Rheological control on distributed aftershock activity: insights from the Mw 6.5 Norcia seismic sequence

Francesca Rossi [1], Giovanni Guglielmi [1], Fabio Trippetta [1] and Cristiano Collettini [1,2]

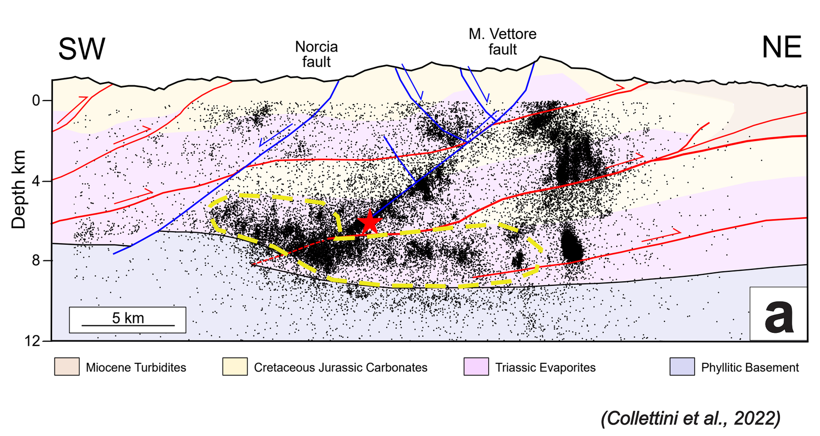
1) Department of Earth Sciences, Università La Sapienza di Roma, Rome, Italy 2) Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

Contacts
- *francesca.rossi3@uniroma1.it*
- *giovanni.guglielmi@uniroma1.it*
- *fabio.trippetta@uniroma1.it*
- *cristiano.collettini@uniroma1.it*

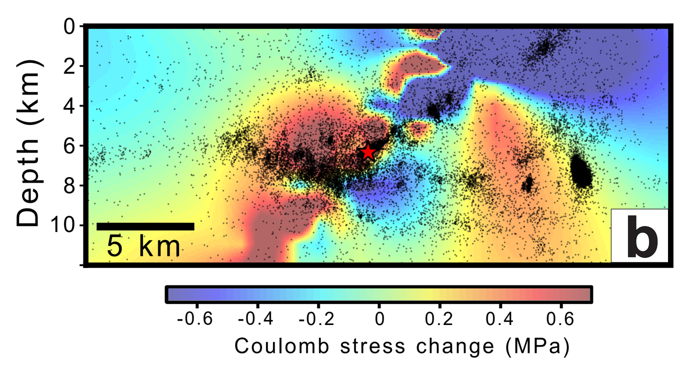
1 Introduction

During a seismic sequence, the spatial distribution of aftershocks typically reveals the structural architecture of the fault zone activated during the mainshock. However, within the seismogenic crust, seismicity is not necessarily exclusive of the mainshock rupture plane.

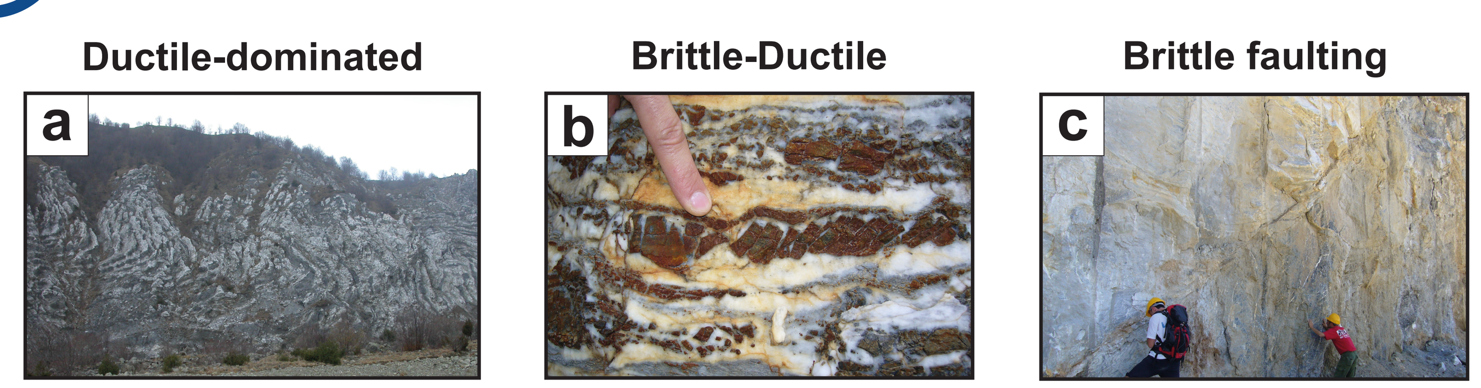
In the case of the Mw 5.9 and Mw 6.5 2016-2017 Visso-Norcia (Central Italy) seismic sequence, widespread distributed seismicity (Mw < 4) has been recorded in a large volume below the tip of the ruptured fault in the depth range of 4-11 km (DS). Here, the seismic reflection profiles (**a**) identify the presence of Triassic Evaporites, TE, a geological formation composed of anhydrites and dolostones. In the same volume, the Coulomb stress change produced by the Norcia mainshock suggest an increase in strain rate (**b**).



