Faults and earthquakes: a geological approach to seismology

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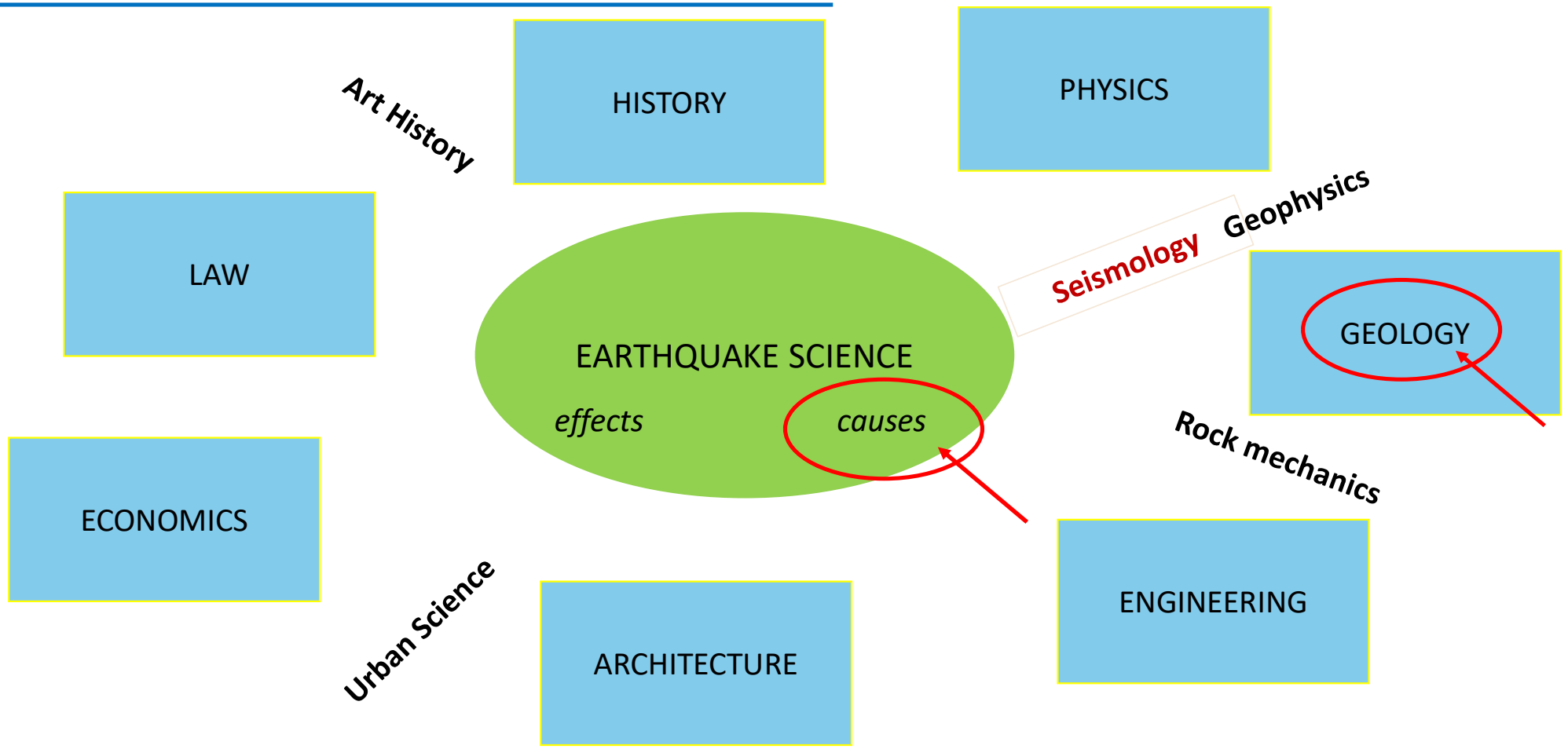
Orvieto, 24/07/2024

The Multidisciplinary Science of Earthquakes



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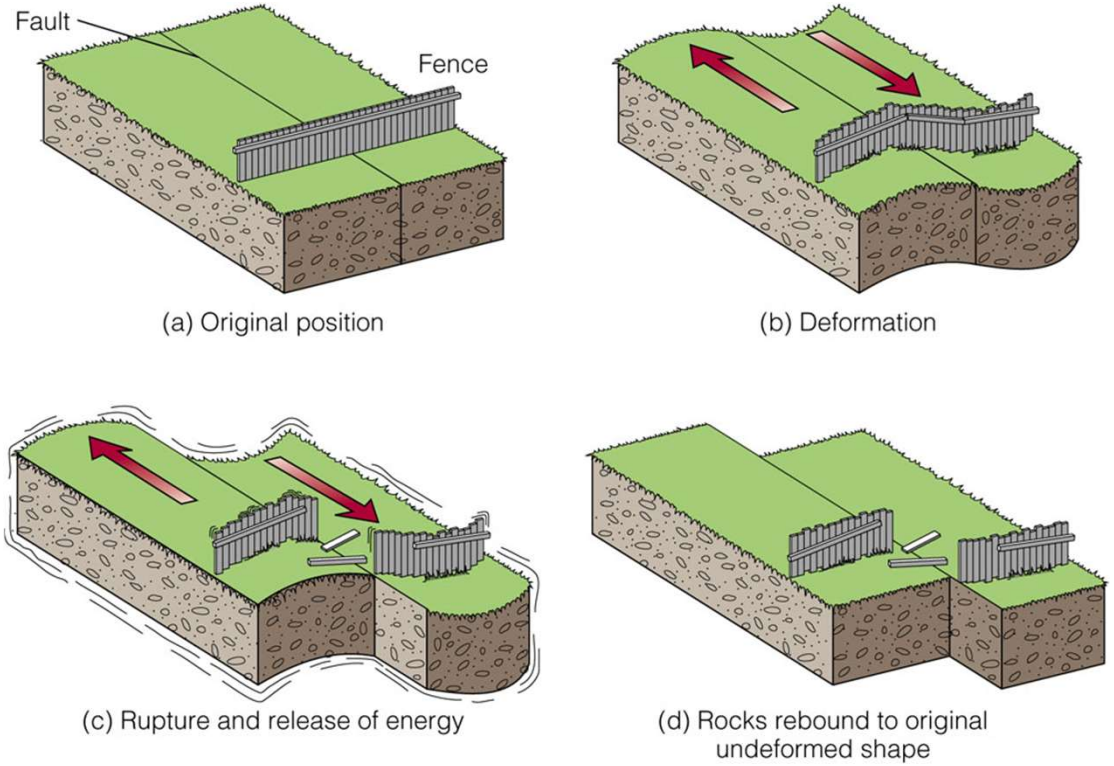
The Elastic Rebound Theory – Reid, 1910

- (Tectonic) Earthquakes are related to the rupture of the Earth crust along a fault surface, when the shear stress becomes larger of the fault strength.

- When the faults ruptures, energy is released in a seismic wave.

Darfield Earthquake, New Zealand, 3 September 2010, M = 7.1



Reid, H.F., The Mechanics of the Earthquake, The California Earthquake of April 18, 1906, Report of the State Investigation Commission, Vol.2, Carnegie Institution of Washington, Washington, D.C. 1910

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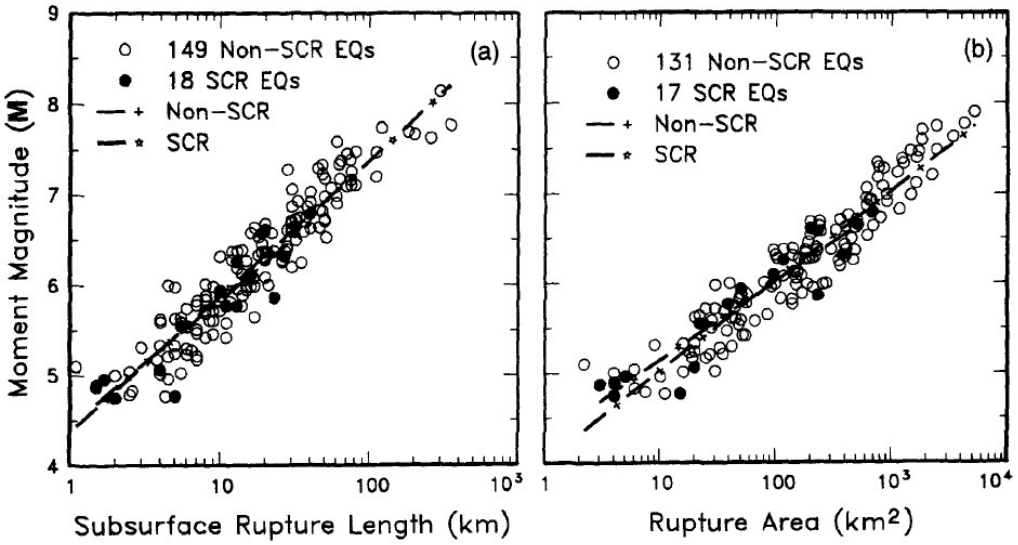
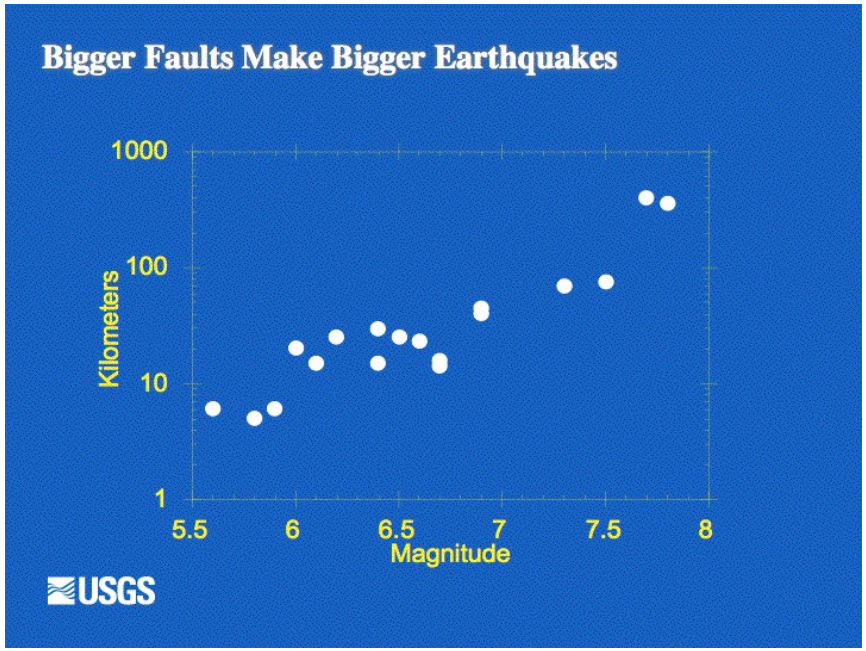
Size of Ruptured Fault vs. Earthquake Magnitude - Wells & Coppersmith, 1994





The magnitude of the earthquake depends on the size of the ruptured fault: larger/longer ruptured faults produce stronger earthquakes.

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Seismo-tectonics (Faults and Earthquakes)

- **Seismotectonics is the study of the relationship between the earthquakes, active tectonics and individual faults of a region.**
- It seeks to understand which faults are responsible for seismic activity in an area by analysing a combination of regional tectonics, recent instrumentally recorded events, accounts of historical earthquakes and geomorphological evidence.
- This information can then be used to quantify the **seismic hazard** of an area.

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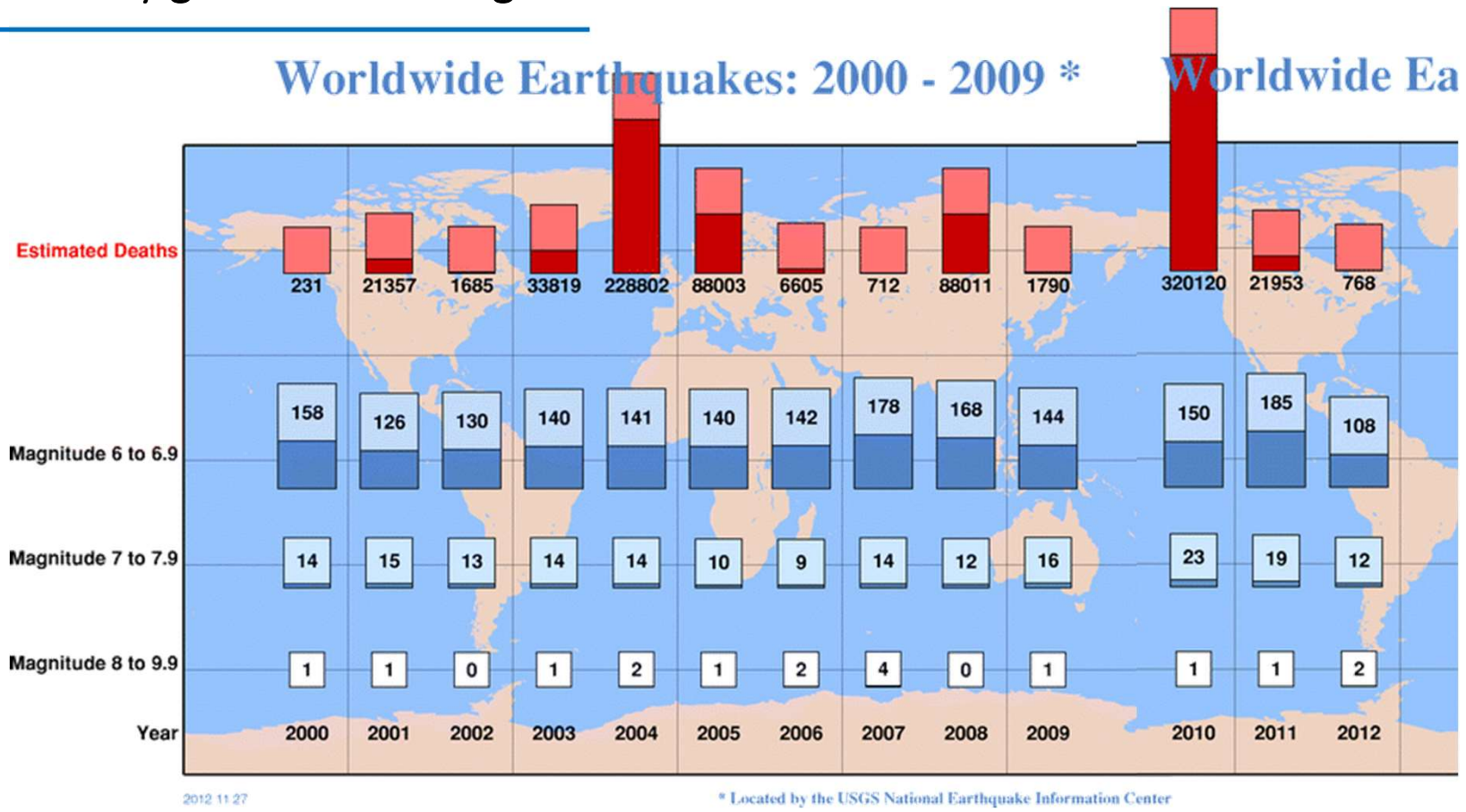
Earthquakes are continuously generated through time

- At global scale, a similar number of earthquakes occur every year.
- Most of these earthquakes are of natural origin
- Most natural earthquakes are related to tectonics
- Every year INGV registers about 16,000 in Italy, including over 2,000 earthquakes with M>2.0



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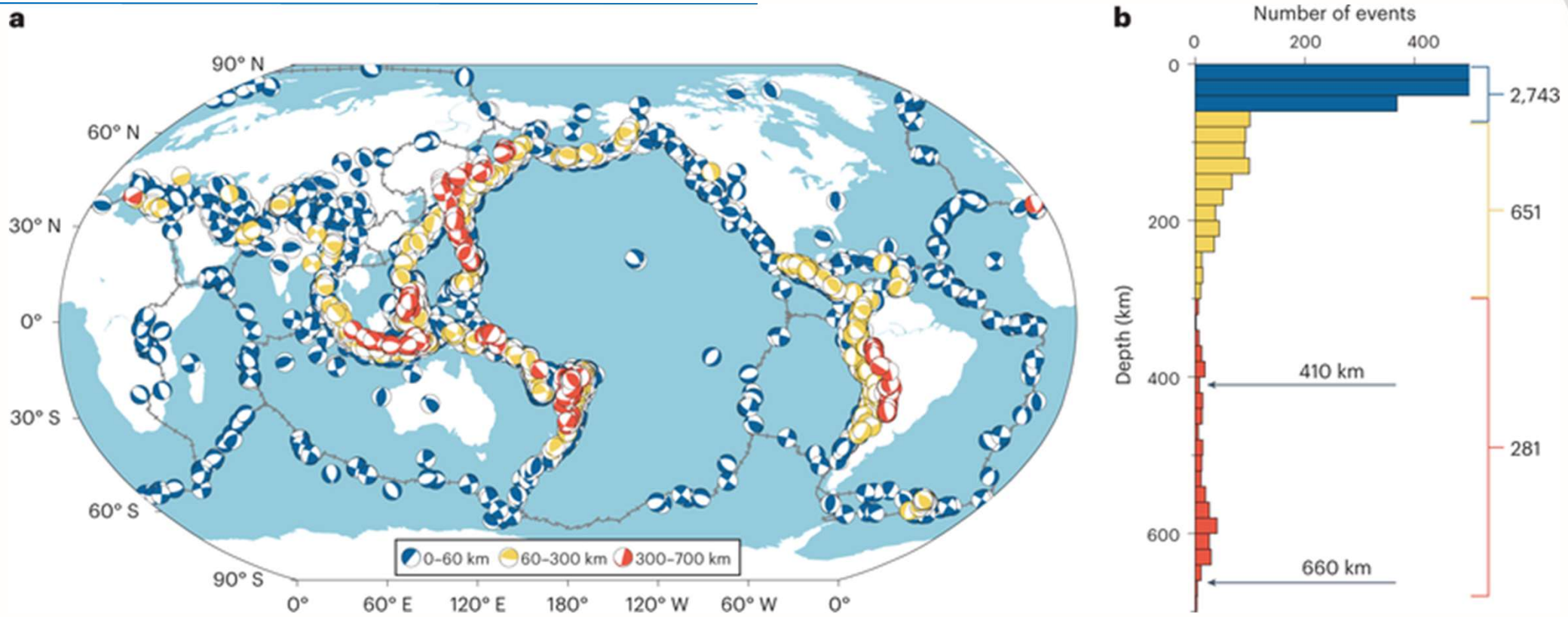
Global and depth distribution of earthquakes



Global and depth distributions of 3,675 moment magnitude (Mw) > 5.5 shallow, intermediate-depth and deep-focus earthquakes a, Geographic distribution of shallow, intermediate-depth and deep-focus earthquakes colour coded by depth categories. b, Depth distribution of earthquakes in 20-km bins. The total number of events in each depth category is marked on the right. Shallow earthquakes are clipped due to the plotting range.

