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INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

CAPABLE FAULT, GROUND SHAKING & DISPLACEMENT HAZARDS

AN ILLUSTRATION OF THE PHENOMENA BEHIND THE REGULATORY GUIDELINES

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Independent observer at the Hungarian-Austrian professional workshop on the Paks II site characteristics in Budapest, Feb 15, 2022

MEMBRE DE ETSON

Capable faults, Ground shaking and Fault displacement hazards

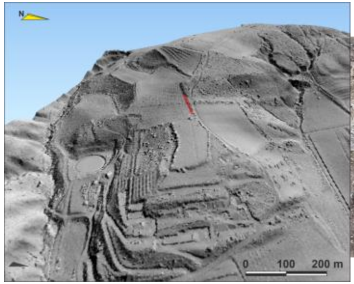
[WHAT'S THAT?

- Capable fault is an active fault that can generate faulting/rupture at the ground surface during earthquakes
  - Assessment based on paleoseismology: geometry, slip rate, recurrence, etc

- Challenges to the safety of the nuclear installation in terms of **ground motion and/or fault displacement hazards** shall be evaluated (IAEA, 2021)

- **(Surface) fault displacement** may jeopardize buildings, pipelines, transportation routes, etc
  - Prediction based on empirical approaches

Anghiari Fault, N. Apennines



Testa PhD thesis

2016 M6.5 Norcia earthquake

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Capable faults, Ground shaking and Fault displacement hazards

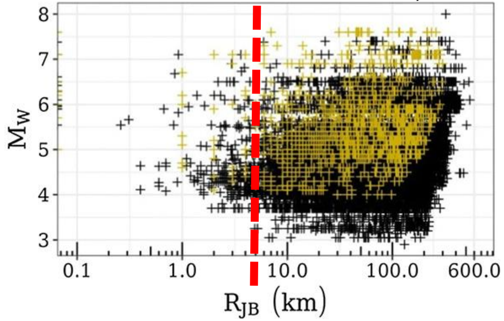
[WHAT'S THAT?

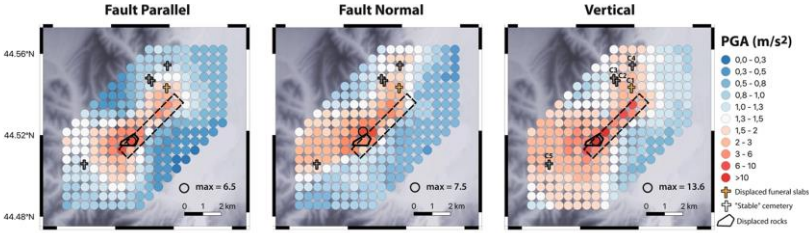
▌ **(Surface) fault displacement** may jeopardize buildings,…

▌ **Near-field shaking**

- High frequency, short duration & high peak ground acceleration
- Recordings are rare, empirically-based prediction is weakly supported
  - European database
- Modelling
  - Simulation of ground shaking caused by the 2019 M4.9 earthquake in France

