	2.5-6.4 km	""	""	X	X
2	Fabrianese	1741	4	24	9	20	43.4250	13.0050	6.17	10-30 km	14-17 km	34.94 km	20 km	X	X
3	Riminese	1786	12	25	1		43.9910	12.5650	5.66	≤ 10 km	3-6 km	""	""	X	X
4	Sarnano	1873	3	12	20	4	43.0890	13.2440	5.85	10-30 km	17-19.3 km	13.67 km	""	X	
5	Riminese	1875	3	17	23	51	44.2090	12.6590	5.74	≤ 10 km	3-6 km	""	""	X	X
6	Adriatico	1916	5	17	12	50	44.1190	12.7480	5.82	≤ 10 km	3-5.5 km	""	""	X	X
7	Adriatico	1916	8	16	7	6	44.0190	12.7370	5.82	≤ 10 km	3-5.5 km	≤ 5 km	""	X	X
8	Senigallia	1930	10	30	7	13	43.6890	13.3850	5.83	≤ 10 km	4-7.5 km	63.17 km	""	X	X
9	Offida	1943	10	3	8	28	42.9400	13.6260	5.67	10-30 km	4.5-8.7 km	8.51 km	""	X	

Possible associations explored in **two different scenarios**

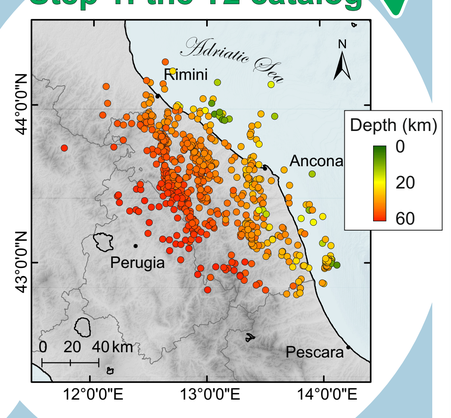
The T2 thrust

Step 1: the T2 catalog

Relocated high-quality seismic catalog from Lavecchia et al. (2023) selected to identify T2 activity

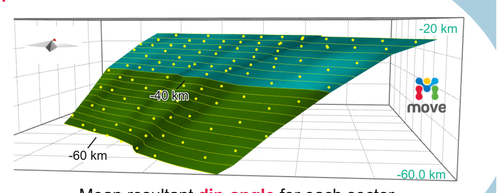
648 earthquakes recorded between 2010 and 2021

Magnitude from 0.0 to 4.4 ML



Step 2: the T2 3D grid

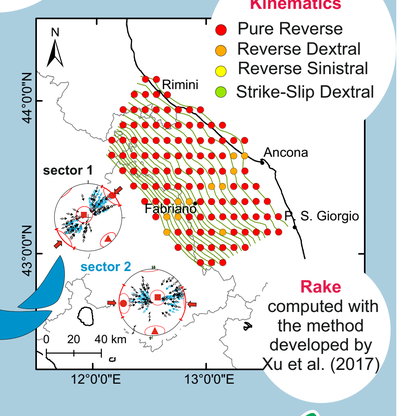
Regular grid **0.1° x 0.1°**



Mean resultant **dip-angle** for each sector by Move statistics

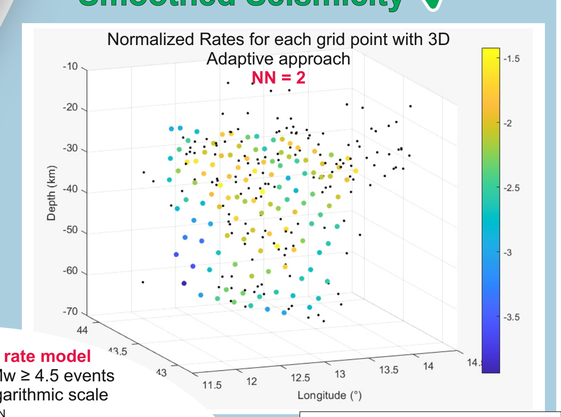
Depth contour lines for **strike** and hypocentral **depth**

35° 19°



Rake computed with the method developed by Xu et al. (2017)

Step 3: 3D Adaptive Smoothed Seismicity



$$K_j = \frac{1}{2\sqrt{2\pi^{3/2}\sigma^3}} \exp\left(\frac{-R3_{ij}^{\,2}}{2\sigma^2}\right)$$