(Collettini et al., 2022)

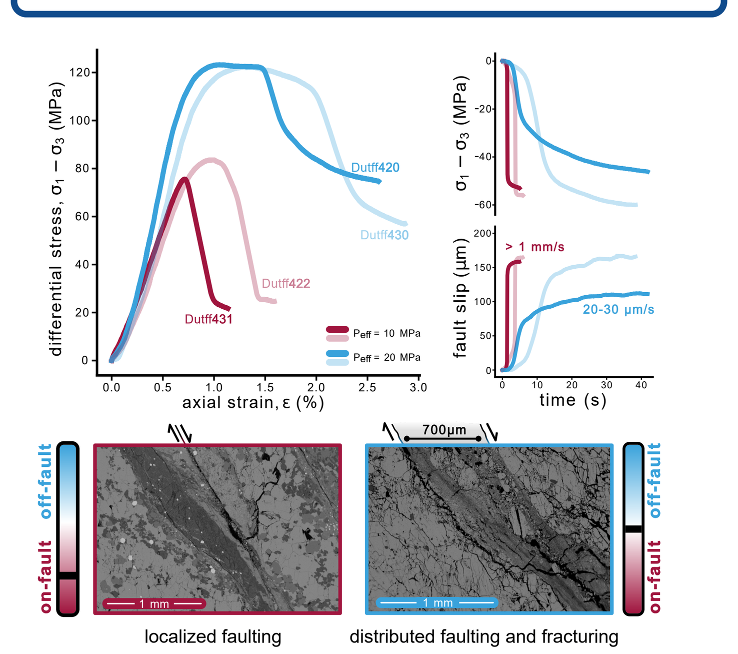


2 Rheology of the Triassic Evaporites

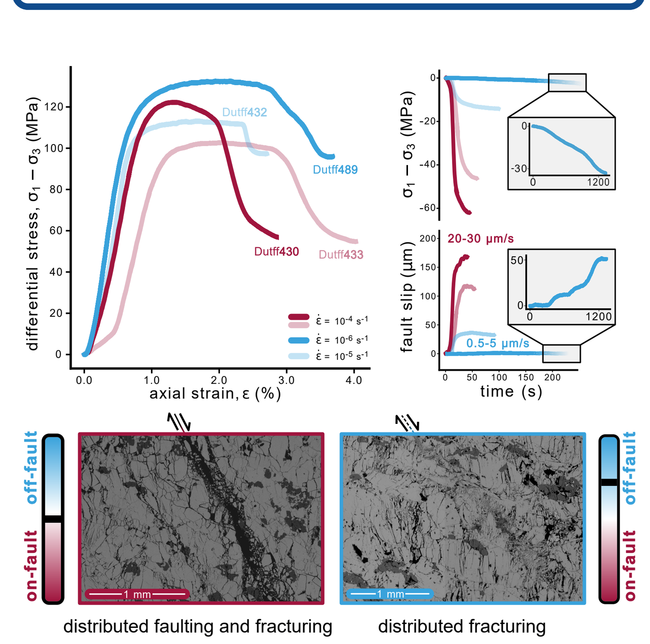


Field observations show that, away from the major faults, TE deformation consists of a background ductile deformation interspersed with brittle processes in the form of distributed failure and folding of the anhydrites associated with boudinage hydro-fracturing and faulting of dolostones. Recent laboratory experiments reveal that a swicth from ductile, distributed deformation to brittle, localized faulting occurs for an increase of strain rate, and/or a decrease of effective pressure (a proxy for fluid pressure in nature).