Cui, Xin & Li, Zefeng & Hu, Yan. (2023). Nature Geoscience. 16. 1-7. 10.1038/s41561-023-01176-5.

Summary of the first part

- (Tectonic) Earthquakes occur when a fault is ruptured
- Bigger earthquakes are generated by larger ruptured faults
- Earthquakes are continuous through time (millions of earthquakes occur every years)
- Earthquakes are discontinuous through space (most tectonic earthquakes occur at plate boundaries).

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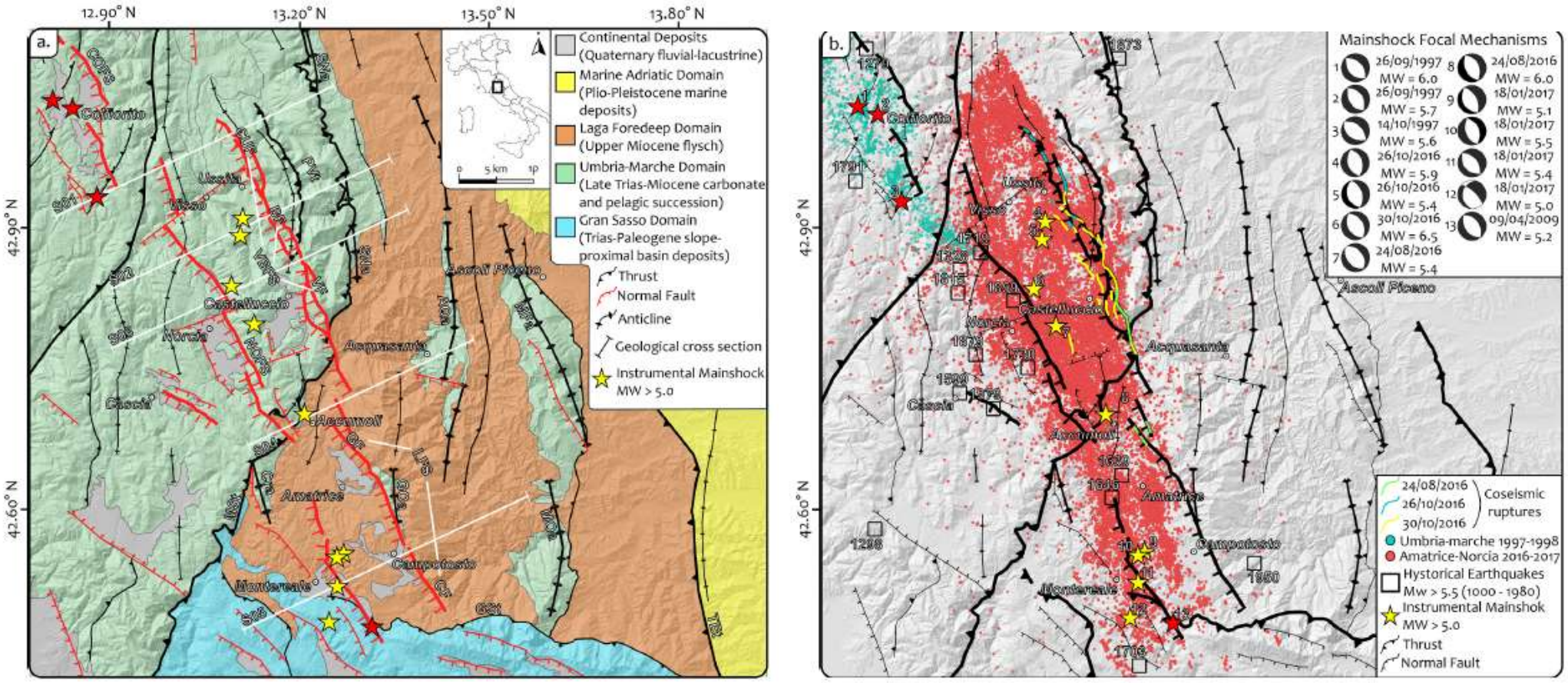
The 2016-2017 Central Italy seismic sequence



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Normal faults and crustal extension

- The fault rupture initiate at depth (hypocenter) and then propagates laterally and along the fault-dip, eventually reaching (rupturing) the Earth surface.

- Central Italy earthquake are related to «normal faults», effect of crustal extension: the hangingwall block is lowered.

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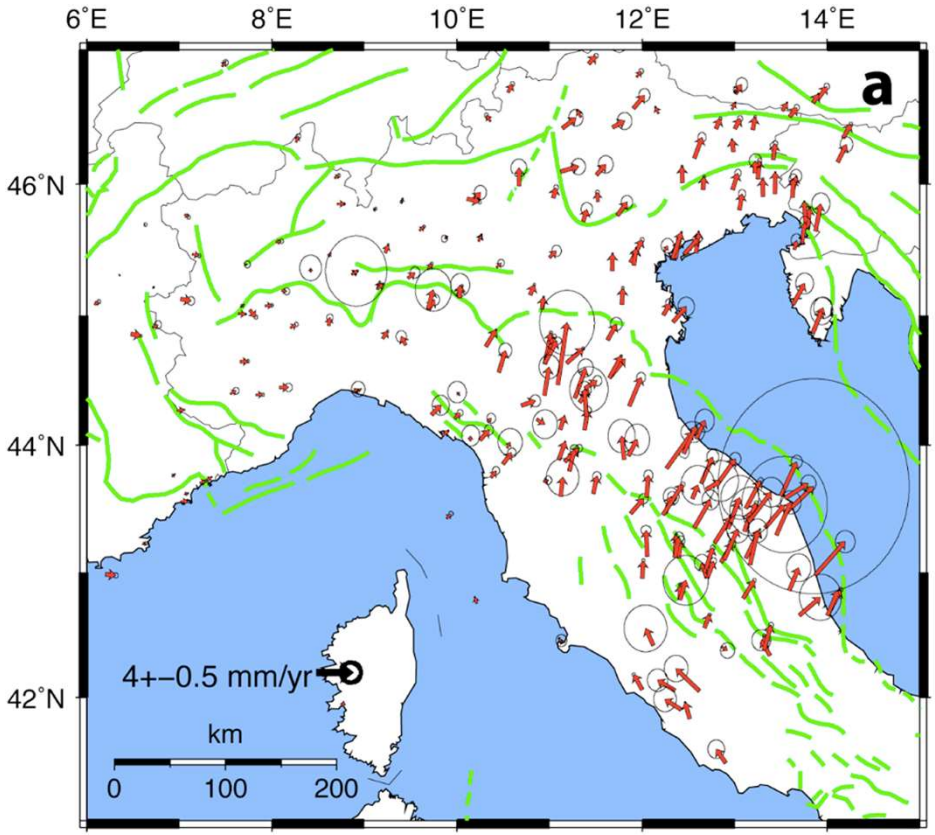
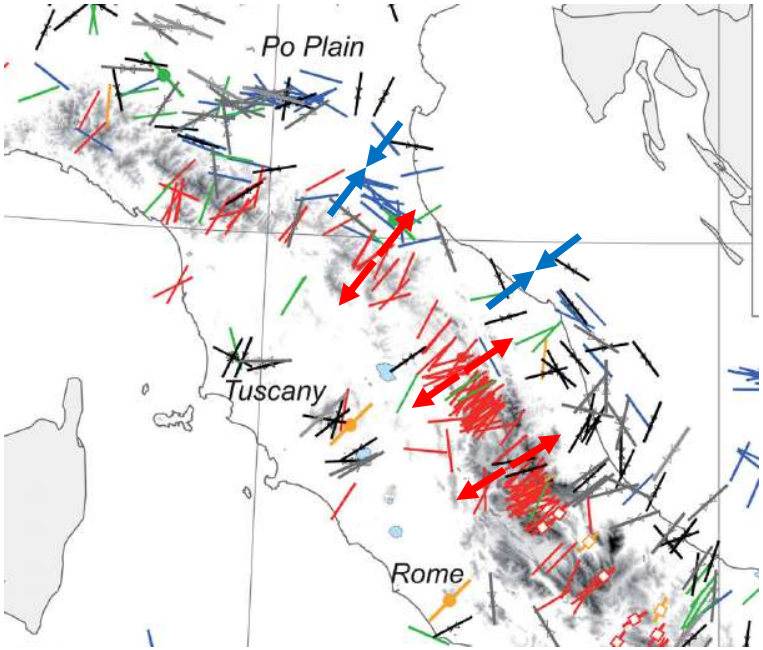
Regional-scale deformation and stress field



Bennett et al., 2012 - JGR



Montone e Mariucci, 2016 – GJI

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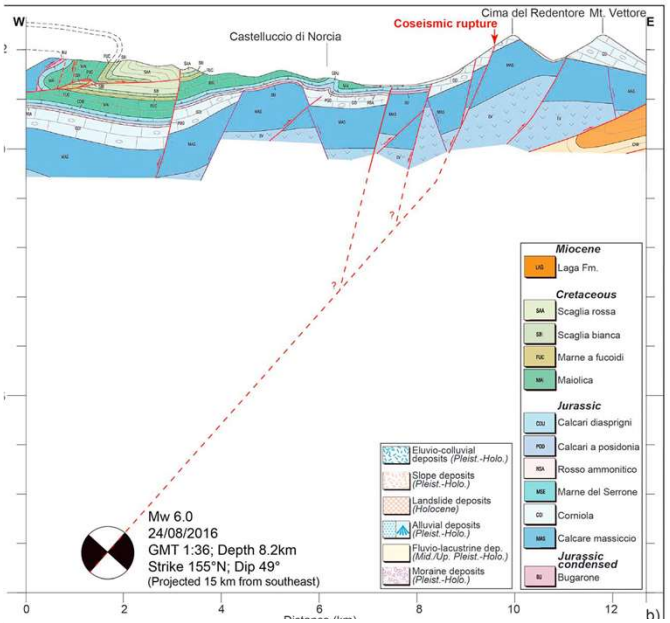
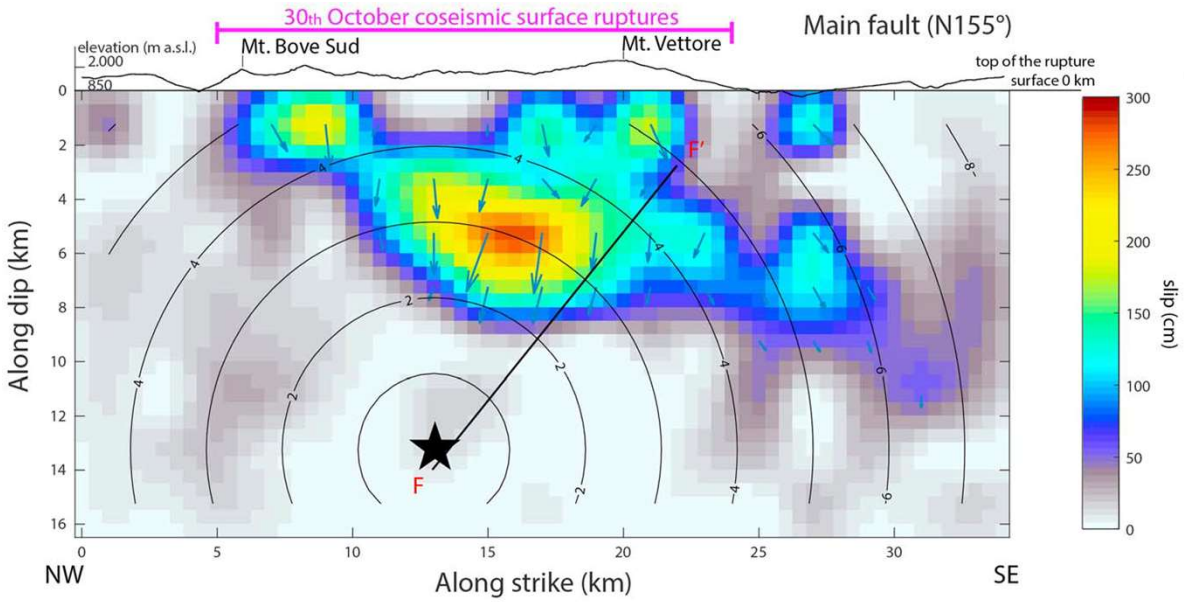
Faults and Earthquakes: Problems of depth and lifespan

- Faults are observed at the surface, but earthquake ruptures occur at seismogenic depth (frequently in the upper crust, down to 10-15 km of depth)

- **Earthquakes are almost instantaneous events of the much longer tectonic history of a fault.**



Pucci et al., 2017 - GRL



Scognamiglio et al., 2018 – JGR Solid Earth

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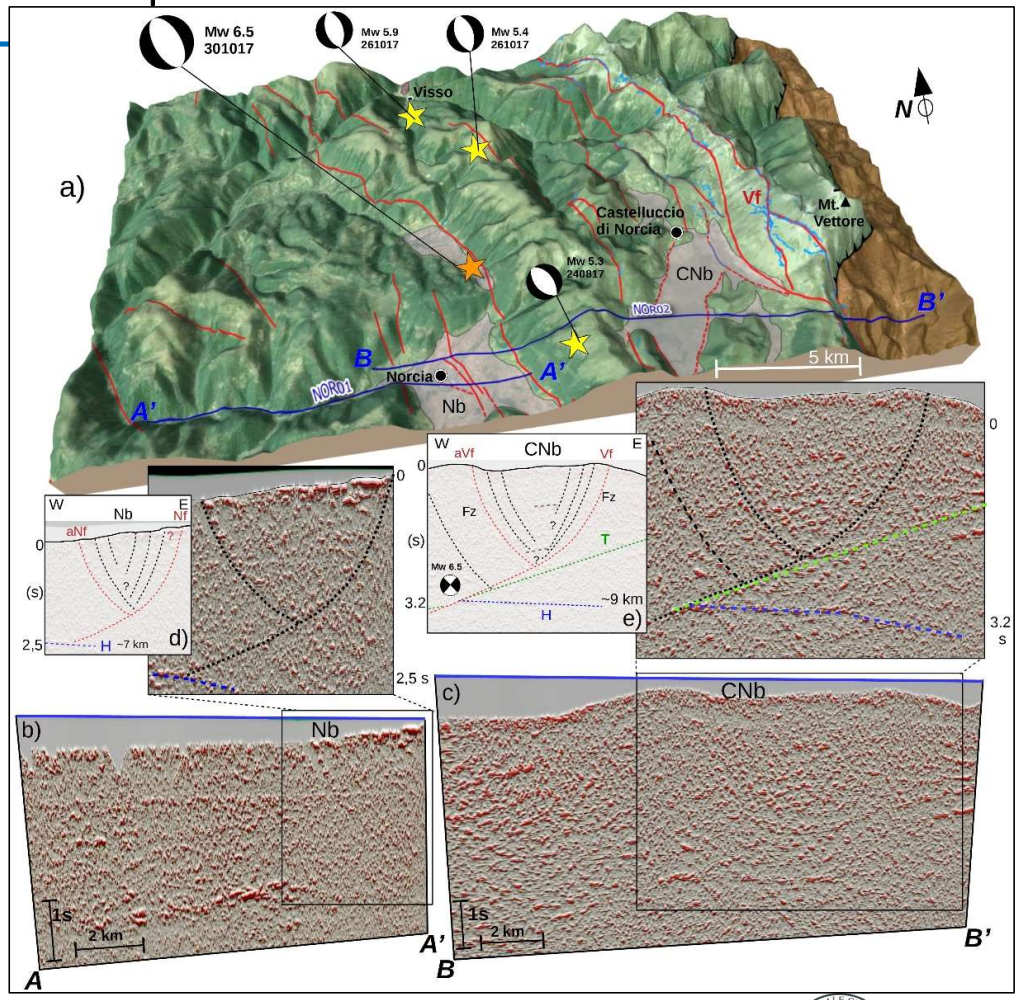
Linking surface ruptures to seismogenic source at depth

- **Seismic reflection profiles** are the most powerful tool for tracing faults geometry from the surface down to the seismogenic depth.
- The ex-novo acquisition of deep reflection data for scientific research, is often hampered by environmental problems, complex logistics, and high costs, all seriously limiting the widespread use of this technique.