Kotha et al., 2020





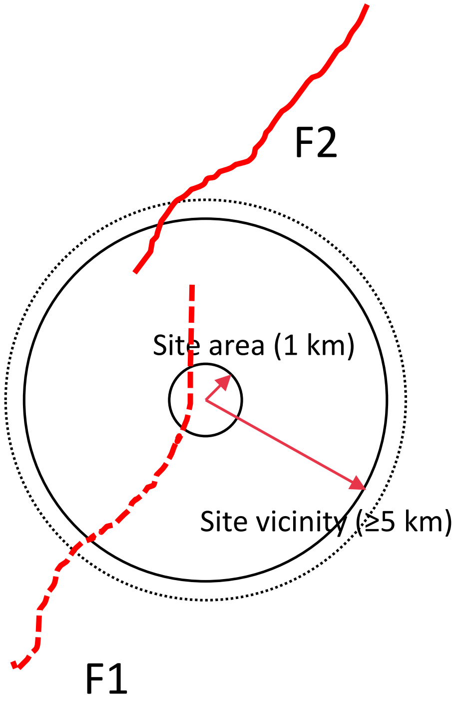
Causse et al., 2021

Nuclear sites and capable faults

IAEA – SEISMIC SAFETY REQUIREMENTS, SITE SUITABILITY

- *“A proposed new site shall be considered unsuitable when reliable evidence shows the existence of a capable fault that has the potential to affect the safety of the nuclear installation and which cannot be compensated for by means of a combination of measures for site protection and design features of the nuclear installation,”*

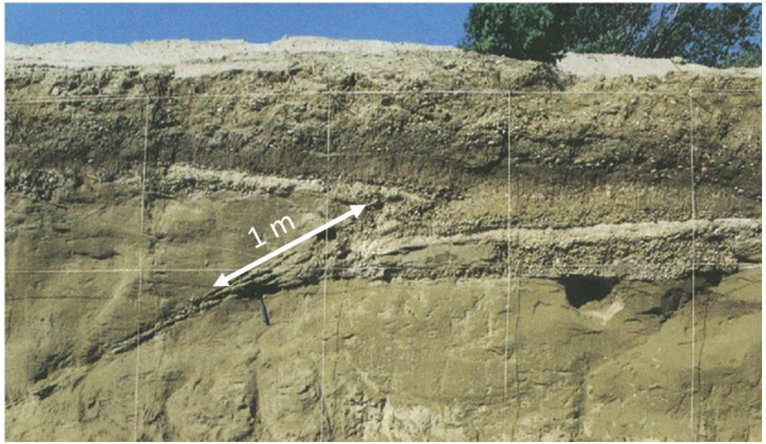
- *“If a capable fault is identified in the **site vicinity** of an existing nuclear installation, the site shall be deemed unsuitable if the safety of the nuclear installation cannot be demonstrated”*
  - Threat of ground shaking caused by EQ on F1 and F2
  - Threat of principal surface rupture caused by EQ on F1, and secondary rupture on F1 during EQ caused by F2)



IAEA – SSG-9, new release 2021

[A FAULT IS CONSIDERED CAPABLE…

- Geological evidence
  - *If it shows **evidence of past movement** within such a period that it is reasonable to conclude that further movements at or near the surface might occur over the lifetime of the site*
  - *Or, if it could be structurally linked with a known capable fault*
  - *if the potential maximum magnitude is sufficiently large and the seismic activity is suspected at such a shallow depth that movement at or near the surface could occur.*



Post-120 ky reverse faulting, Nîmes fault, SE France

IAEA – SSG-9, new release 2021

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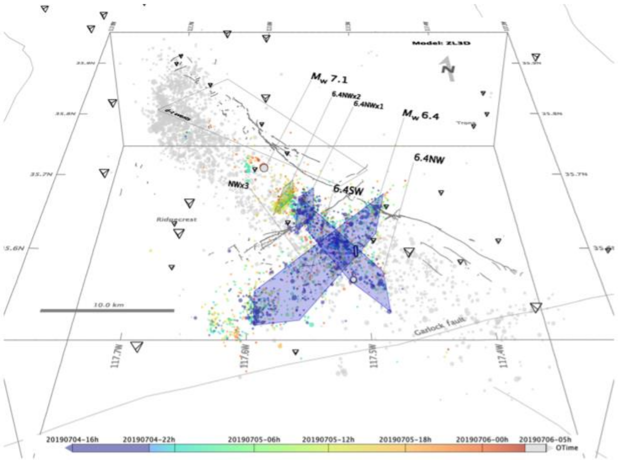