THE ROLE OF EFFECTIVE PRESSURE



THE ROLE OF STRAIN RATE

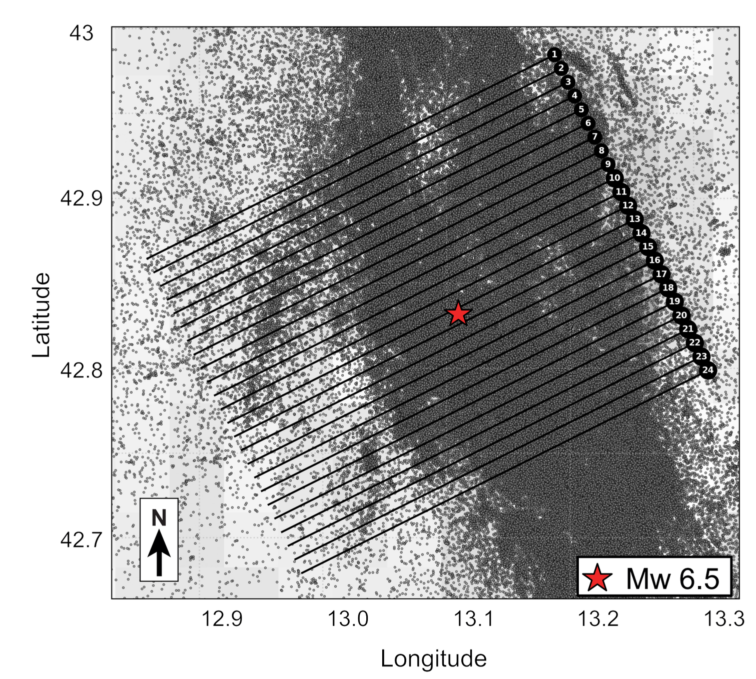


In this work we used the DS to highlight the seismological evidence of distributed deformation within a layer of the seismogenic crust affected by a background ductile deformation.

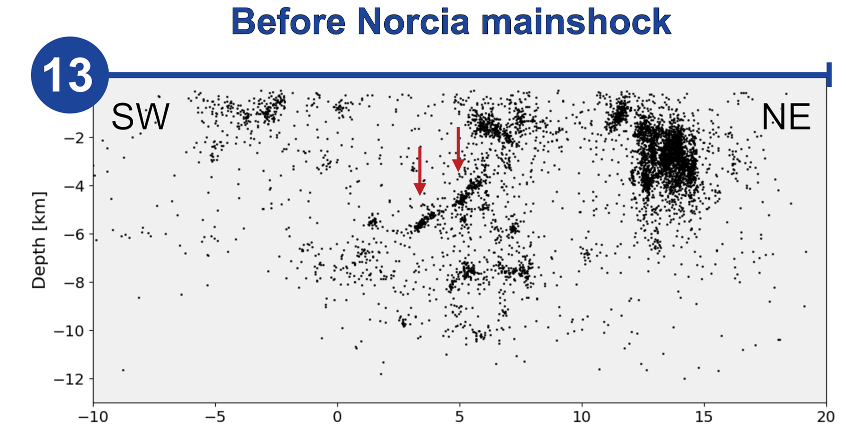
3 Seismological analysis

• DS selection

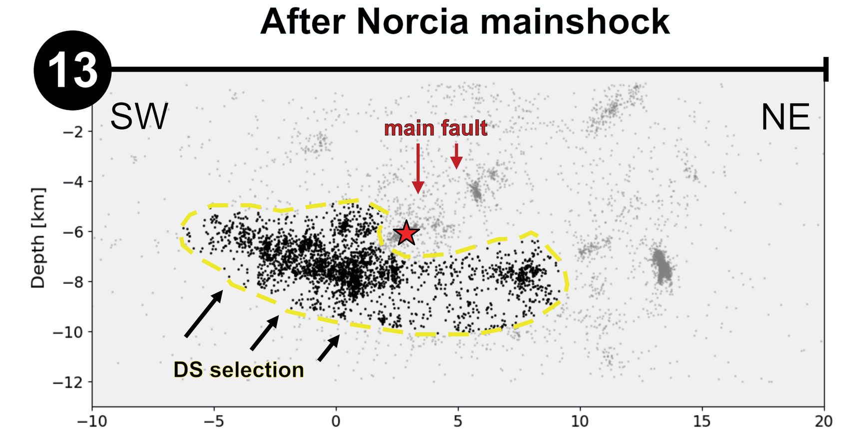
We built 24 seismological cross-sections 1 km-spaced and oriented perpendicularly to the strike of the mainshock rupture plane (155°N). For each cross-section, aftershocks within 0.5 km was projected using the high-resolution earthquake catalog of Tan et al. (2021), and DS events were subsequently selected.