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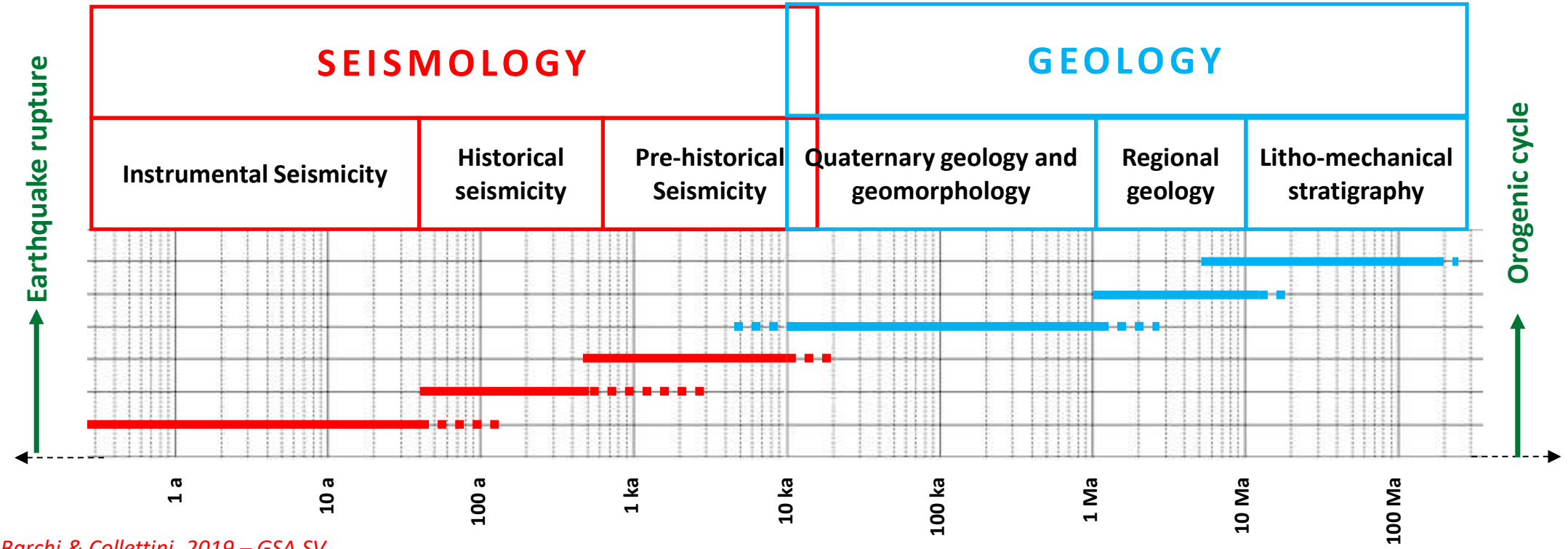
Earthquakes and Geological History (TIME MATTERS !)

- **Each earthquake can be viewed as an episode of a much longer tectonic history.**
- Each chapter of this long history is studied by using appropriate methods, offering a contribute to the overall picture.



Barchi & Collettini, 2019 – GSA SV

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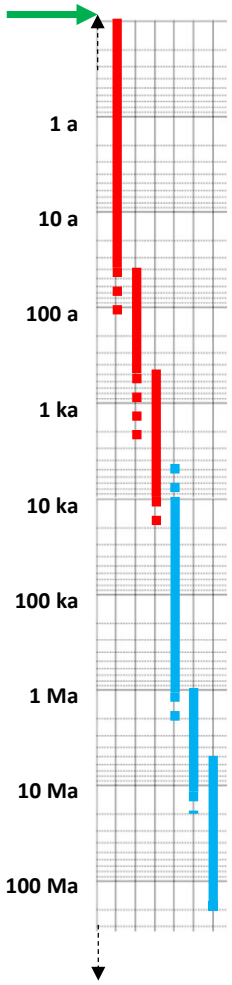
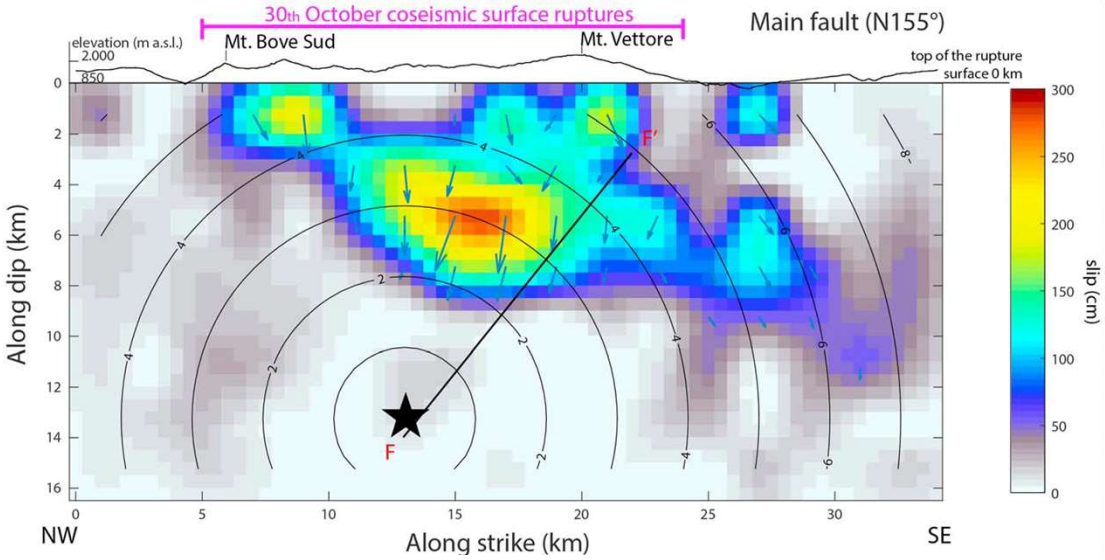
The seismic rupture (few seconds) – rupture of a single fault





Scognamiglio et al., 2018 – JGR Solid Earth

Rupture model of the 30th October 2016 (M 6.5) Norcia earthquake, and associated surface fault

- Seismic rupture is an almost instantaneous process
- This “instantaneous” rupture is described by geodetical, seismological and geological data and observations.

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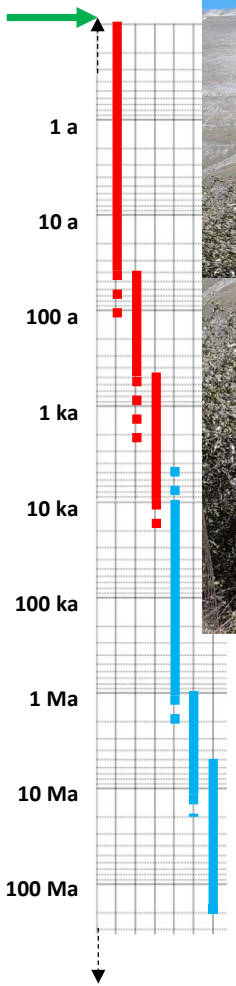
Co-seismic deformation: co-seismic rupture



- In few seconds, the seismic rupture propagates from the hypocenter up to the surface

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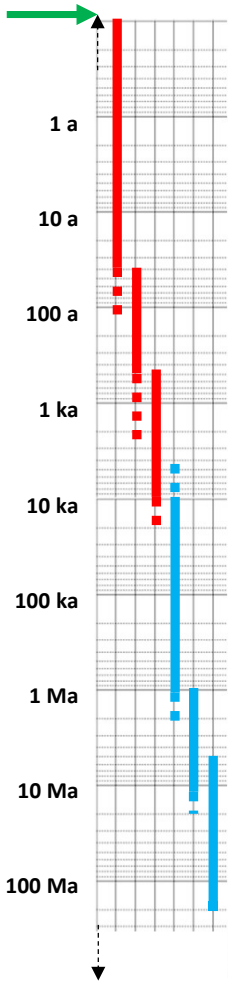
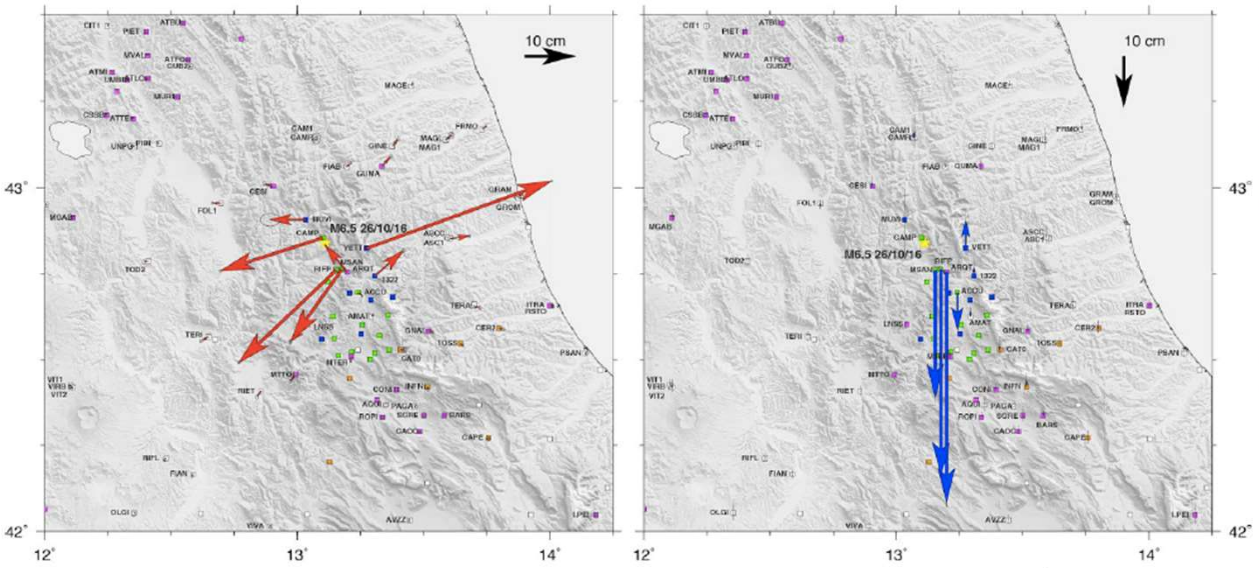
Co-seismic deformation: geodetic data



GNSS survey



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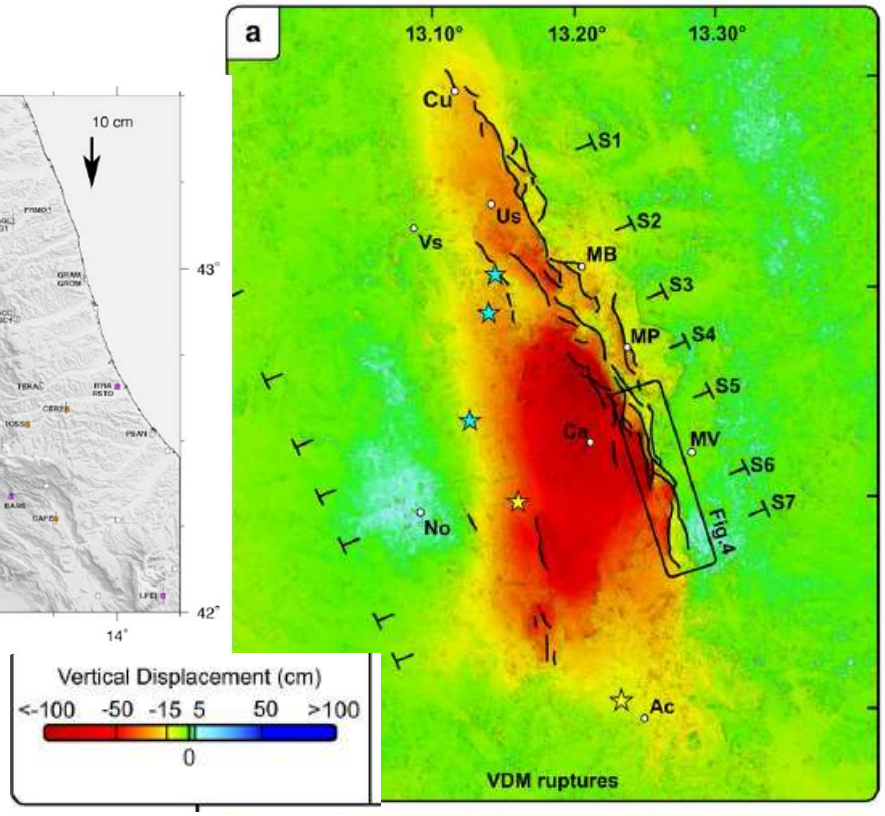
- The instantaneous rupture is described by geodetical, seismological and geological data and observations.

InSAR survey



Carboni et al., 2022 – Scientific Report

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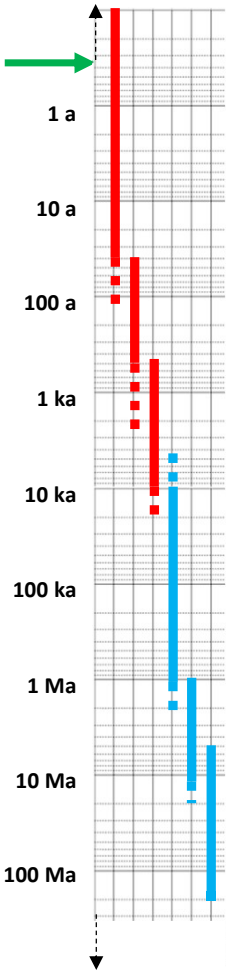
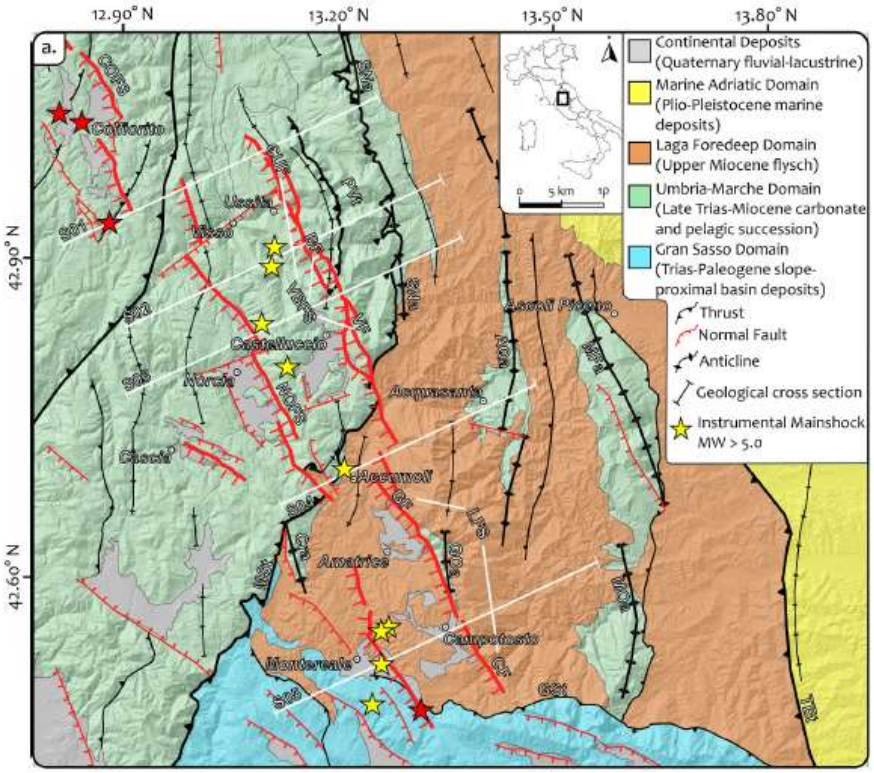
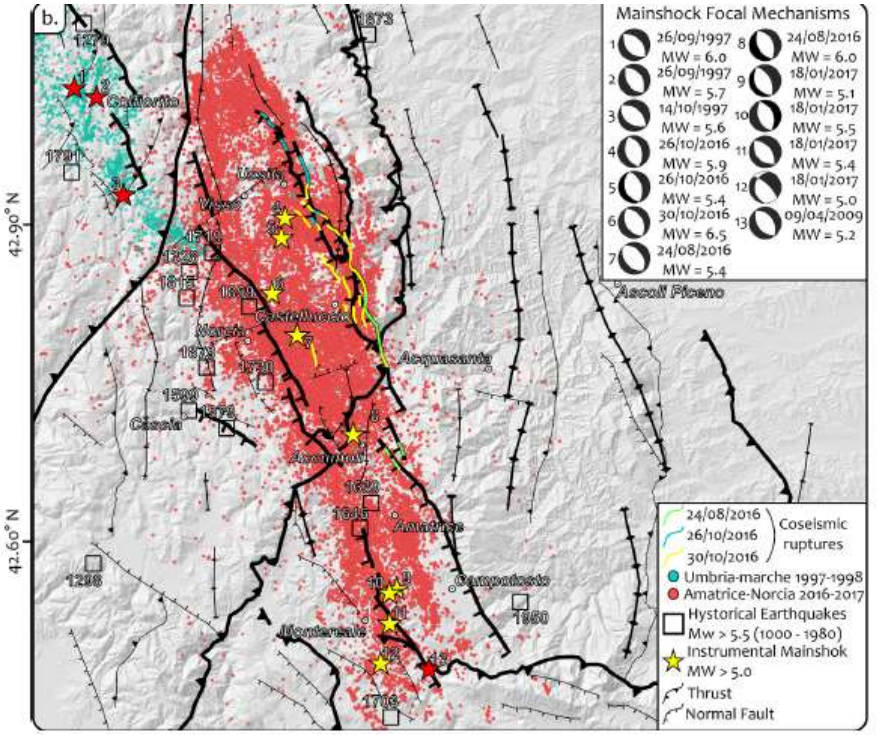
The seismic sequence (few months) – rupture of a segmented fault system







- **The complexity of the seismic sequences reflects the segmented nature of the fault systems.**
- A seismic sequence consists of one or more mainshocks, preceded and followed by a multitude of minor events
- A fault system consists of a set of fault segments.

