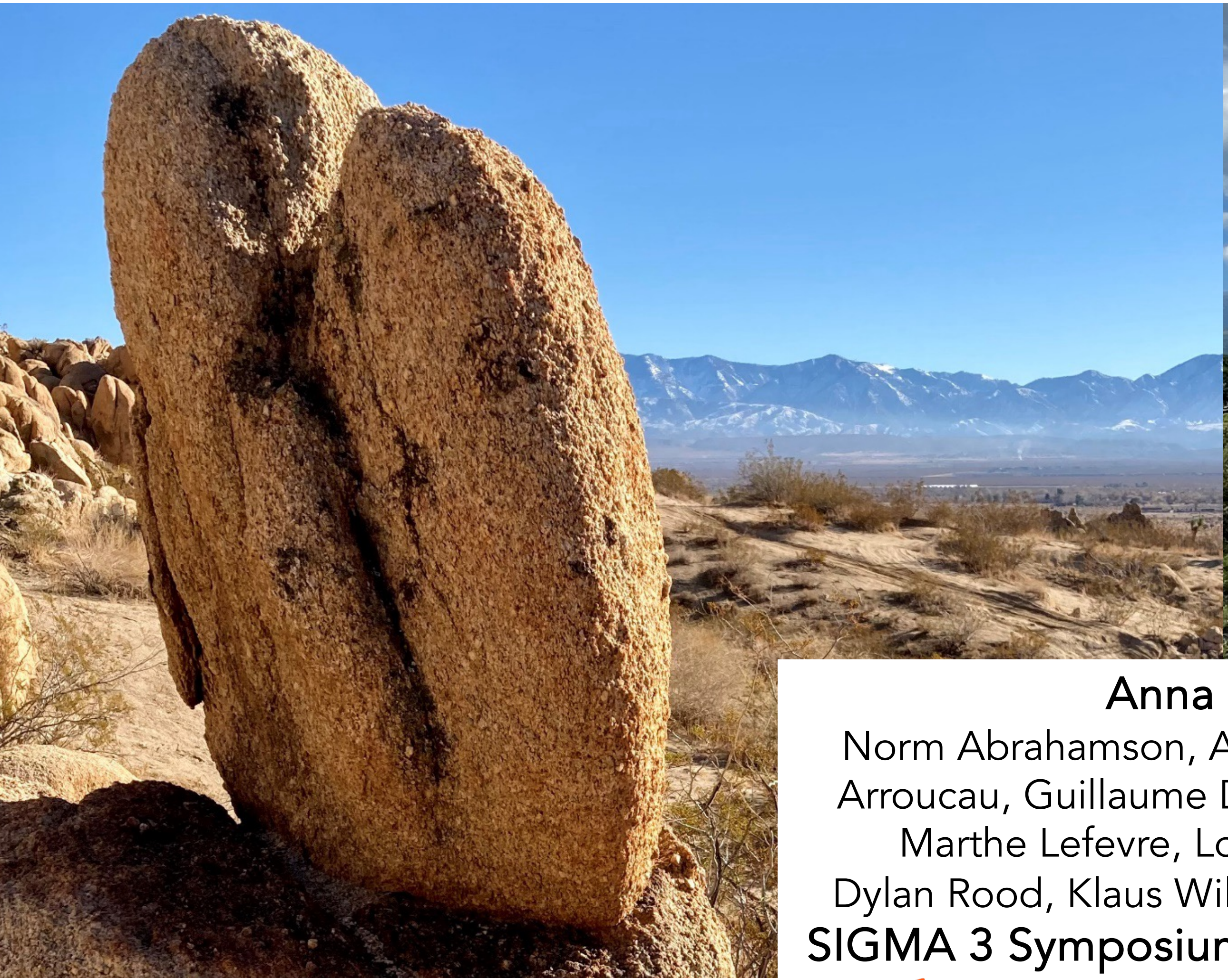
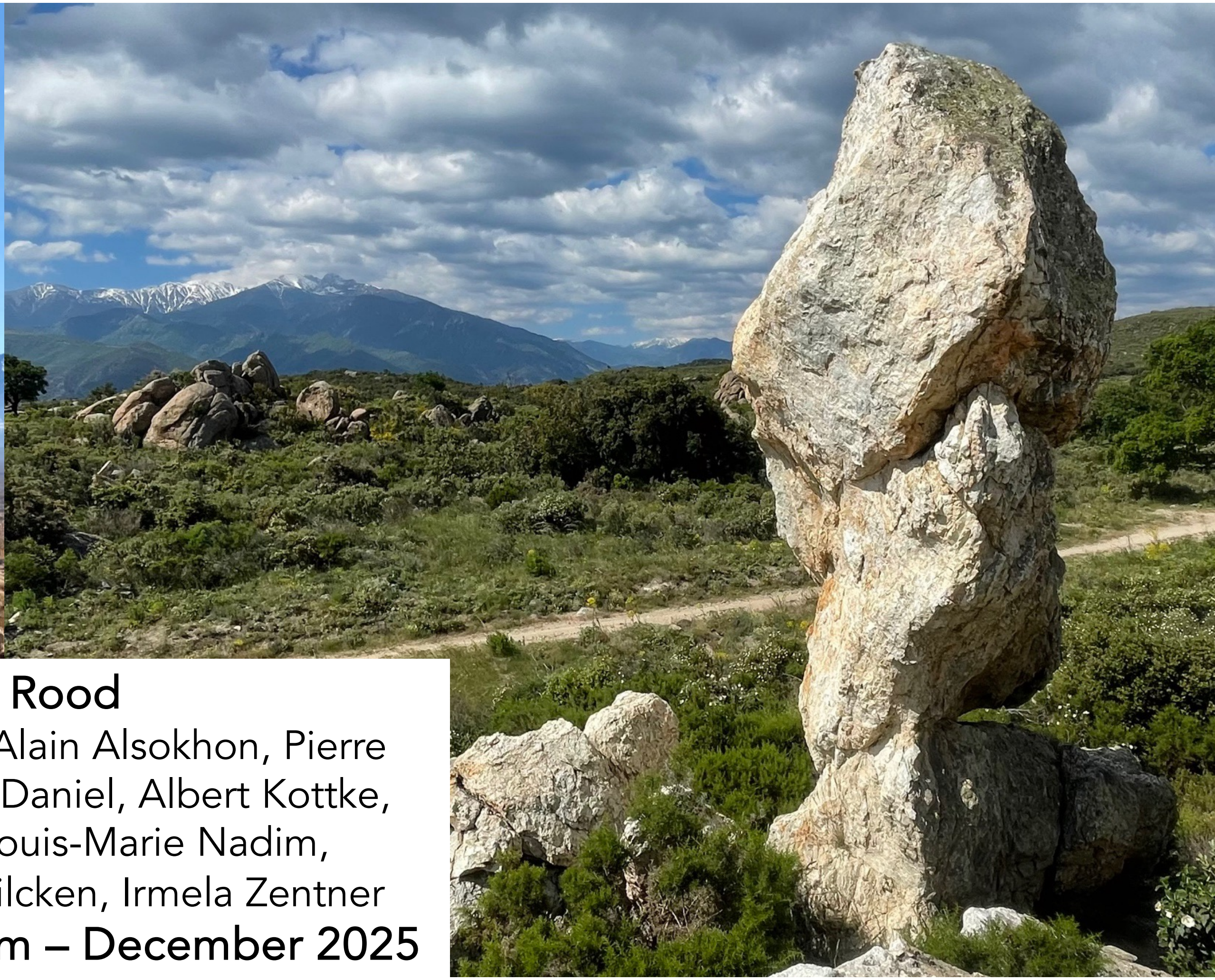
Validation Of Seismic Hazard Models In France Using Fragile Geologic Features