Lomax, 2020: 2019 Ridgecrest sequence

IAEA – SSG-9, new release 2021

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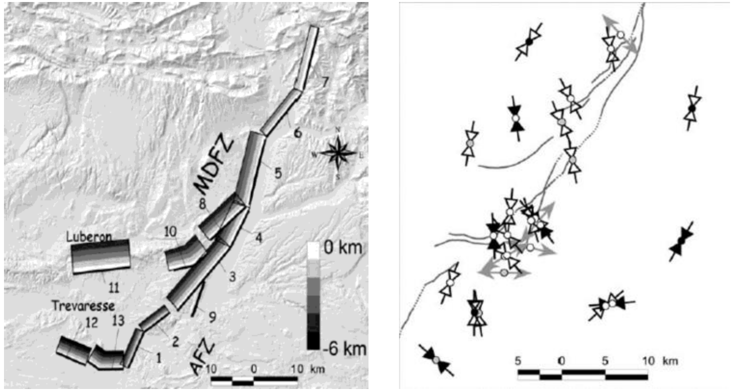
- Time frame
  - In highly active areas, evidence of past movements in the Upper Pleistocene to the Holocene might be appropriate for the assessment of capable faults
  - In less active areas, it is likely that much longer periods (e.g. the Pliocene to the Holocene) are appropriate.

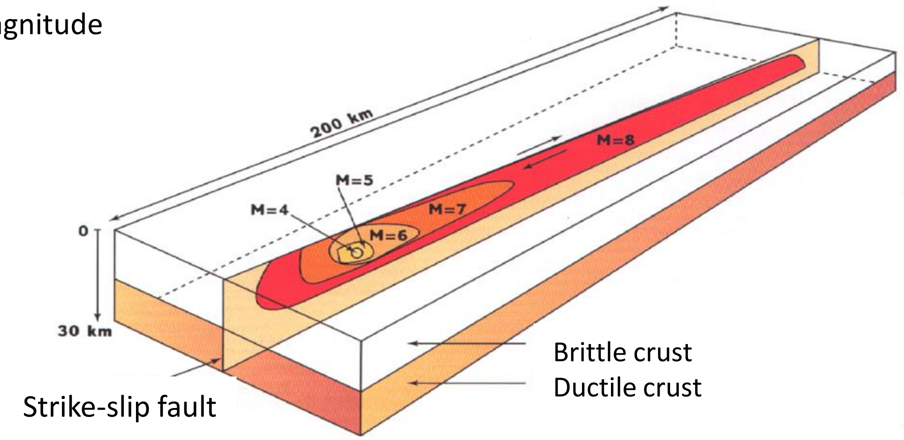


Cushing et al. 2008: Provence fault system

Surface faulting during earthquakes

GENERAL TRENDS

- Scaling relationships
  - **Higher is the magnitude, longer/wider is rupture area**
  - Larger is the surface displacement, bigger is the magnitude
- Surface rupture probability
  - As a consequence, it increases with magnitude



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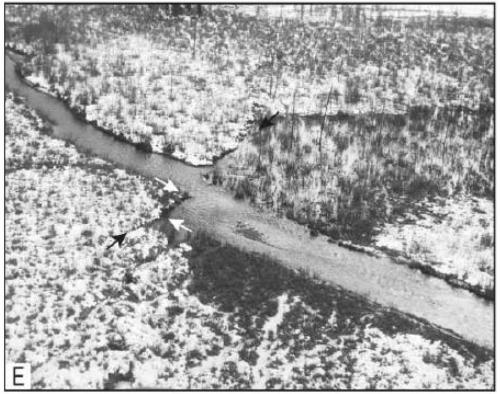
2014 West Napa quake surface faulting : tar road offset measured 0.4 m in Dec. 2014