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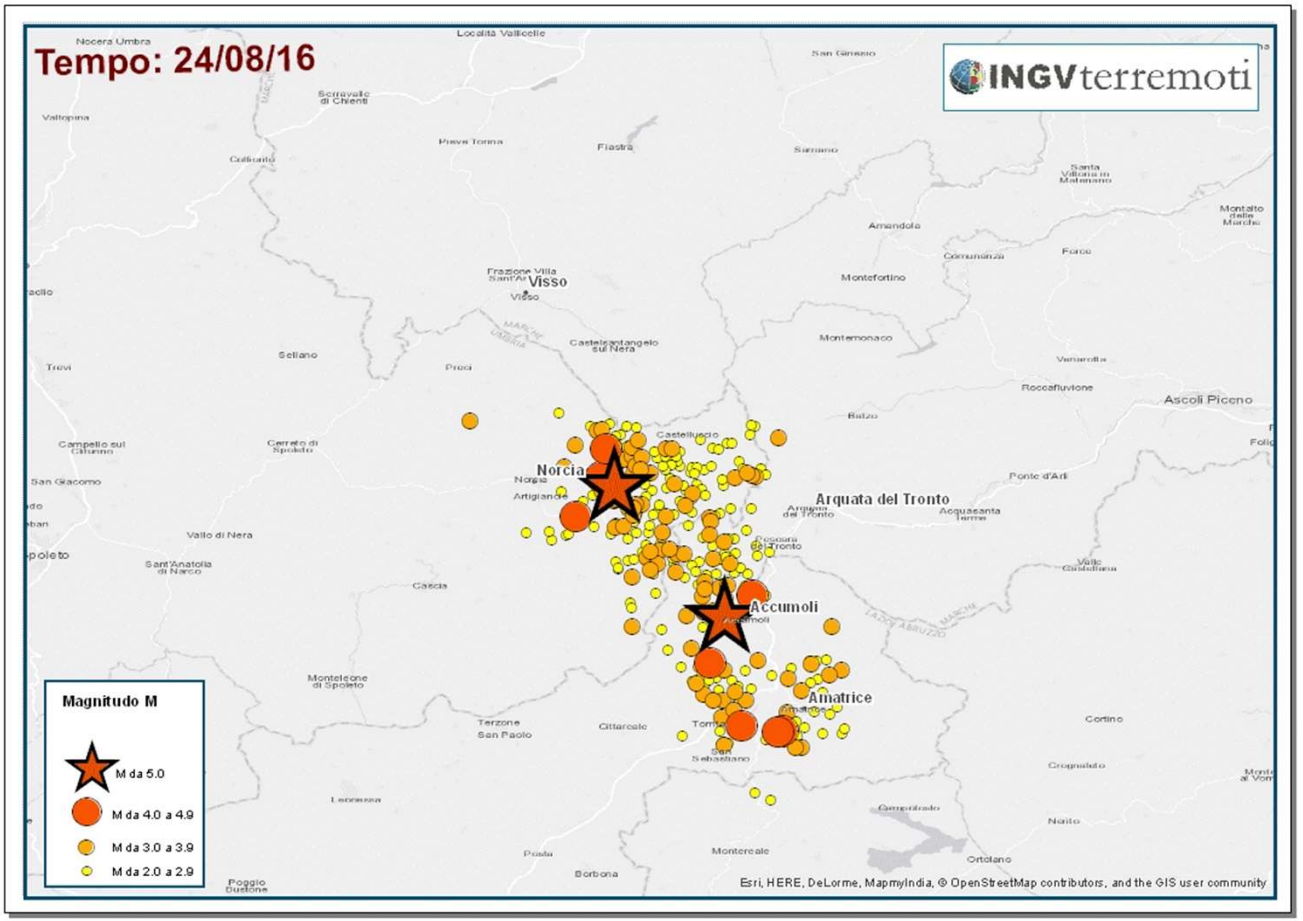
Rupture propagation (24 August- 31 October 2016)



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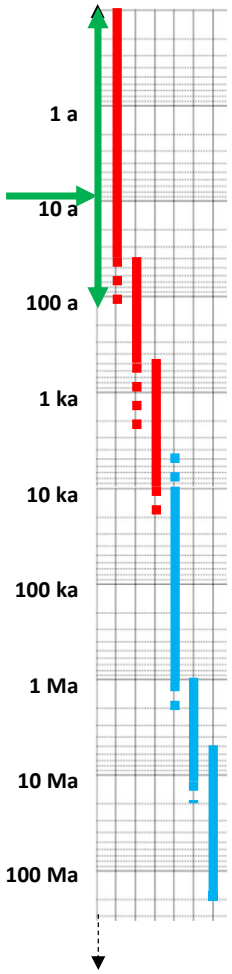
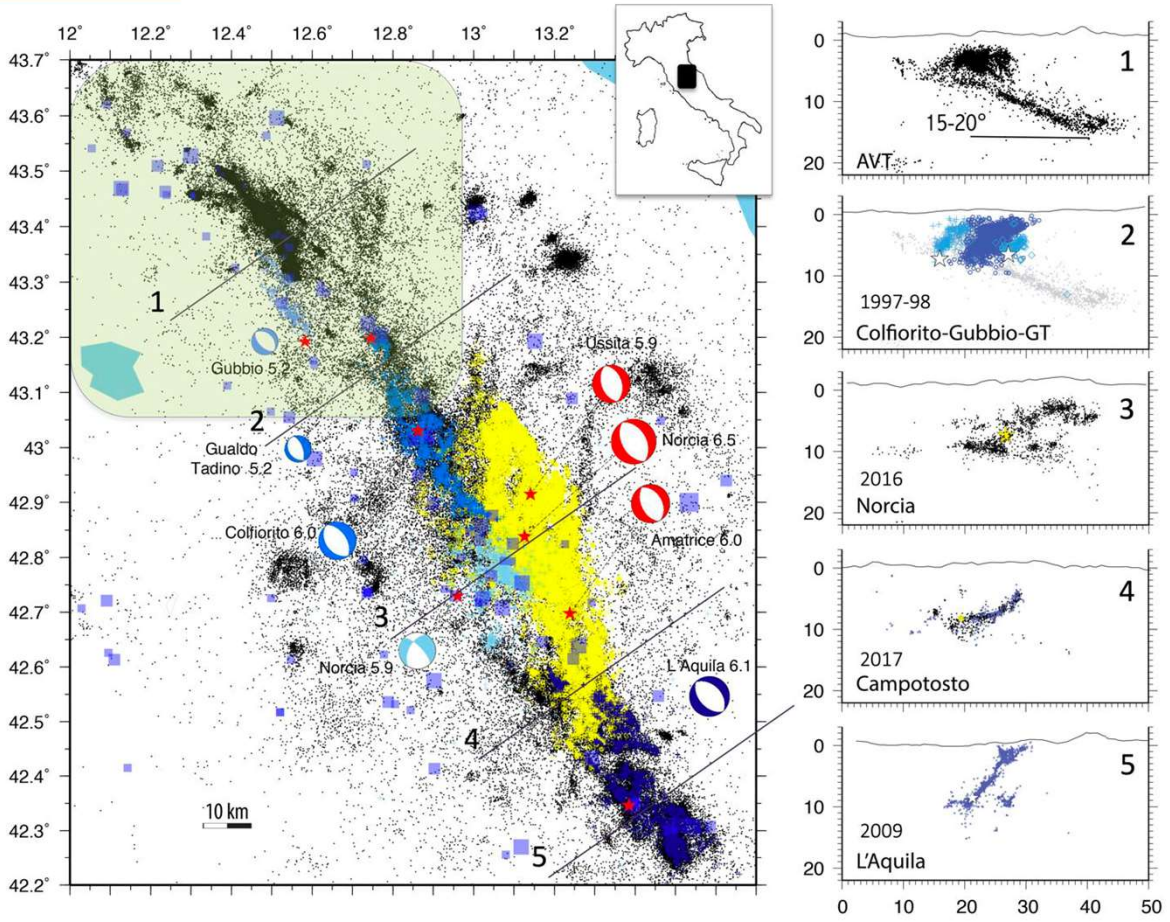
40 years of Seismic sequences in Central Italy (1979-2017)



During the last 40 years 5 major seismic sequences ruptured a 120 km long extensional belt of Central Italy

- Norcia (1979) – M = 5.9
- Gubbio (1984) – M = 5.2
- Colfiorito-Gualdo Tadino (1997-98) – M = 6.0
- L'Aquila (2009) – M = 6.1)
- Amatrice-Visso- Norcia (2016) – M = 6.5



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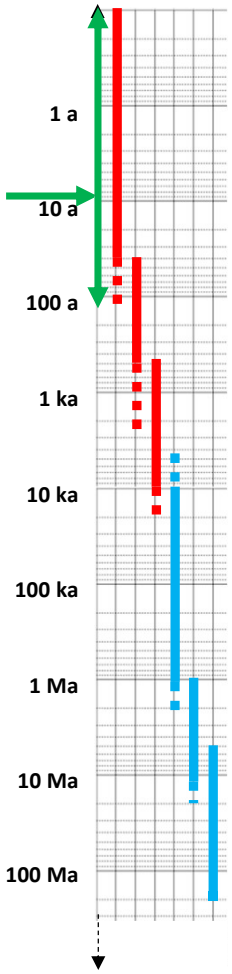
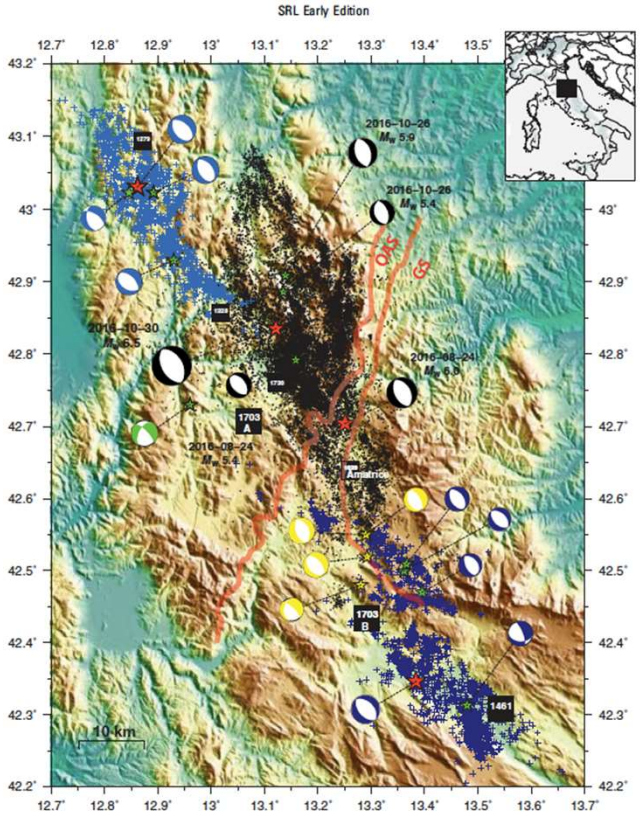
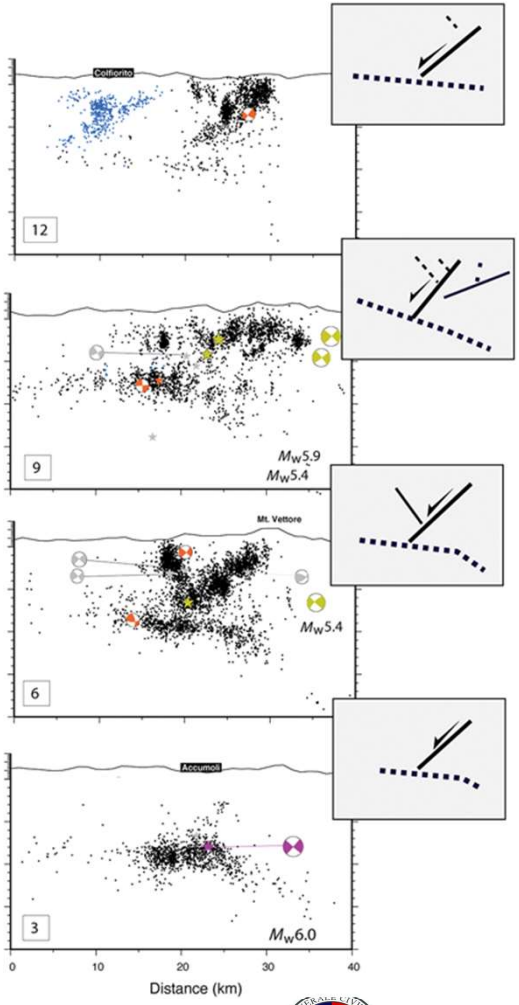
Instrumental seismicity and geodetic data – back to ca. 100 years (but detailed images only for the last 20-40 years)



- Focal mechanisms and accurate location of earthquakes and seismic sequences, along with geodetic data, provide detailed images of activated fault systems for the last 20 years.
- Data become progressively poorer and sparser, back to a maximum age of about 110 years.



Chiaraluce et al., 2017 – S.R.L.



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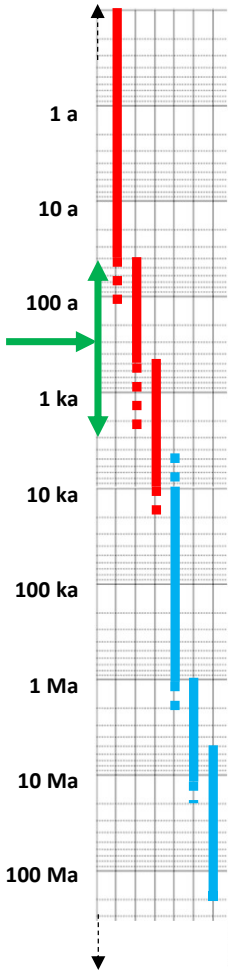
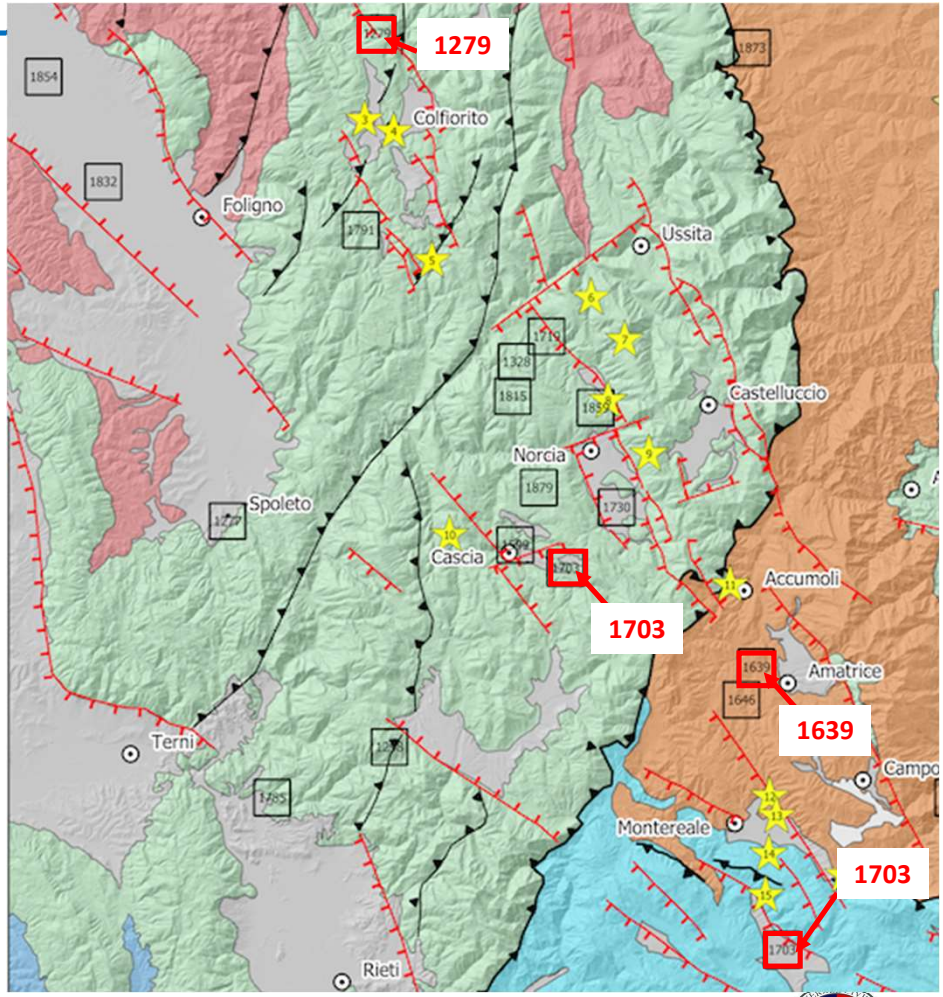
Historical seismicity – back to ca. 2000 years (but better for the last 500-1000 years)



- Documented damage in historical buildings provides news about some relevant earthquakes in the past.
- In Italy a pretty complete record is available for the last 500 years, sparse news back to about 2-3 ka.