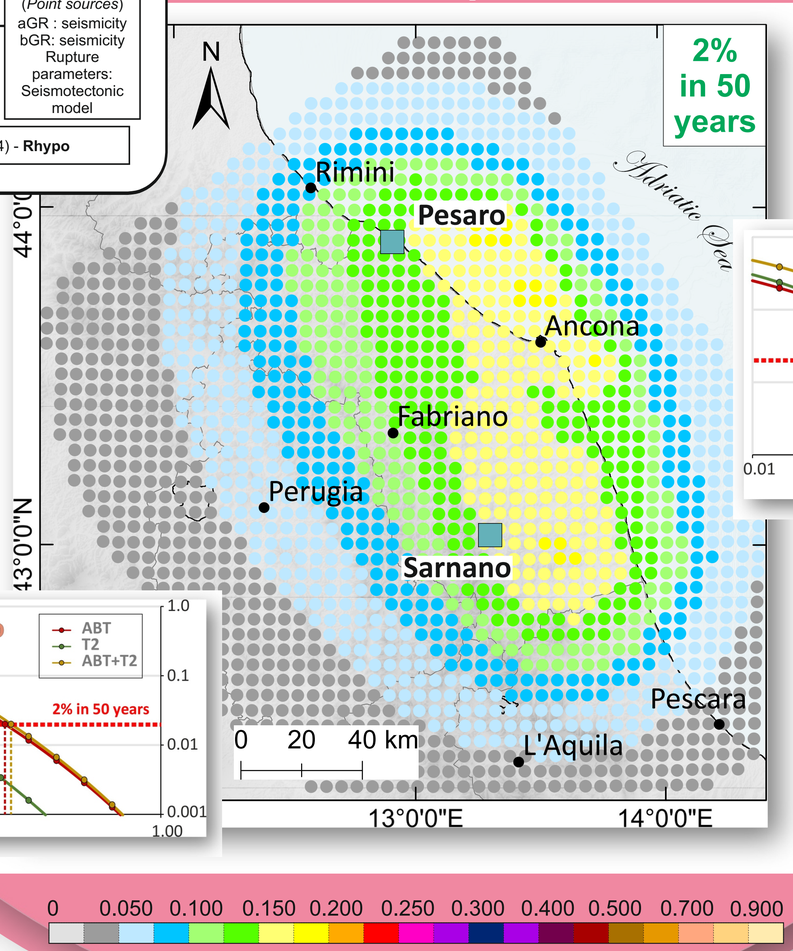
The new 3D approach includes **hypocentral depths** and create a smoothed earthquake distribution over three-dimensional spatial cell grids using a 3D kernel, which employs a 3D distance (**R3**)

The PSHA map

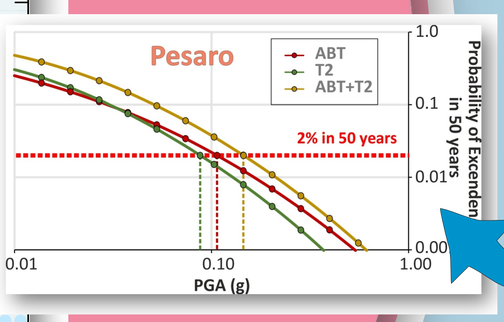
ABT+T2 as separate sources

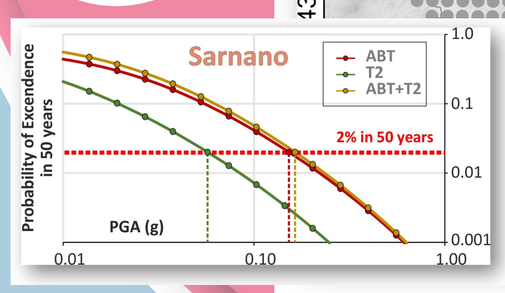
Workflow for Openquake

Seismic Source Model *weight: 1*	**ABT** (*Point sources*) aGR : seismicity bGR: seismicity Rupture parameters: Seismotectonic model	**T2** (*Point sources*) aGR : seismicity bGR: seismicity Rupture parameters: Seismotectonic model
Ground Motion Model *weight: 1*	Bindi et al. (2014) - **Rhypo**	



The combined approach, integrating seismotectonic- and catalog-based data, resulted in **higher resolution hazard maps**, revealing higher PGA values in the coastal area offshore Pesaro and Ancona

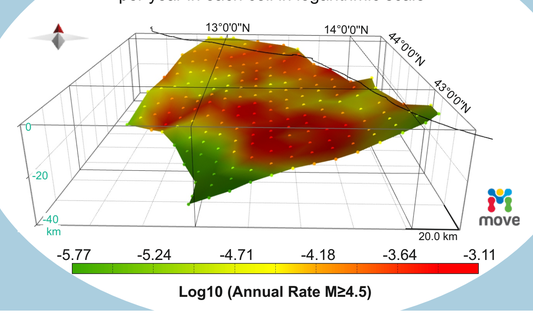




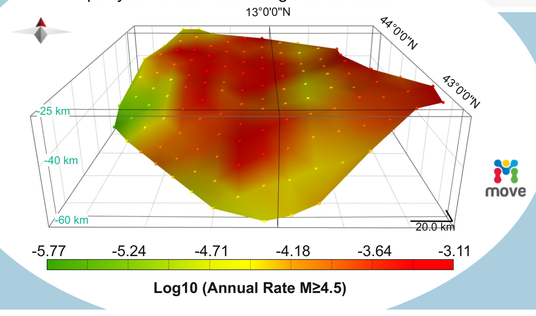
The ground motion near **Sarnano** is predominantly influenced by the ABT. The contribution of the T2 thrust becomes more significant near **Pesaro**

To emphasize our multi-depth scenario, we evaluated the **hypocentral distance (Rhypo)**, which is the distance between the hypocenter and the site where the hypocenter is assumed to be at the center of a rupture

The ABT 3D earthquake rate model with expected number of Mw ≥ 4.5 events per year in each cell in logarithmic scale



The T2 3D earthquake rate model with expected number of Mw ≥ 4.5 events per year in each cell in logarithmic scale



Remarks

Applicability in subduction zones where depth is crucial to improve the reliability of seismic and tsunami hazard assessments

The new approach allows to work with multi-layered and multidepth structures, characterizing their contribution to ground motion

Attributing seismicity to specific seismogenic and kinematic domains has significant implications for the b-value, the rate distribution, and the rupture-site distance

Useful approach with complex geological features, such as extensive regional or offshore structures