Before Norcia mainshock



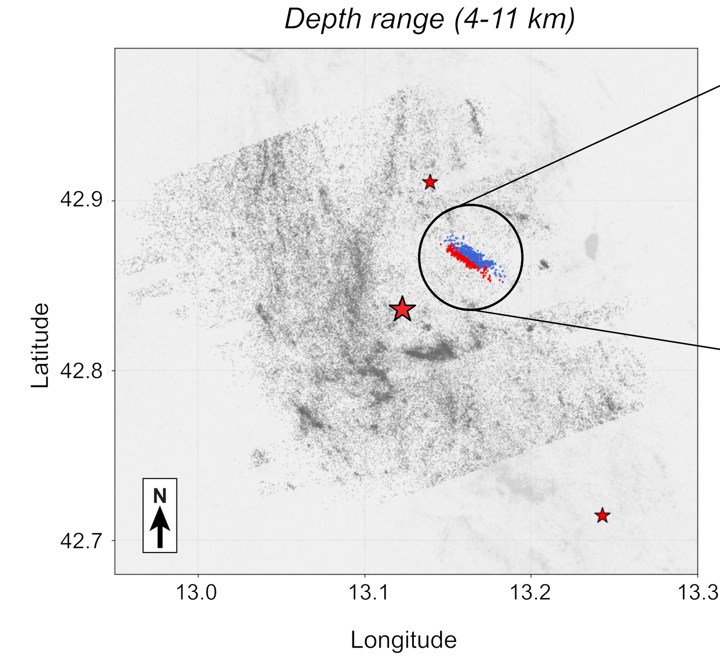
After Norcia mainshock

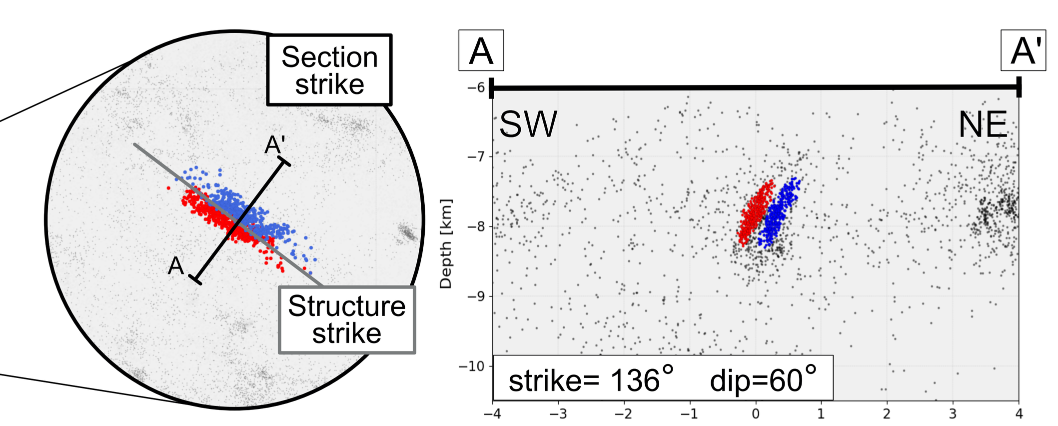


• Structure selection and analysis

Map view of merged DS

Depth range (4-11 km)





In map view, major alignments and clusters of seismicity were identified. For each structure, a seismological cross-section was built perpendicularly to its strike. Structures were then selected and isolated based on their expression in the corresponding cross-sectional profiles.