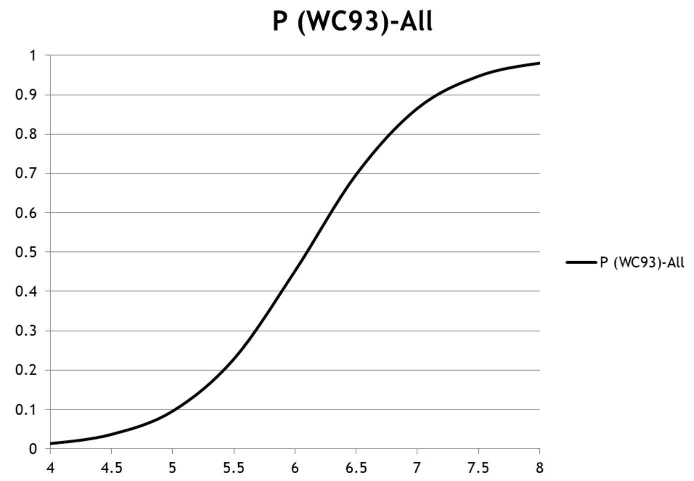
2002 Denali quake surface faulting at Bone Creek: Channel offset measured 5.5 m in Nov. 2002 & 6.6 in Jul. 2003 (Haeussler et al., 2002)

Surface faulting during earthquakes

GENERAL TRENDS

- Scaling relationships
  - Higher is the magnitude, larger/wider is rupture area and bigger is the slip
  - Higher is the surface displacement, bigger is the magnitude

- **Surface rupture probability**
  - **As a consequence, it increases with magnitude**



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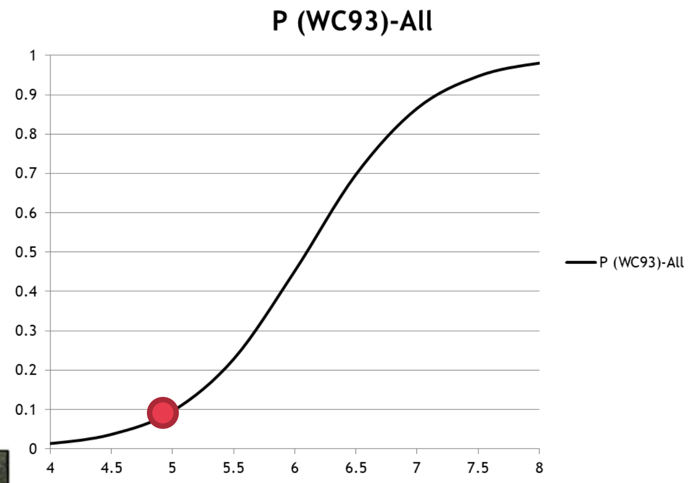


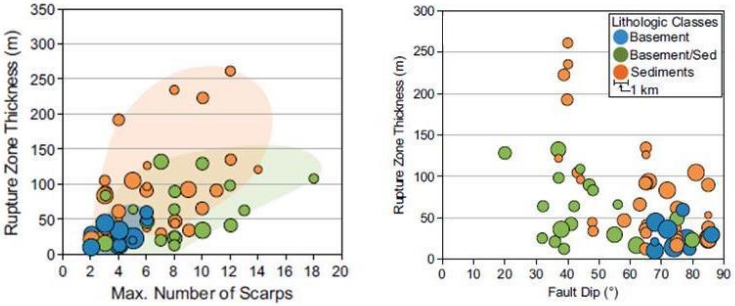
2019 M4.9 Le Teil earthquake; France
(Ritz et al., 2020)

Surface faulting during earthquakes

[GENERAL TRENDS, BUT SURFACE RUPTURES ARE COMPLEX…

- **Other controls on surface rupture**
  - Shallow fault dip, shallow depth and soft surface conditions may critically change the 1st order trend

- Surface rupture variability
  - Distribution of slip along and off the principal rupture
  - Amount of displacement