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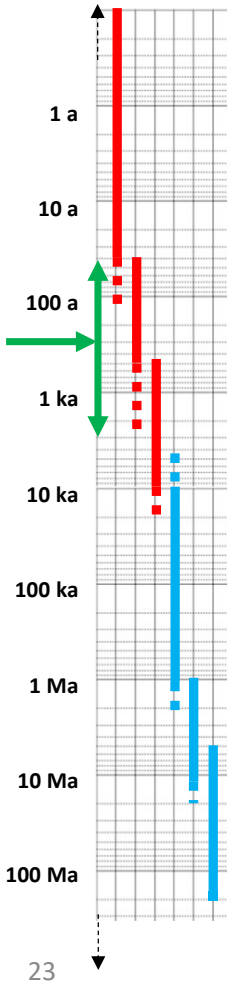

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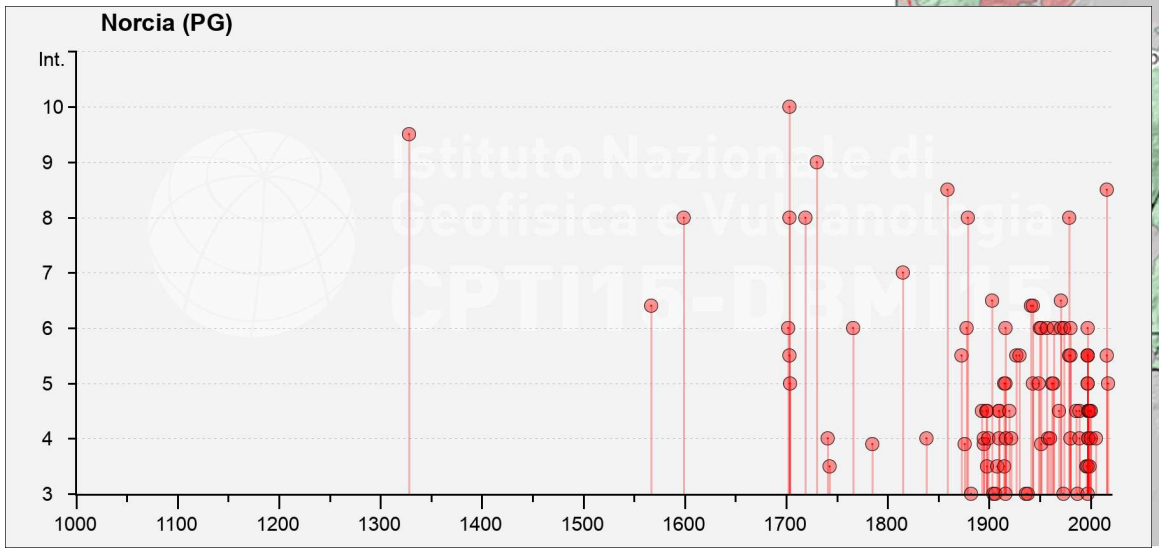
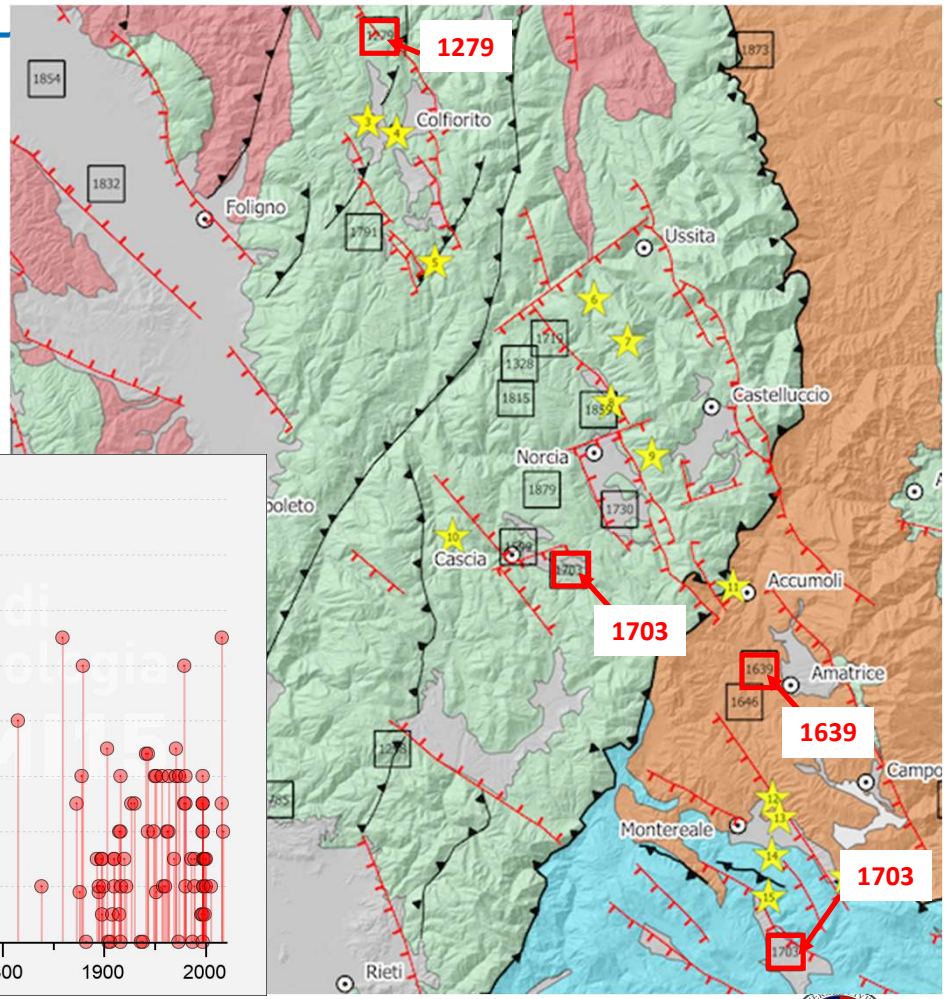


DMBI15, INGV



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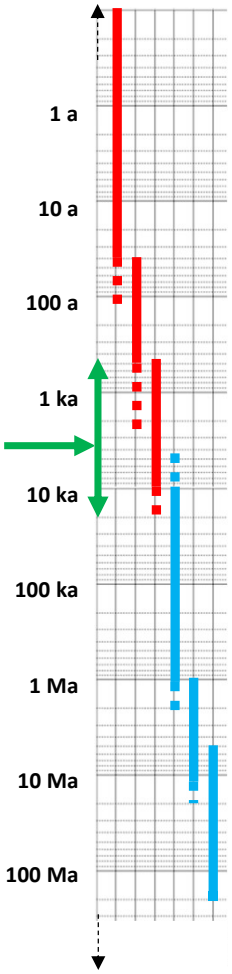
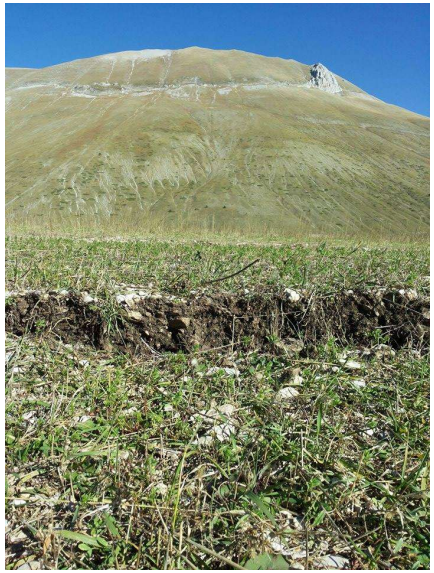
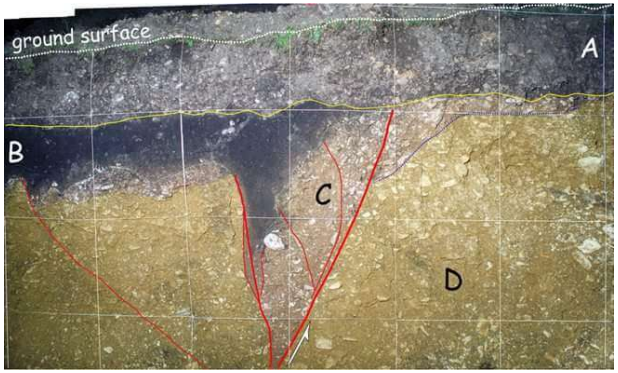
Pre-historical seismicity (paleo-seismology) – back to ca. 20 ky



- **Paleoseismological trenches across active fault scarps affecting datable sediments and soils.**
- Study of cosmogenic nuclides along bedrock fault scarps

A paleo-seismological trench across the M.Vettore "silent" fault revealed three pre-historic/proto-historic events in the last 10-20 ka.





Galadini & Galli, 2003 – Annals of Geophysics; Galli et al. 2017 - Tectonics

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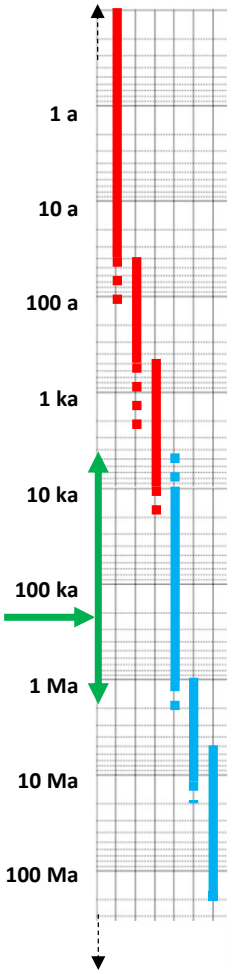
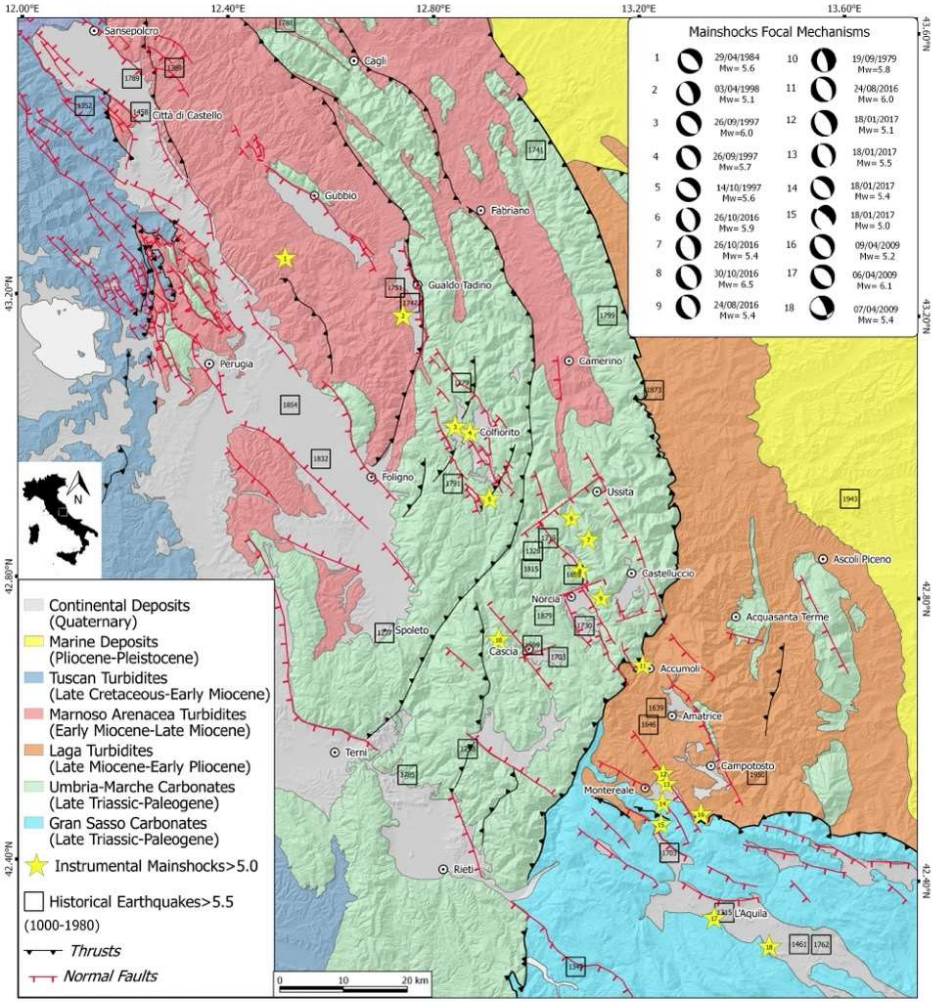
Quaternary Geology and Geomorphology – back to ca. 2 Ma)



The belt of seismically active faults responsible for the present-day extensional seismicity of central Italy is linked with the system of Quaternary normal faults in the axial zone of the Apennines, where the faults border extensional continental basins.

The alignment of these basins strictly coincides with the distribution of instrumental and historical seismicity.



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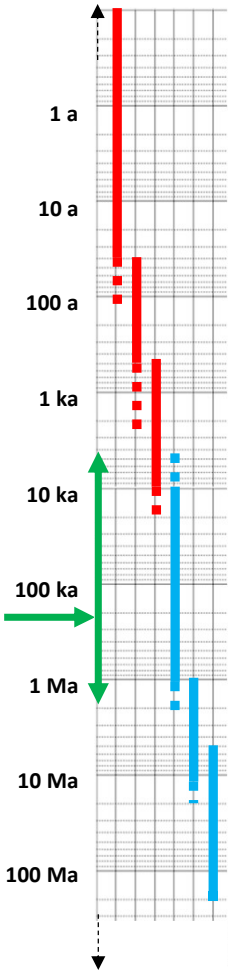
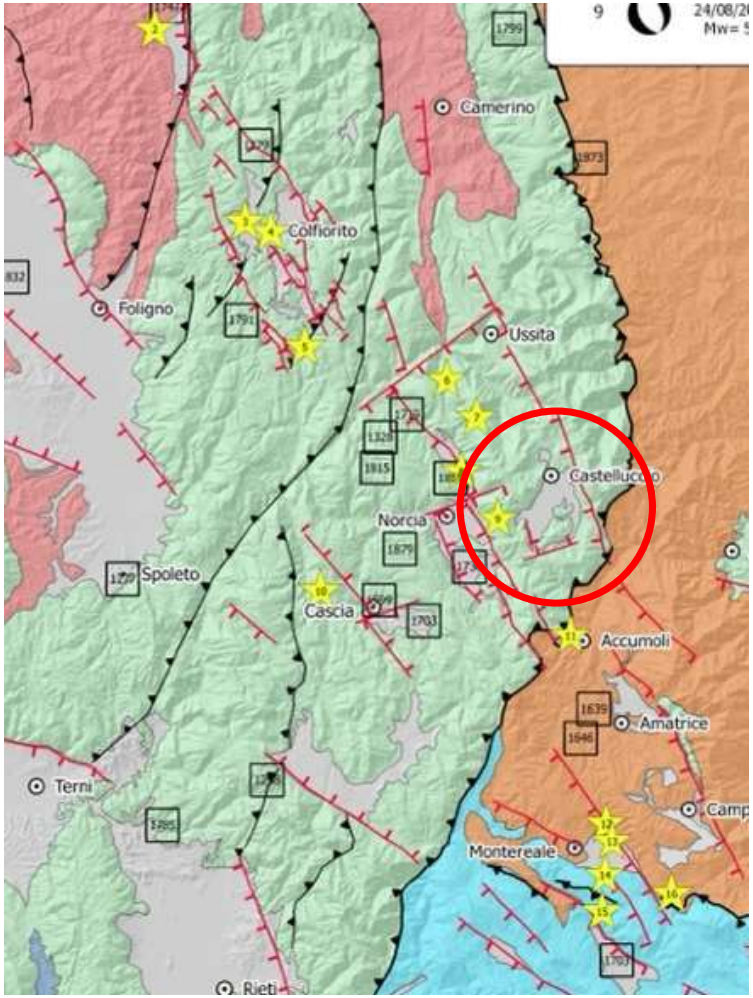
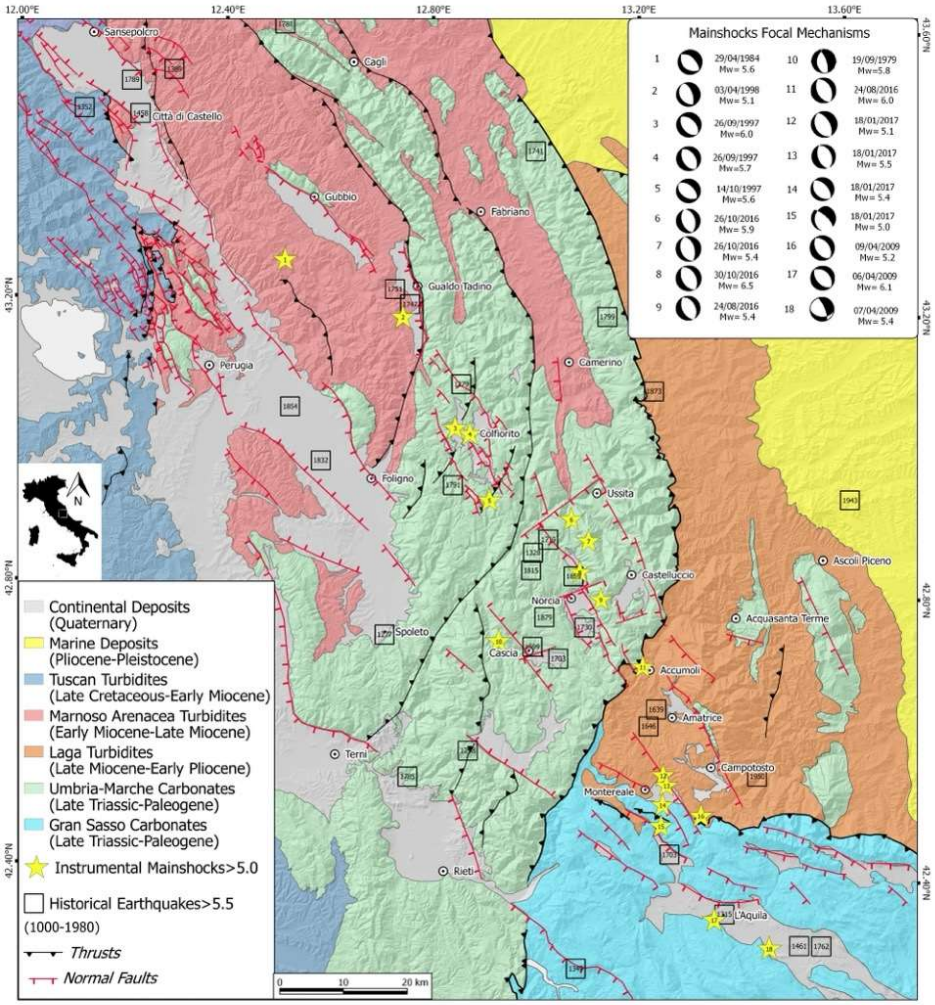
Quaternary Geology and Geomorphology – back to ca. 2 Ma)







Faults and earthquakes: a geological approach to seismology
Altascuola, Orvieto, 24 luglio 2024

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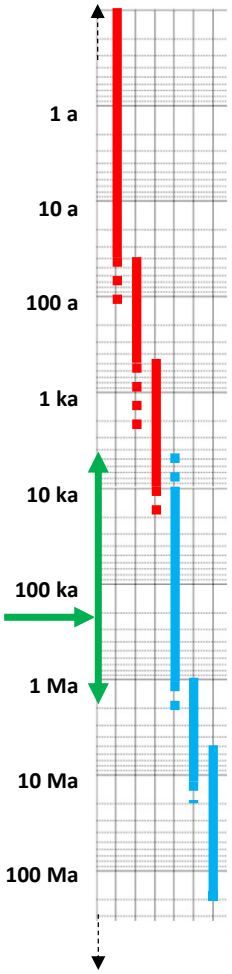
Quaternary Geology and Geomorphology – back to ca. 2 Ma)

- Study of displaced/deformed Quaternary landforms (e.g. paleo-surfaces, terraces); study of faults and associated basins, formed in the past under the same stress field which generates the present-day seismicity.