In order to characterize the seismological behavior, for each selected structure we have analyzed:

Seismicity rate

Time evolution of the daily number of events:

- **Omori-like decay:** the rate of aftershocks decreases with time after the mainshock.
- **Swarm-like activity:** elevated earthquake activity not preceded by a clear mainshock

(Omori, 1894; Shelly, 2024)

Coefficient of Variation of Interevent time

To quantify the level of time clustering of the seismicity:

$$COV\ (\tau) = \sigma_\tau/\bar{\tau}$$

$COV = 0$ **periodic** occurrence

$COV = 1$ **random Poisson** occurrence

$COV > 1$ **temporally clustered** seismicity

(Kagan & Jackson, 1991; Cabrera et al., 2022)

Time evolution of seismic moment release

To understand the behavior of different types of seismic sequences:

$$MaxM0 \Big/ \sum M0$$

$\sim 0 =$ stable moment release (**swarm-like sequence**)

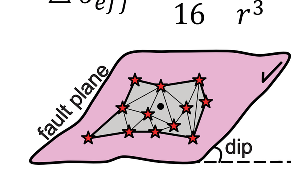
$\sim 1 =$ most of moment released at once (**mainshock-aftershock sequence**)

(Vidale & Shearer, 2006; Cabrera et al., 2022)

Effective Stress Drop

To analyze the relation between the size of the activated area and the cumulative seismic moment of the sequence.

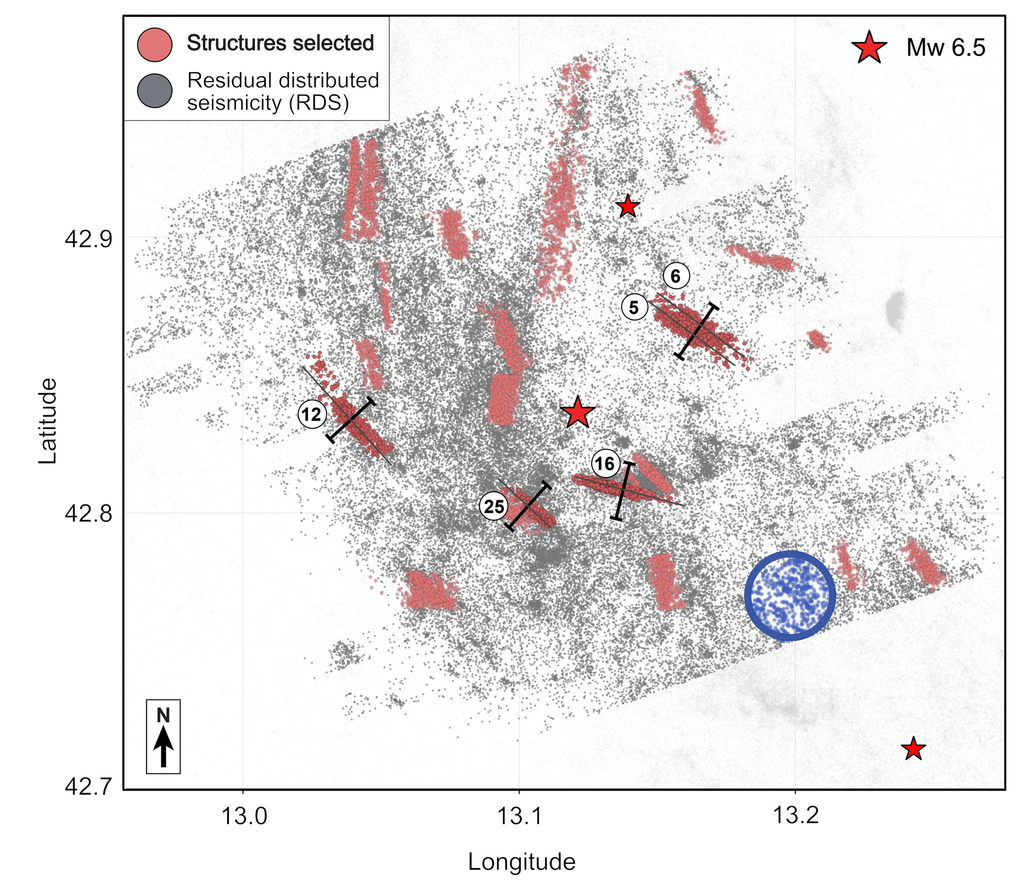
$$\Delta\sigma_{eff} = \frac{7}{16}\frac{\sum M0}{r^3}$$



Fischer & Hainzl, 2017

4 Results

From the seismological analysis of DS, we identified **28 distinct structures** (red points), resulting from the alignment of earthquakes both in map view and cross-section.