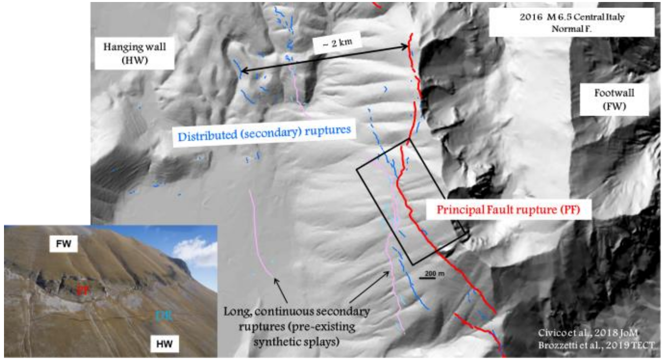


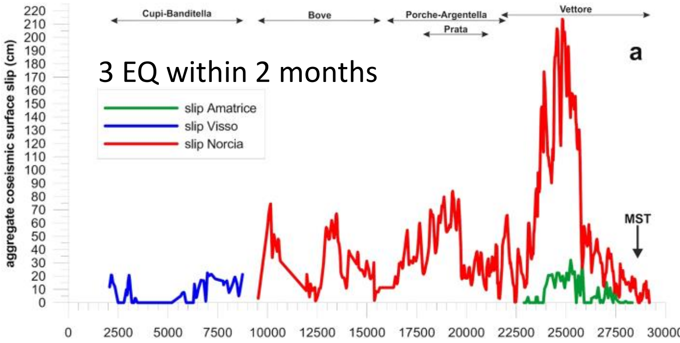
Influence of local geology on fault scarp number and dip
(M7.2 El Mayor Cucapah earthquake, Mexico, from Teran et al. 2015)

Surface faulting during earthquakes

[GENERAL TRENDS, BUT SURFACE RUPTURES ARE COMPLEX…

- Other controls on surface rupture
  - Shallow fault dip, shallow depth and soft surface conditions may radically change the 1st order trend
- **Surface rupture variability**
  - **Distribution of slip off the principal rupture**
  - **Distribution of slip along the principal rupture**





Pucci et al. 2018

Surface faulting during earthquakes

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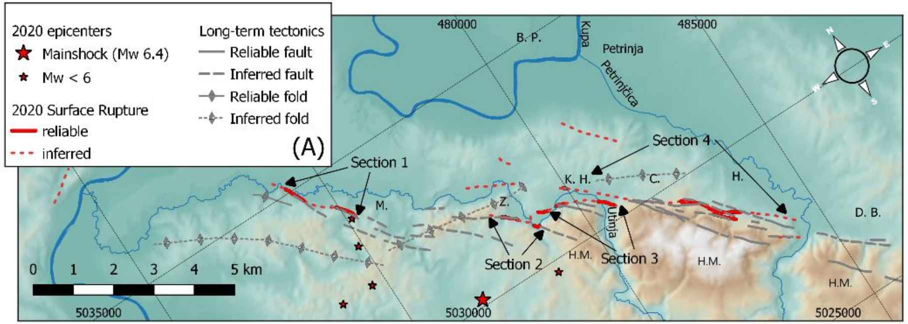
- Other controls on surface rupture
  - Shallow fault dip, shallow depth and soft surface conditions may radically change the 1st order trend

- **Surface rupture variability**
  - Distribution of slip off the principal rupture
  - Distribution of slip along the principal rupture
  - **Rupture can occur off the cumulative fault**

2020 M6.4 Petrinja, Croatia



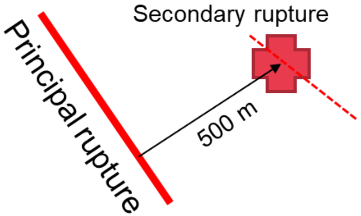
Baize et al. in review

Fault Displacement Hazard

- Surface rupture hazard is thus challenging to estimate

- Hazard due to fault displacement on principal and on distributed ruptures can be treated separately (IAEA):
  - *Primary, or principal, faulting occurs along a main fault rupture plane (or planes) that is the location of release of the energy.*
  - *Secondary, or distributed, faulting is the rupture that occurs near the principal faulting, possibly on splays of the main fault or on antithetic faults.*