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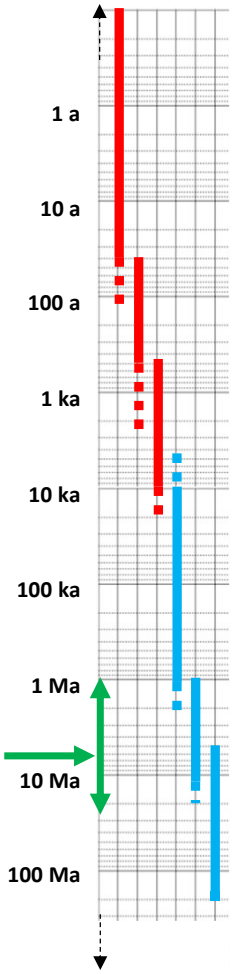
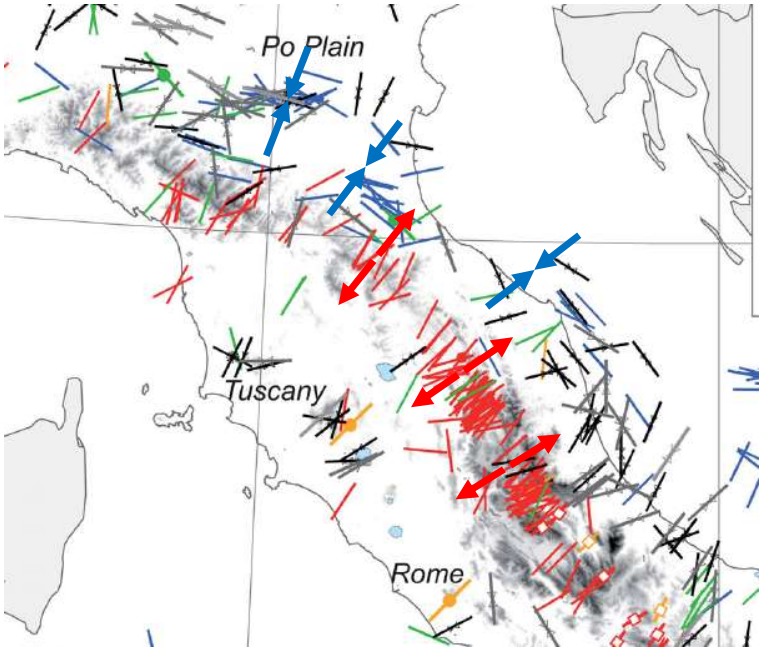
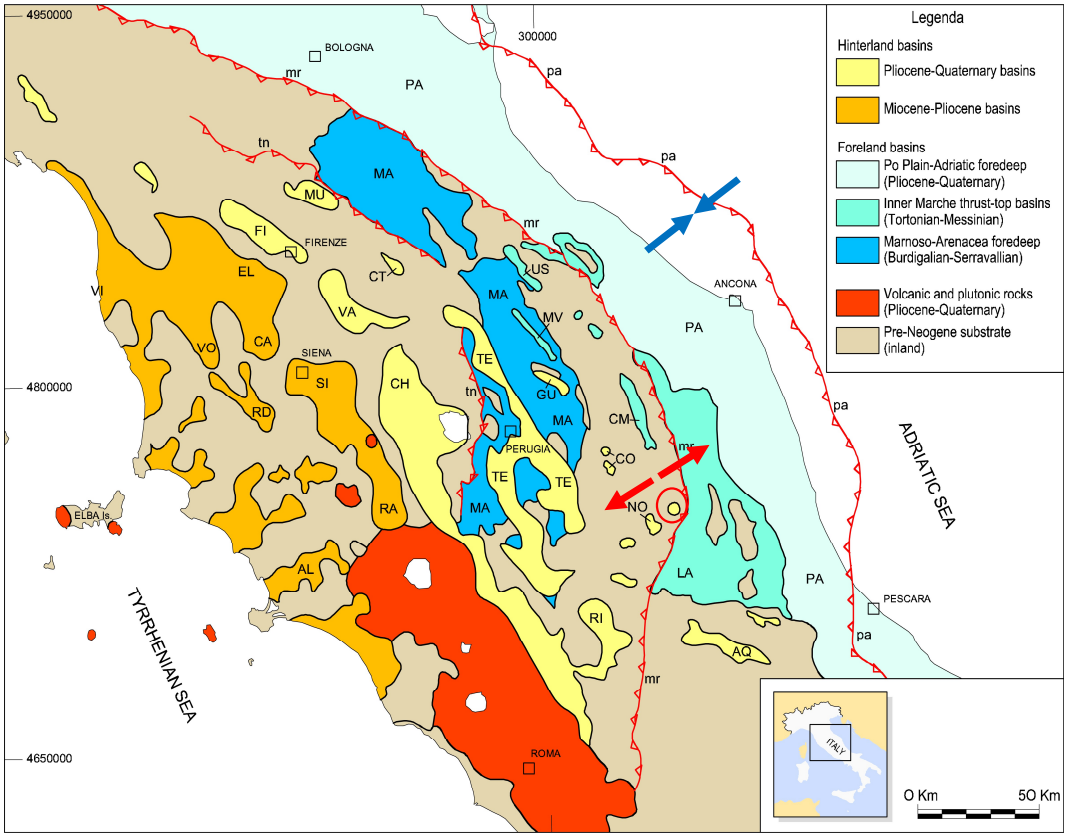
Regional-scale Tectonic evolution – back to ca. 20 Ma





Montone e Mariucci, 2016 – GJI

The distribution of Neogene sedimentary basins of the Northern Apennines reflects the migration of coupled compressional and extensional stress field in the last 15-20 Ma.



Barchi, 2010 – JVE

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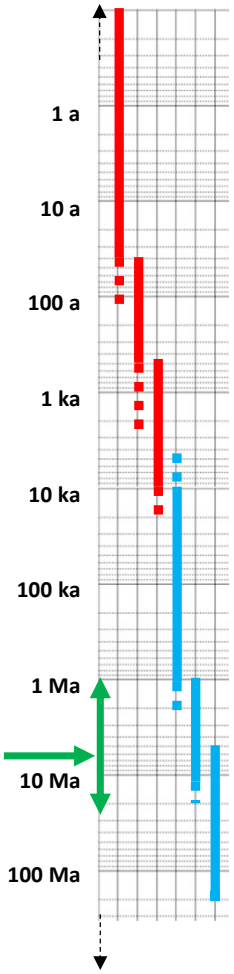
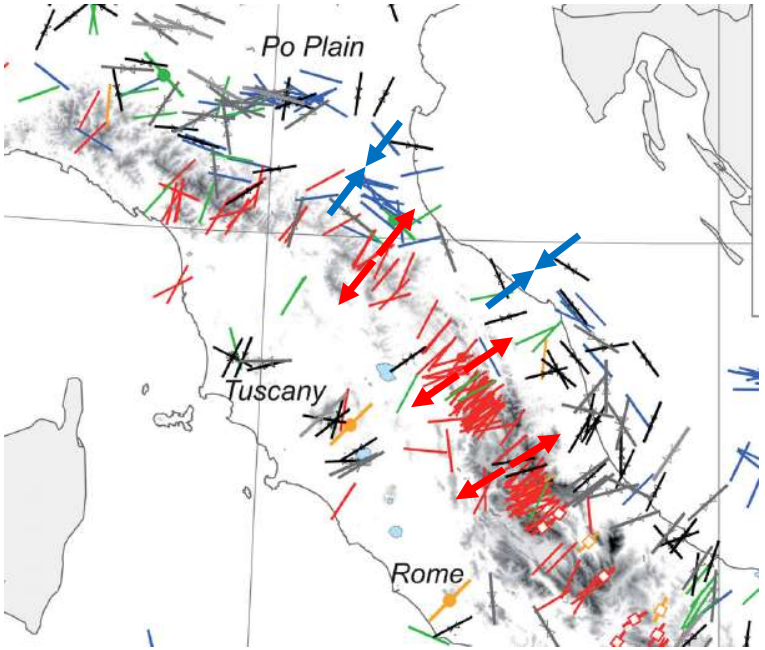
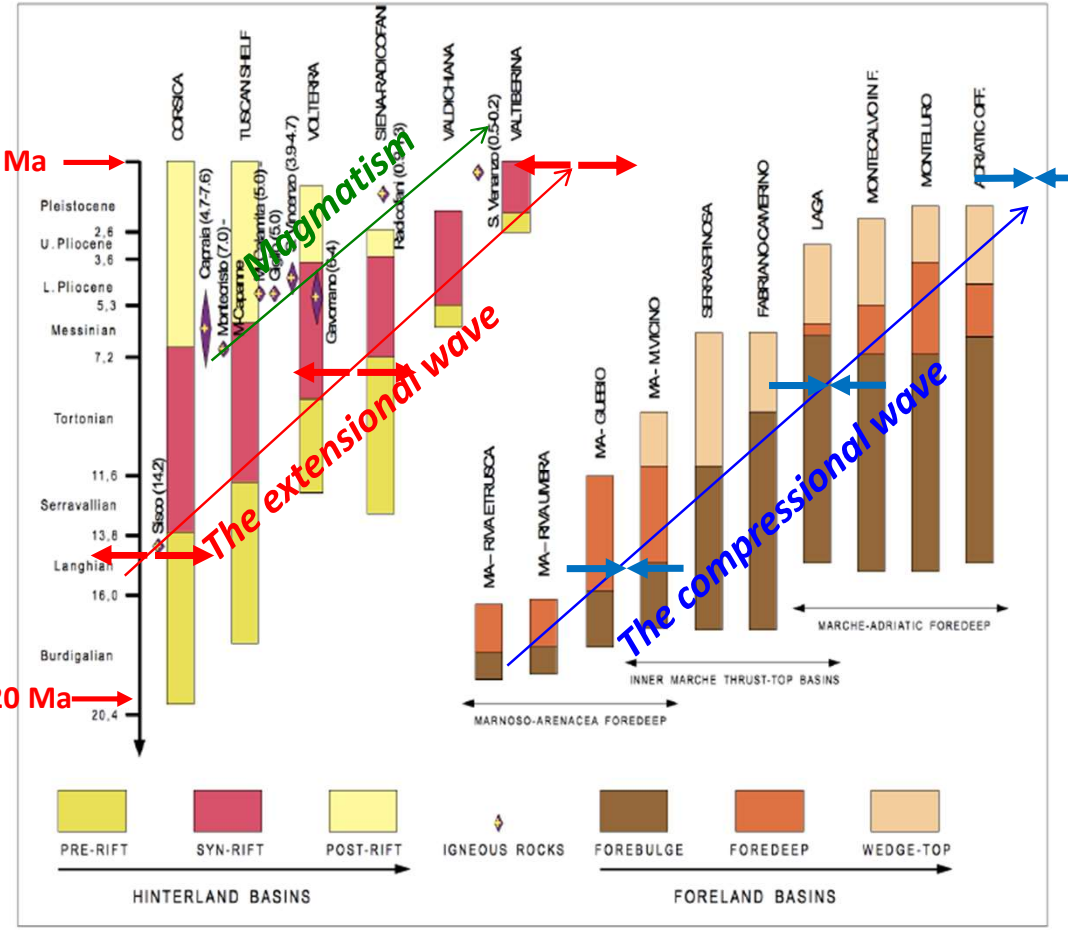
Regional-scale Tectonic evolution – back to ca. 20 Ma





Montone e Mariucci, 2016 – GJI

- The tectono-sedimentary evolution of the Northern Apennines is characterized by a process of coupled extension and compression, active in the last ≈ 20 Ma.



Barchi, 2010 – JVG

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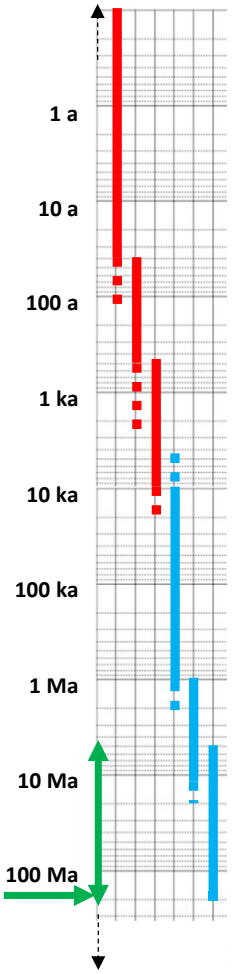
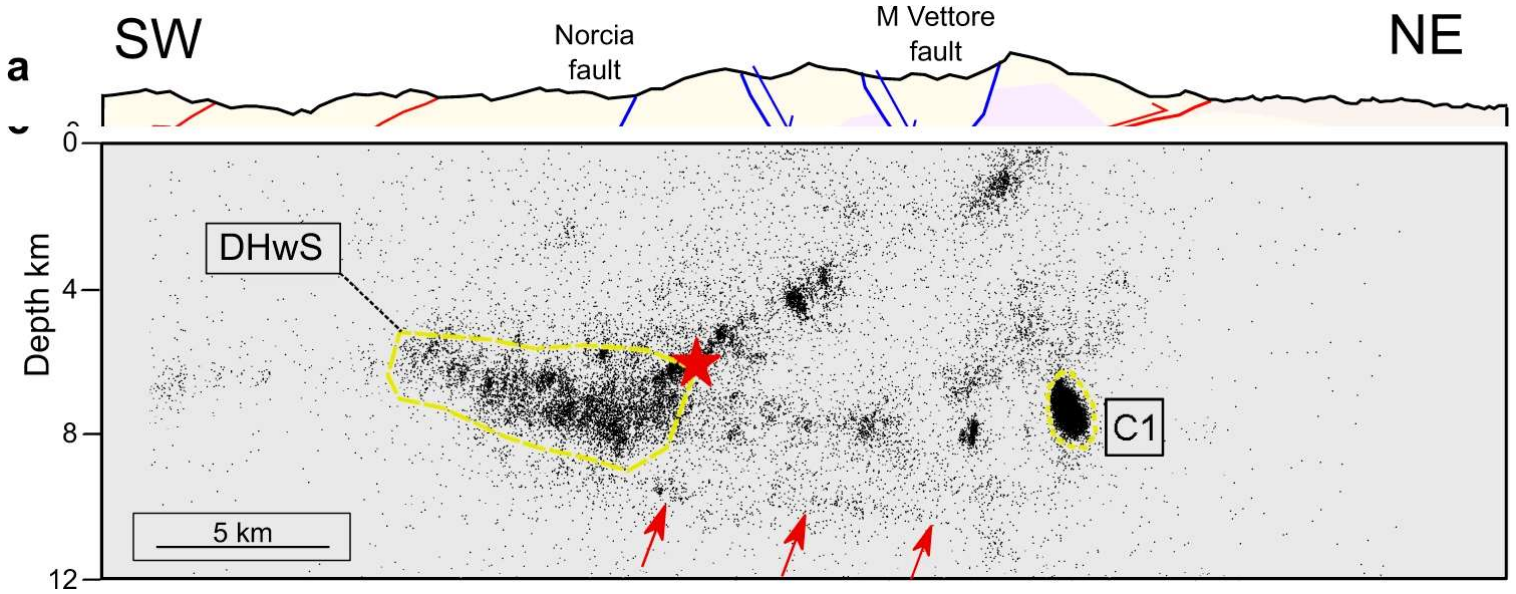
Stratigraphy and rock mechanics – back to ca. 200 Ma





- *During a seismic sequence, seismicity is not necessarily exclusive of the major structures activated within the seismogenic layer, comprising:*
- *"on-fault" seismicity: aftershocks located within the fault structure that is activated by the mainshock*
- *"distributed seismicity": aftershocks occurrence within volumes of the crust not including major faults hosting mainshocks.*

Collettini et al., 2022 – Nature Communications

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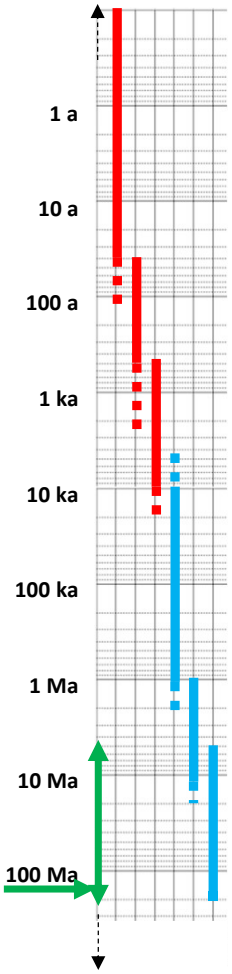
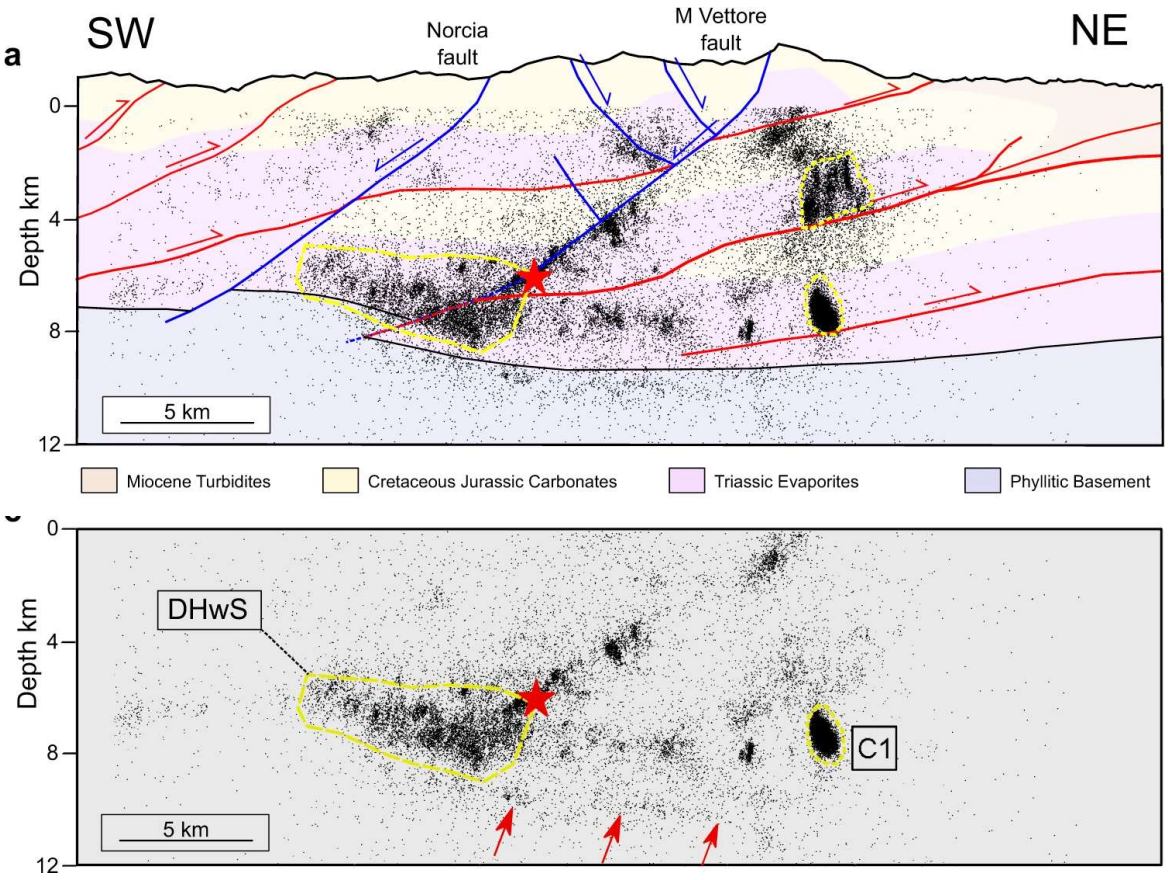
Stratigraphy and rock mechanics – back to ca. 200 Ma



- Study of the litho-mechanical features of the sedimentary succession of the Northern Apennines, where the earthquakes nucleate at depth.
- These rocks formed during the entire Alpine Cycle in the last 250 Ma.