Structures selected

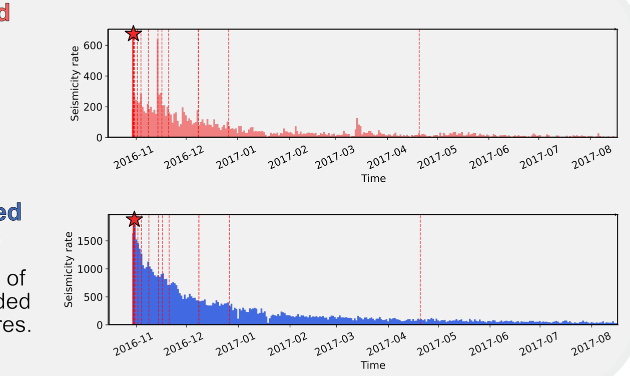
Merged earthquake catalogue of the 28 structures

- 13.901 events

Residual distributed seismicity (RDS)

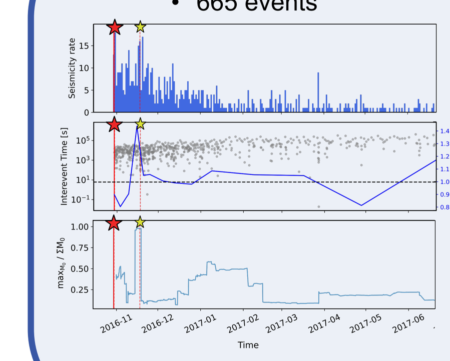
Residual earthquakes of DS, that are not included in the selected structures.