- Nuclear industry
  - For existing nuclear installations, IAEA recommends PFDHA approach, including **secondary rupture probability**



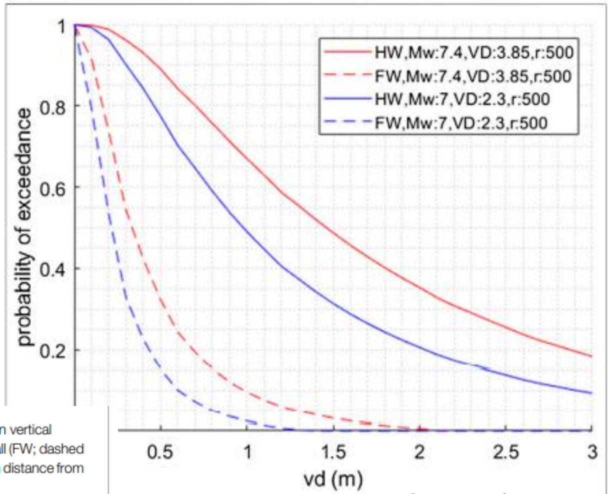


FIGURE 11 | Curves for the probability of exceedance for given vertical displacement levels for hanging wall (HW; solid lines) and footwall (FW; dashed lines) for M_w 7 (blue lines) and M_w 7.4 (red lines) at a site in 500 m distance from the PF.

Nurminen et al. 2020

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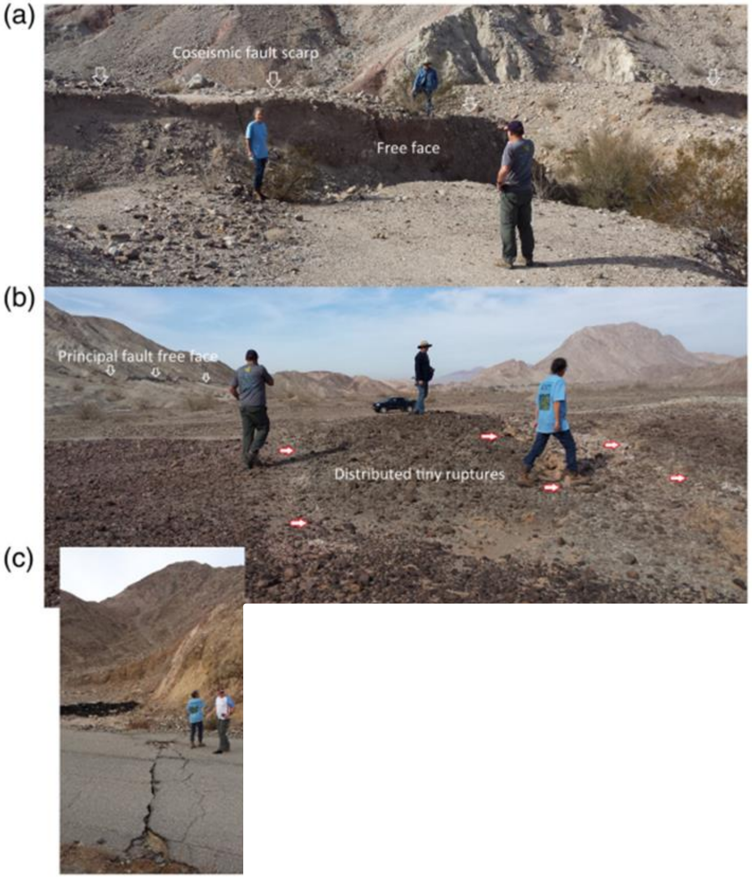
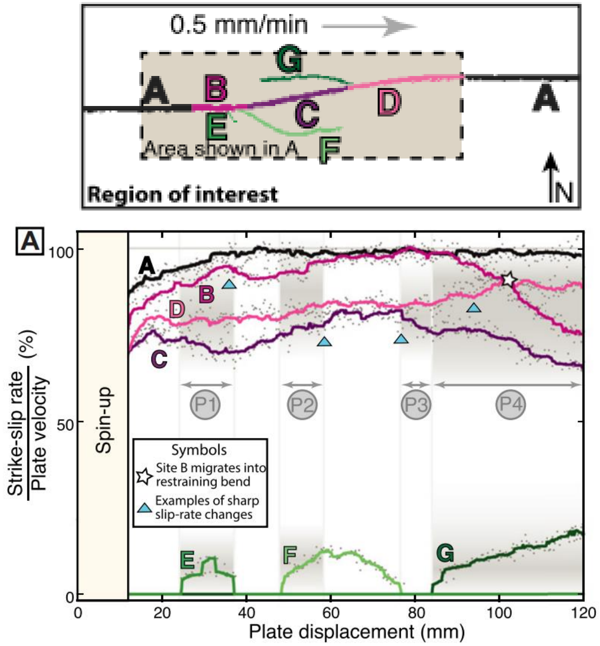
- Nuclear industry
  - For existing nuclear installations, IAEA recommends PFDHA approach
  - For new sites, IAEA SSG9 – Rev1
    - *if reliable evidence is collected demonstrating the existence of a capable fault with potential for seismogenic (i.e. primary) fault displacement within the **site vicinity**, or within the site area, and its **effects cannot be compensated** for by proven design or engineering protective measures, this issue **should be treated as an exclusionary attribute** and an alternative site should be considered.*