- *The earthquakes (including mainshocks) are preferentially located within the Late Triassic Burano Fm., consisting of alternating anhydrites and dolostones.*
- *Few seismicity penetrates the underlying basement.*



Collettini et al., 2022 – Nature Communications

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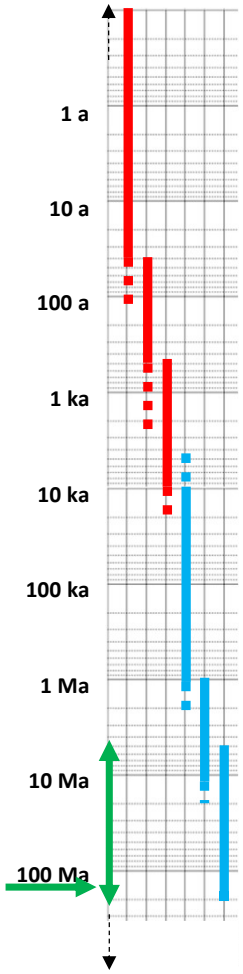
Stratigraphy and rock mechanics – back to ca. 200 Ma



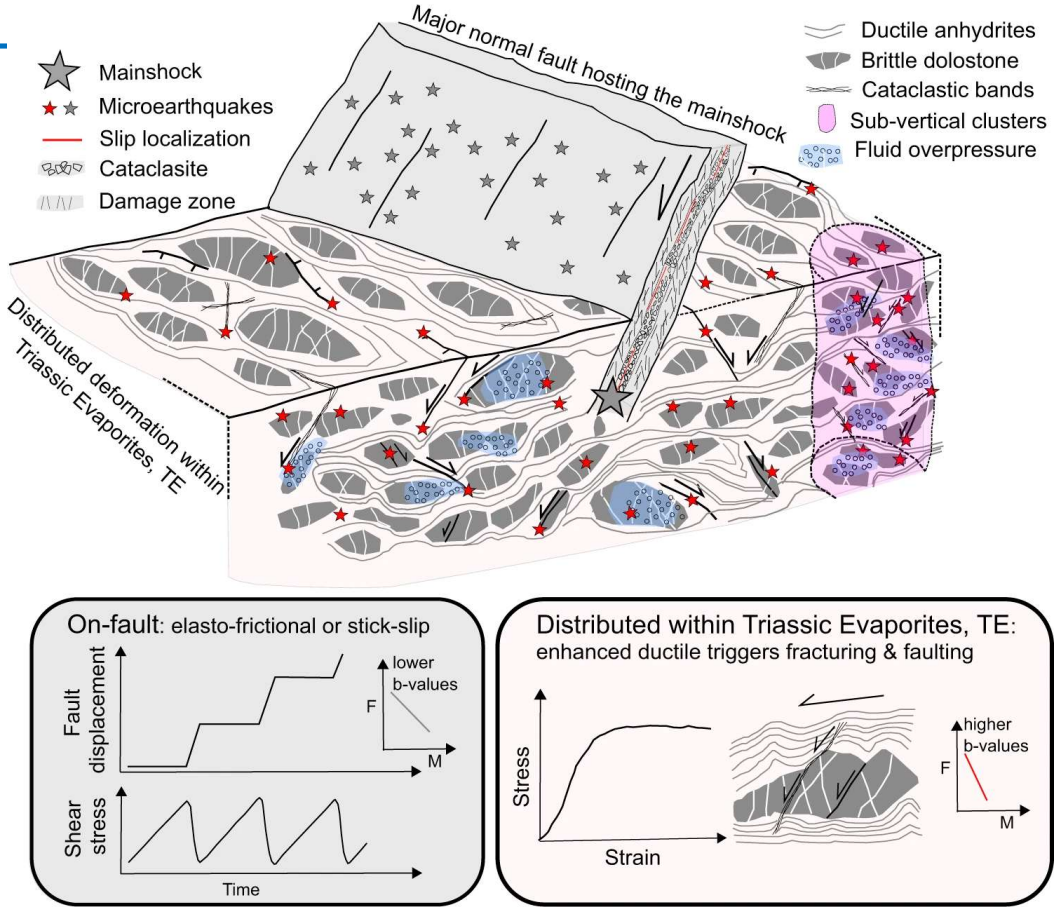
nature communications

Article

https://doi.org/10.1038/s41467-022-33373-y

Rock and fault rheology explain differences between on fault and distributed seismicity

- ***Distributed seismicity can be explained by the coexistence of brittle and ductile rheology within the Triassic Evaporites (alternation of anhydrites and dolostones).***



Collettini et al., 2022 – Nature Communications

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Concluding remarks

1. The larger earthquakes of the Central Apennines are related to a system of NNW-SSE trending (WSW-dipping) extensional faults

2. A strict relation exists between the instrumental and historical seismicity and the alignment of Quaternary intermountain, extensional basins

3. Both the Quaternary basins and the present-day seismicity are expression of the Late Miocene to present tectonic evolution of the Northern Apennines

4. Mechanical stratigraphy of the upper crust controls the distribution of seismicity in depth and ultimately the thickness of the seismogenic layer

- ***Knowledge of regional geology (i.e. stratigraphy, tectonics, geomorphology) is still fundamental in seismotectonic studies.***

- ***TIME MATTERS***

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Refrerences

- Barchi M.R. & Collettini C. (2019). Seismicity of central Italy in the context of the geological history of the Umbria-Marche Apennines, in Koeberl, C., and Bice, D.M., eds., 250 Million Years of Earth History in Central Italy: Celebrating 25 Years of the Geological Observatory of Coldigioco: Geological Society of America Special Paper 542, p. 1–16, https://doi.org/10.1130/2019.2542(09).
- Barchi M. R., Carboni F., Michele M., Ercoli M., Giorgetti C., Porreca M., Azzaro S., Chiaraluce L. (2021). The influence of subsurface geology on the distribution of earthquakes during the 2016-–2017 Central Italy seismic sequence. TECTONOPHYSICS, vol. 807, ISSN: 0040-1951, doi: 10.1016/j.tecto.2021.228797.
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- 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), 1-11.

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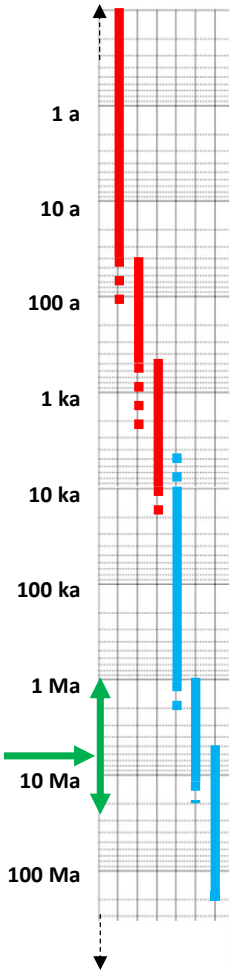
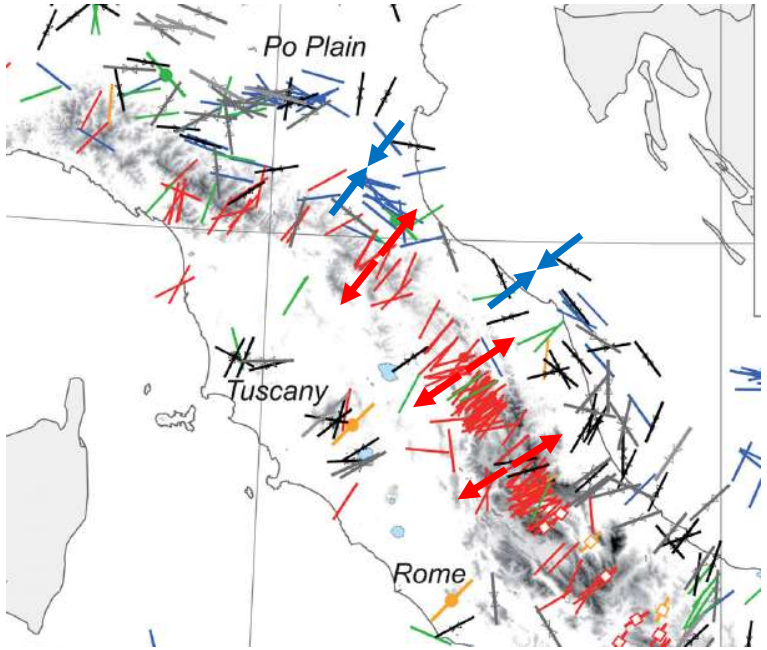
E-MAIL


Thank you for the attention

Regional-scale Tectonic evolution – back to ca. 20 Ma





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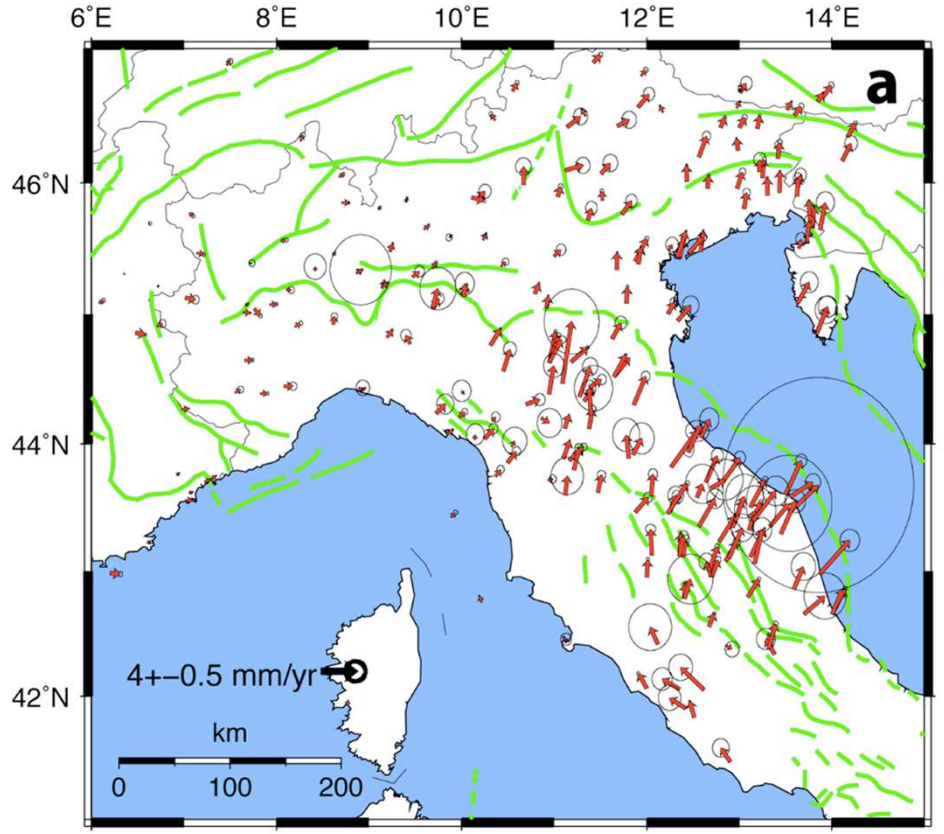

Bennett et al., 2012 - JGR

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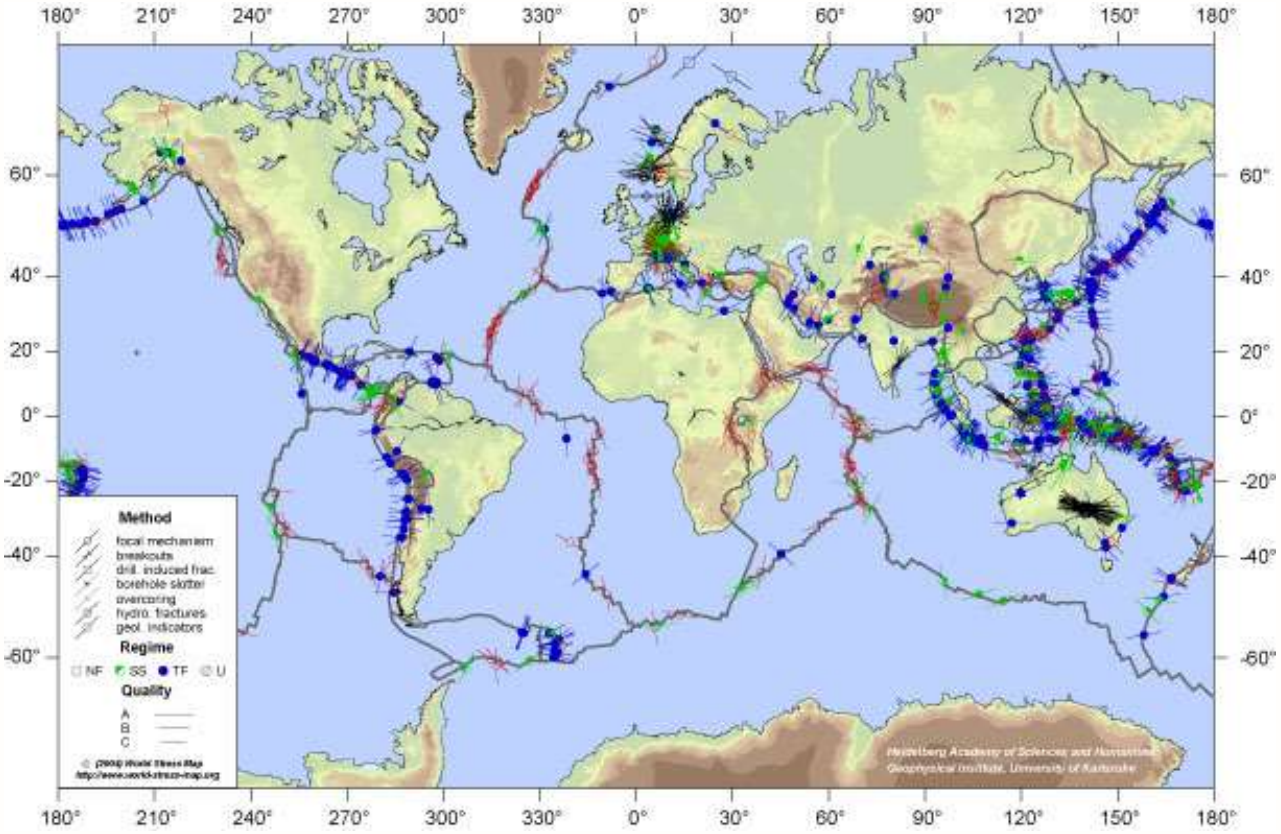
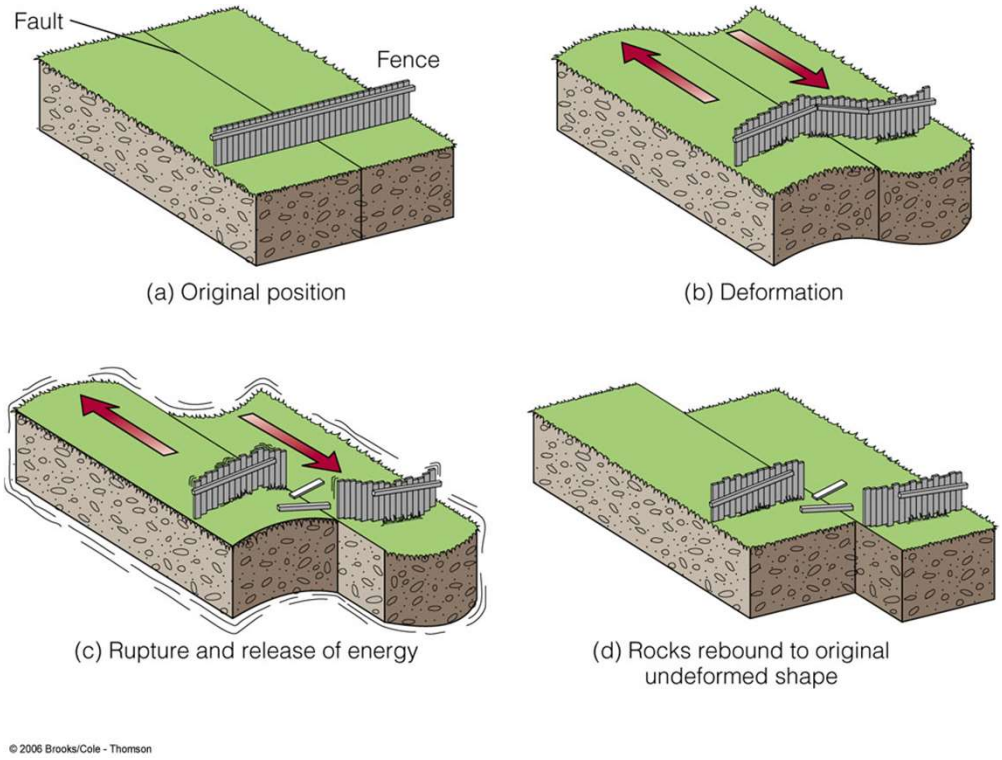
Plate Tectonics and Earthquakes (earthquakes at continental margins)