- 66.506 events



Random selection of RDS

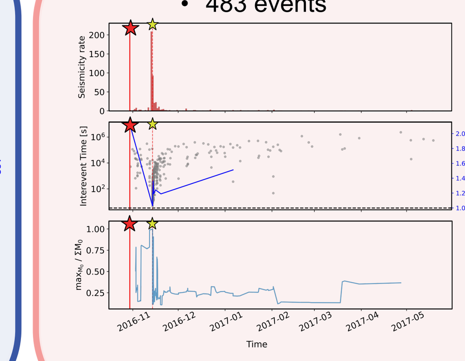
- 665 events



- $COV_{(mean)} = 1.03$

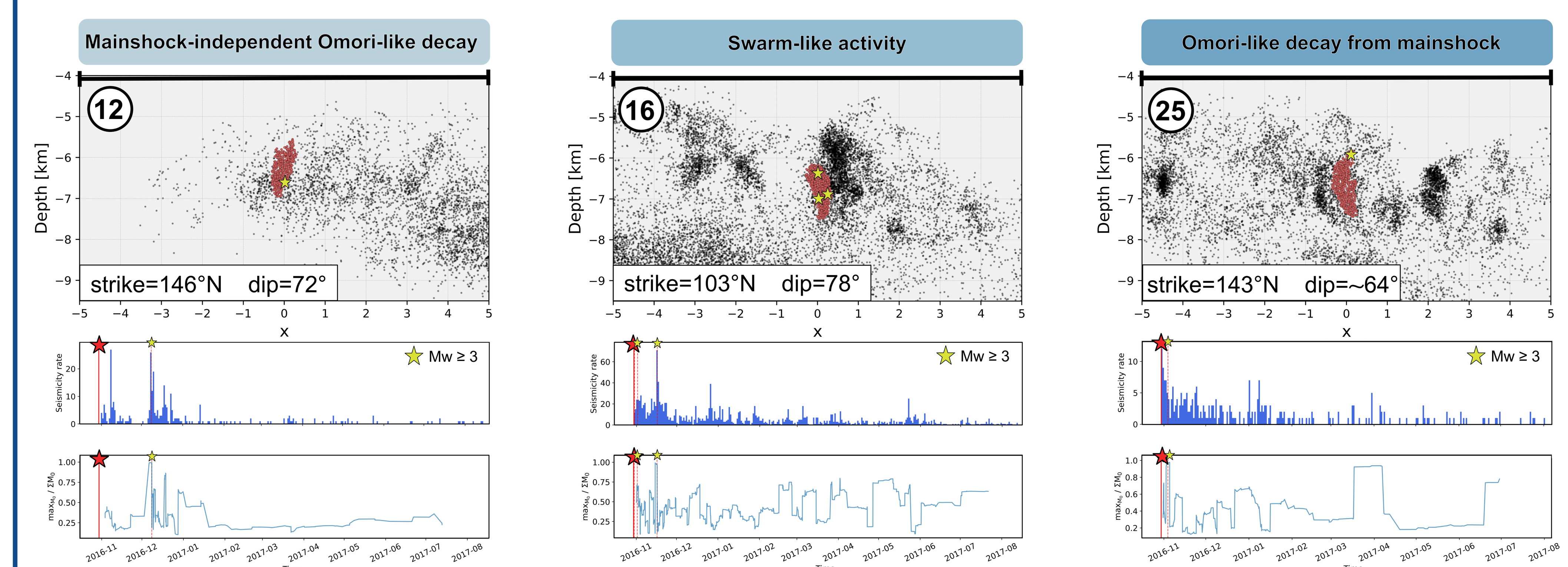
Structure 5

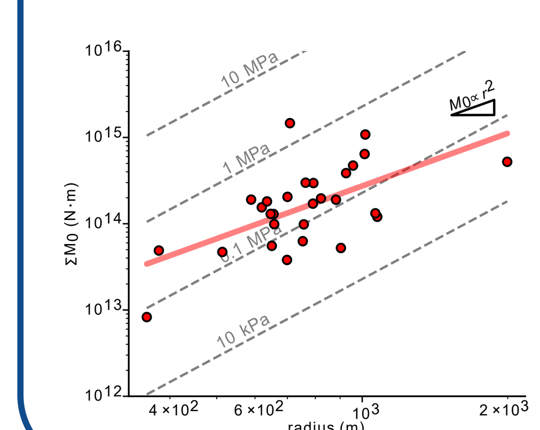
- 483 events



- $COV_{(mean)} = 1.31$

From the analysis of the single structures, we have identified three different time evolutions, suggesting three different behaviors:





Following the analysis of Fischer & Hainzl (2017), a square scaling between the cumulative seismic moment and the cumulative equivalent radius of the sequence suggests the **failure of brittle asperities surrounded by ductile material** which favors aseismic creep and inhibits repeated rupture of strong patches.

★ Mw 6.5
Norcia mainshock

stress and strain rate increase

- microsequences of mainshock-aftershock
- swarm-like activity (high fluid pressure)
- small faults illuminated

To learn more about the behavior of Triassic Evaporites in laboratory experiments, don't miss:

Rheology and fault slip behavior of Triassic Evaporites: an experimental study

Today 01 May, 15:35 – 15:45 Room G2

References

- Collettini, C., Barchi, M. R., De Paola, N., Trippetta, F., & Tinti, E. (2022). Rock and fault rheology explain differences between on fault and distributed seismicity. Nature communications, 13(1), 5627.
- Cabrera, L., Poli, P., & Frank, W. B. (2022). Tracking the spatio-temporal evolution of foreshocks preceding the Mw 6.1 2009 L'Aquila earthquake. Journal of Geophysical Research: Solid Earth, 127(3), e2021JB023888.
- Fischer, T., & Hainzl, S. (2017). Effective stress drop of earthquake clusters. Bulletin of the Seismological Society of America, 107(5), 2247-2257.
- Shelly, D. R. (2024). Examining the connections between earthquake swarms, crustal fluids, and large earthquakes in the context of the 2020–2024 Noto Peninsula, Japan, Earthquake sequence. Geophysical Research Letters, 51(4), e2023GL107897.
- Ōmori, F. (1894). On the after-shocks of earthquakes (Vol. 7). The University.
- Tan, Y. J., Waldhauser, F., Ellsworth, W. L., Zhang, M., Zhu, W., Michele, M., ... & Segou, M. (2021). Machine-learning-based high-resolution earthquake catalog reveals how complex fault structures were activated during the 2016–2017 central Italy sequence. The Seismic Record, 1(1), 11-19.
- Vidale, J. E., & Shearer, P. M. (2006). A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers. Journal of Geophysical Research: Solid Earth, 111(B5).