Reconstruct earthquake history based on geological archives, a complex approach (incl. with pitfalls and uncertainties)

- Natural variability of slip during earthquake cycles
  - **Fault interactions over seismic cycles**
- Completeness of stratigraphic record
  - Under-estimation of number of events
  - Over-estimation of magnitude per event
- Epistemic uncertainties
  - Dating of events
  - Measurement of slip
- Magnitudes from paleo-earthquake data
  - Scaling relationships pitfalls



Elston et al., 2022

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Earthquake sequence in Central Italy, 2016

In the geological recording, we will not be able to separate the 2 offsets

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Earthquake sequence in Central Italy, 2016

In the geological recording, we will not be able to separate the 2 offsets

- **Nuclear industry**
  - *When faulting is known or suspected (…)* ***site vicinity scale investigations should be made that include very detailed geological*** *and geomorphological mapping, topographical analyses, geophysical surveys, trenching, boreholes, age dating of sediments or fault rock, local seismological* ***investigations (…)***

IAEA references

[SITING GUIDELINE AND EARTHQUAKE GEOLOGY RELATED TECDOCS

- Specific Safety Guide No. SSG-9 (Rev. 1), 2021 - Seismic Hazards in Site Evaluation for Nuclear Installations
  - Seismic hazards in site evaluation for nuclear installations (iaea.org)

- TECDOC 1767, 2015 - The Contribution of Palaeoseismology to Seismic Hazard Assessment in Site Evaluation for Nuclear Installations
    - https://www.iaea.org/publications/10887/the-contribution-of-palaeoseismology-to-seismic-hazard-assessment-in-site-evaluation-for-nuclear-installations

- TECDOC 1987, 2020 - An Introduction to PFDHA in Site Evaluation for Existing Nuclear Installations
    - https://www.iaea.org/publications/14915/an-introduction-to-probabilistic-fault-displacement-hazard-analysis-in-site-evaluation-for-existing-nuclear-installations
  - Ongoing benchmark exercise
    - https://pubs.geoscienceworld.org/ssa/bssa/article/111/5/2661/607254/Probabilistic-Fault-Displacement-Hazard-Assessment

Thank you for your attention