- Earthquakes occur mostly along relatively narrow belts (plate boundaries).
- From a kinematic point of view (focal mechanisms), there are three types of earthquakes : extensional, compressional and strike-slip, occurring at divergent, convergent and transform plate boundaries respectively.
- **Very few earthquakes occur at passive continental margins. Many strong earthquakes characterise active continental margins.**

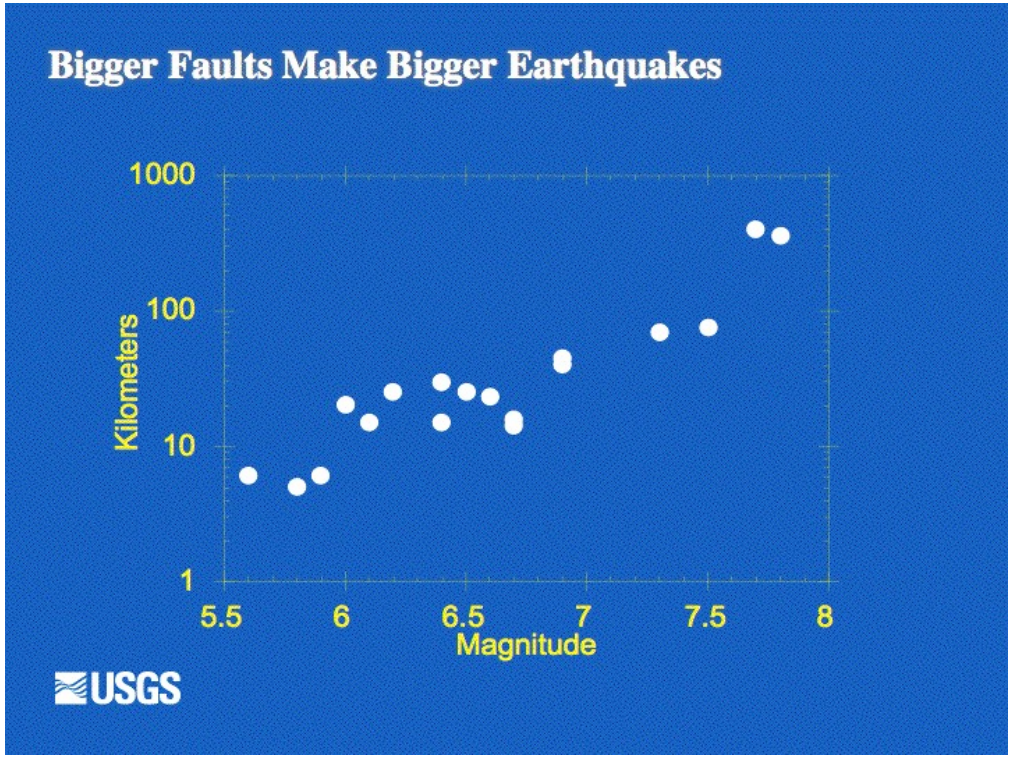


Two mailstones of the Fault – Earthquake relationships

The Elastic Rebound Theory (Reid, 1910)



Empirical Relationships between Fault size and Earthquake Magnitude (Wells and Coppersmith, 1994)



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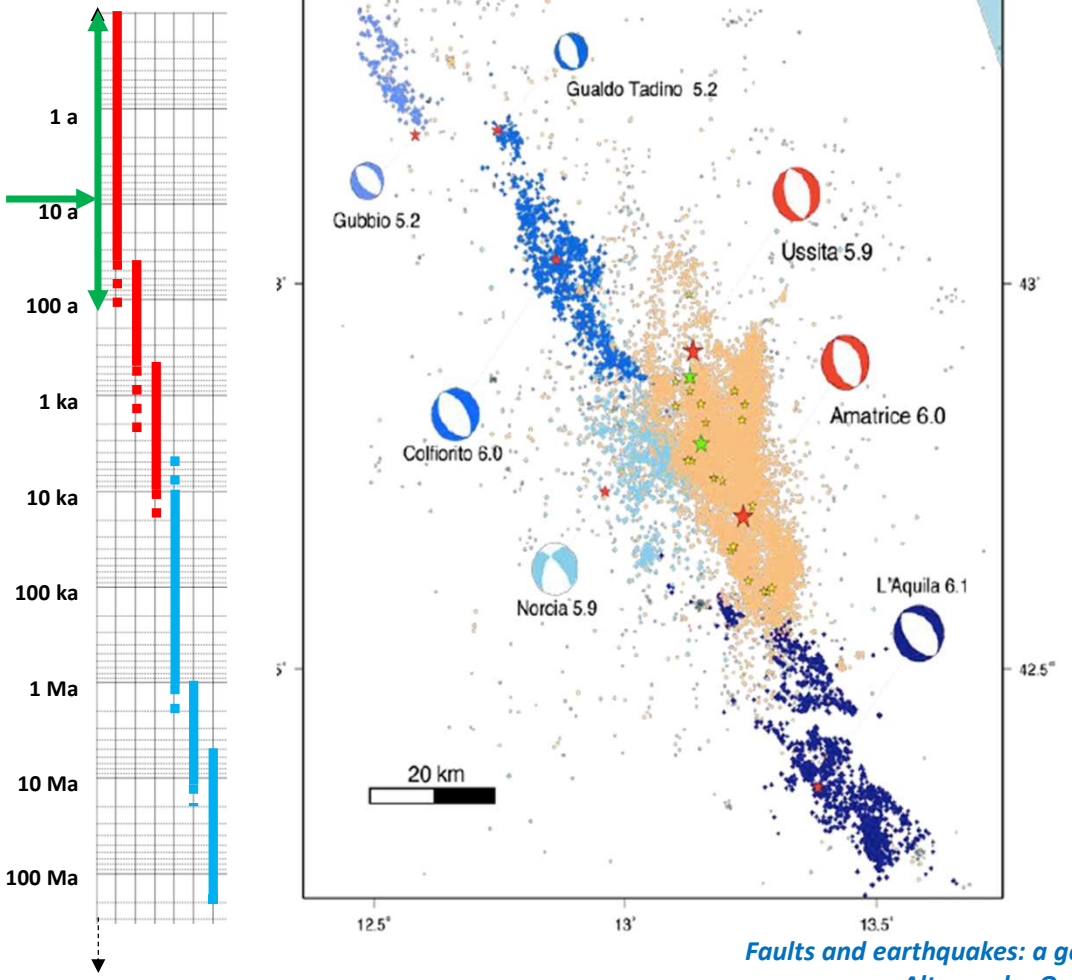
40 years of Seismic sequneces in Central Italy (1979-2017)



- Norcia (1979) – M = 5.9
- Gubbio (1984) – M = 5.2
- Colfiorito-Gualdo Tadino (1997-98) – M = 6.0
- L'Aquila (2009) – M = 6.1)
- Amatrice-Visso- Norcia (2016) – M = 6.5

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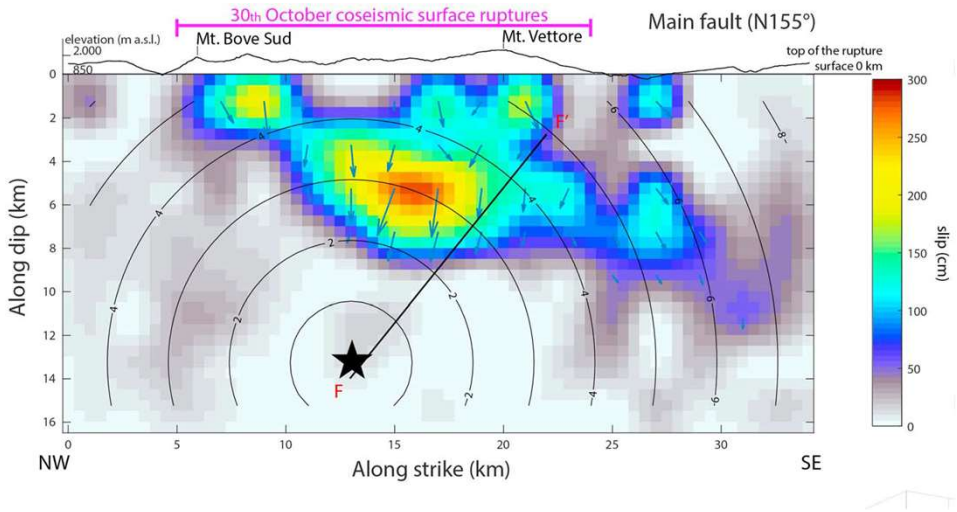
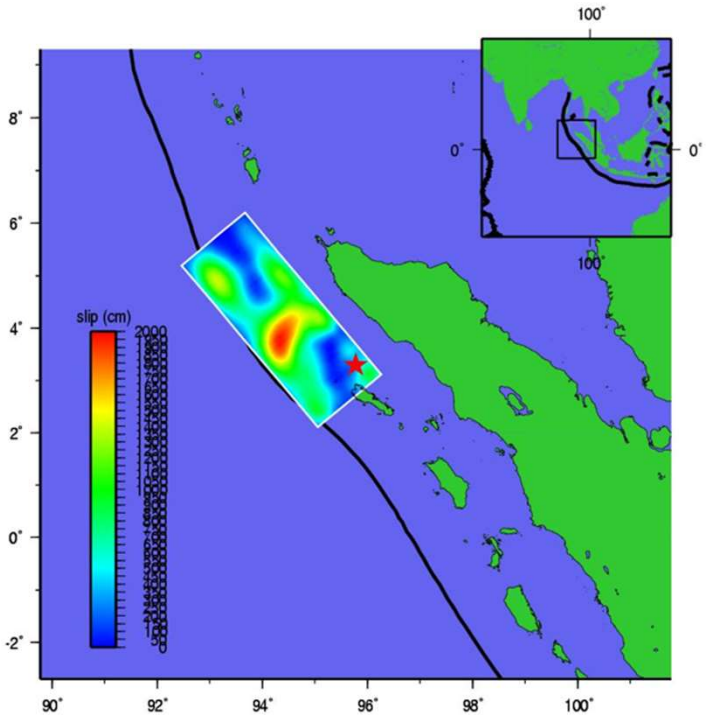
Two Earthquakes of different nature and size





Central Italy (Norcia) – 30/10/2016 –
Magnitude 6.5 - extensional earthquake
Length of the ruptured fault = 35 km
Width of the ruptured fault = 10 km
Maximum displacement _=3 m

Sumatra – 26/12/2004 –
Magnitude 9.1 - compressional earthquake
Length of the ruptured fault = 400 km
Width of the ruptured fault = 50 km
Maximum displacement =20 m

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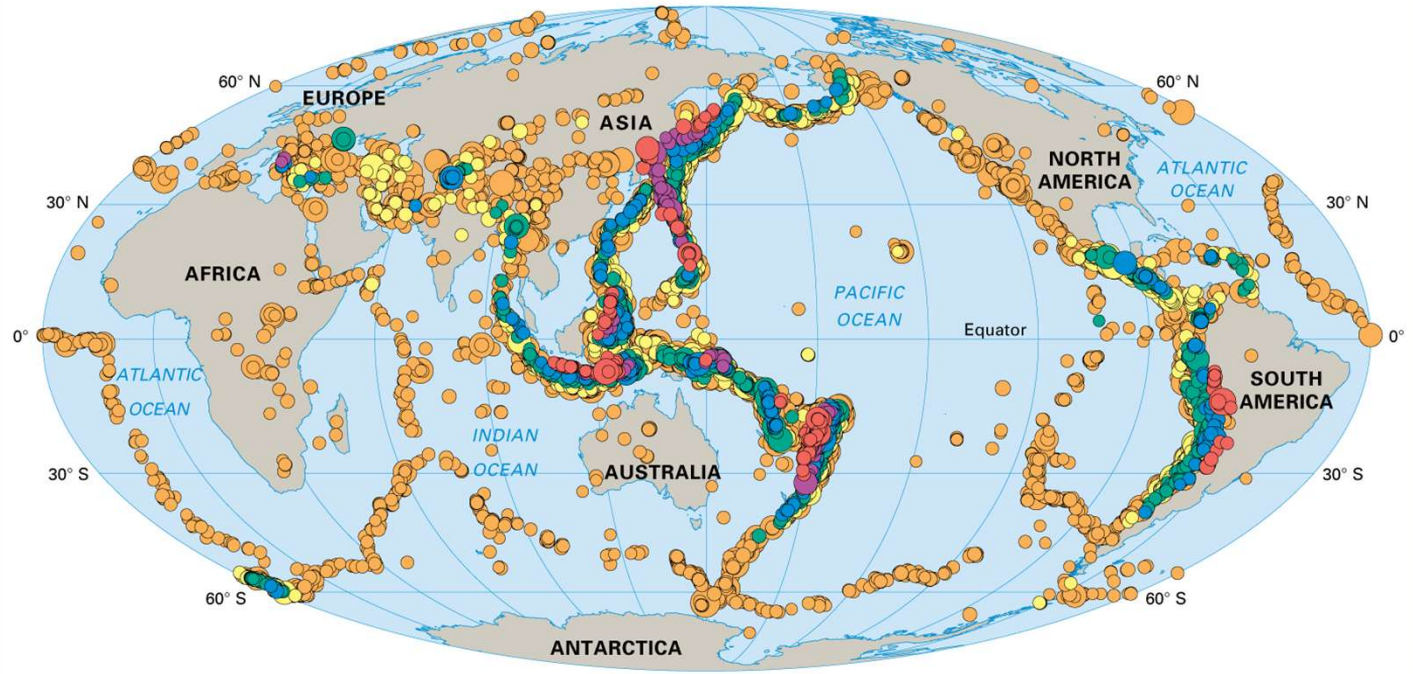
2 questions about Earthquakes, Faults and Plates

- **What is the main cause of earthquakes ?**
- **How are they distributed in space and depth ?**

Global seismic centres in 1975-1999
Earthquakes of magnitude 5.5 and greater

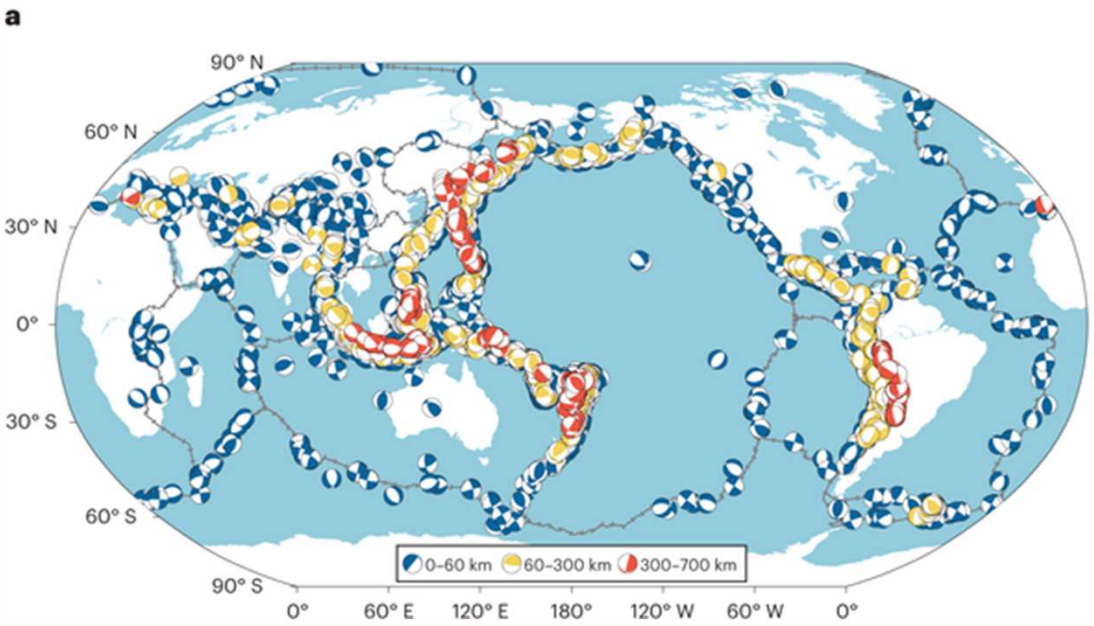


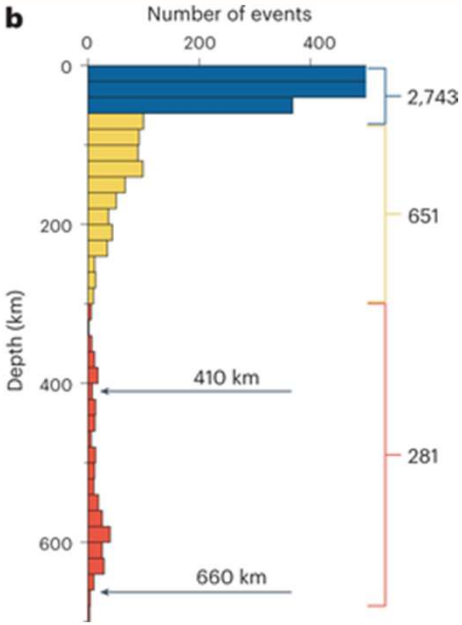
Depth of earthquake focus

km	mi
0	0
33	21
70	43
150	93
300	186
500	311
800	497

Circle size is proportional to earthquake magnitude.

Global and depth distribution of earthquakes





*Earthquakes occur primarily in the **brittle upper crust** of the Earth at **depths of less than 20 km**.*

Most earthquakes occur at or near the boundaries of the tectonic plates, but a few earthquakes occur within plate interiors.

Stress is added to the crust slowly due to the tectonic motion of the plates and is relieved rapidly in earthquakes. The crustal stress oscillates about an equilibrium value.

PRESENTATION

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