Anna Rood

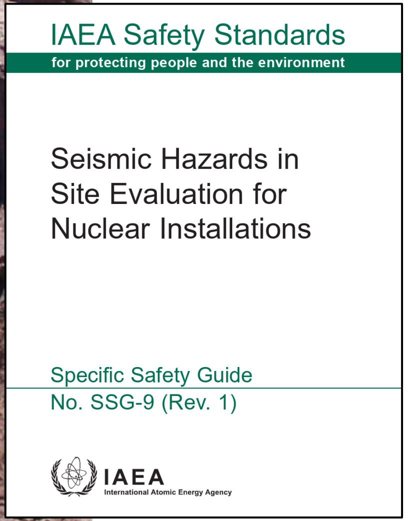
Norm Abrahamson, Alain Alsokhon, Pierre Arroucau, Guillaume Daniel, Albert Kottke, Marthe Lefevre, Louis-Marie Nadim, Dylan Rood, Klaus Wilcken, Irmela Zentner

SIGMA 3 Symposium – December 2025

Rood Geoconsulting ANSTO EDF IMPERIAL PG&E Pacific Gas and Electric Company UC Berkeley

PSHA Validation

(Hanks et al., 2015)



IAEA Safety Standards
for protecting people and the environment

Seismic Hazards in
Site Evaluation for
Nuclear Installations

Specific Safety Guide
No. SSG-9 (Rev. 1)

IAEA
International Atomic Energy Agency

Validation

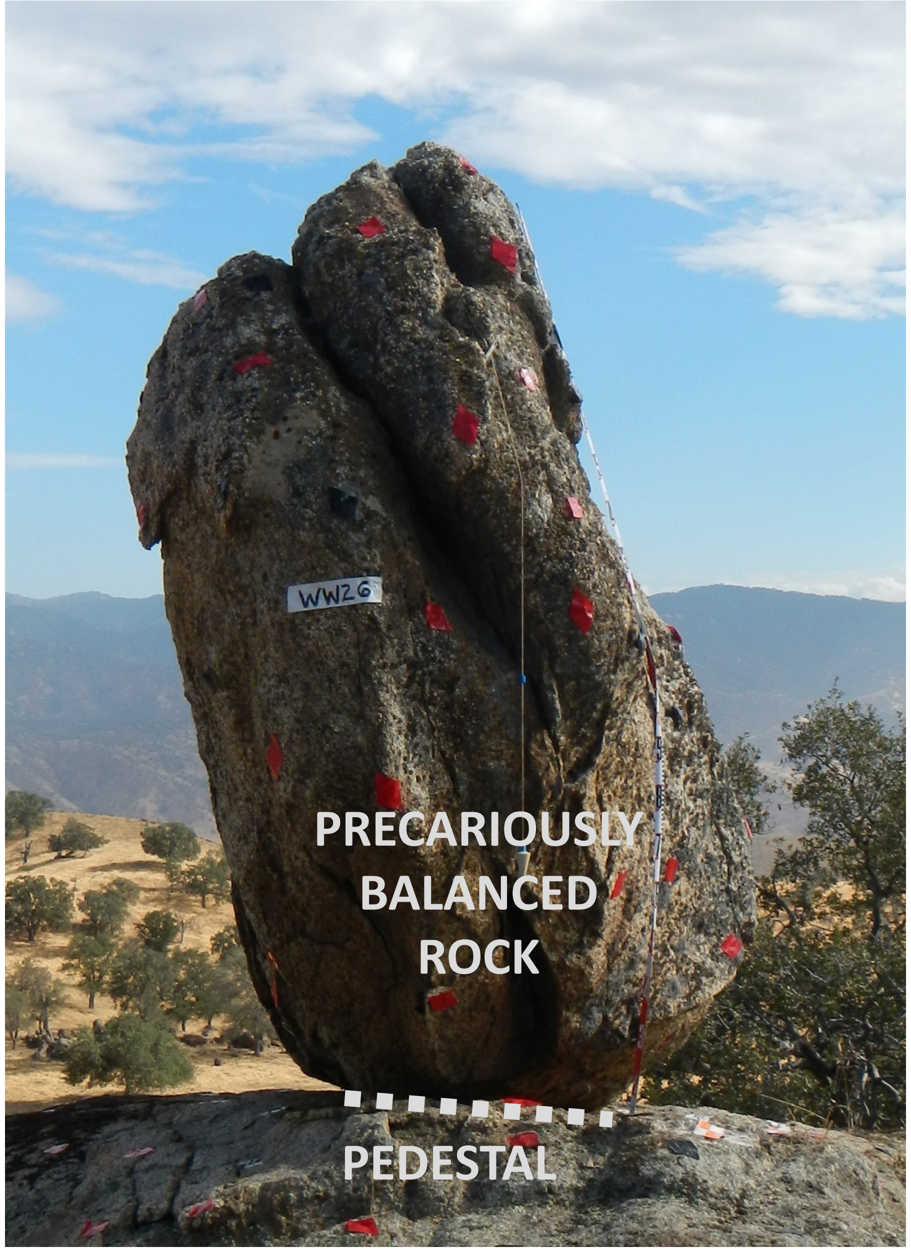
"the process of statistically quantifying the capability of a model to produce forecasts that are consistent with independent observations. Testing can be applied to NSHM and/or to its components. The goals can be multifold and may include, for example, identifying of model components that need to be improved or rejection of a model that is inconsistent with the data."
(Gerstenberger et al., 2020)

Fragile Geologic Features

e.g., Precariously Balanced Rocks

Site-specific constraint on the ground motions over timescales of 1,000s to 10,000s of years using the probability that a rock would have survived to the present day, assuming a realization of the PSHA logic tree is correct.

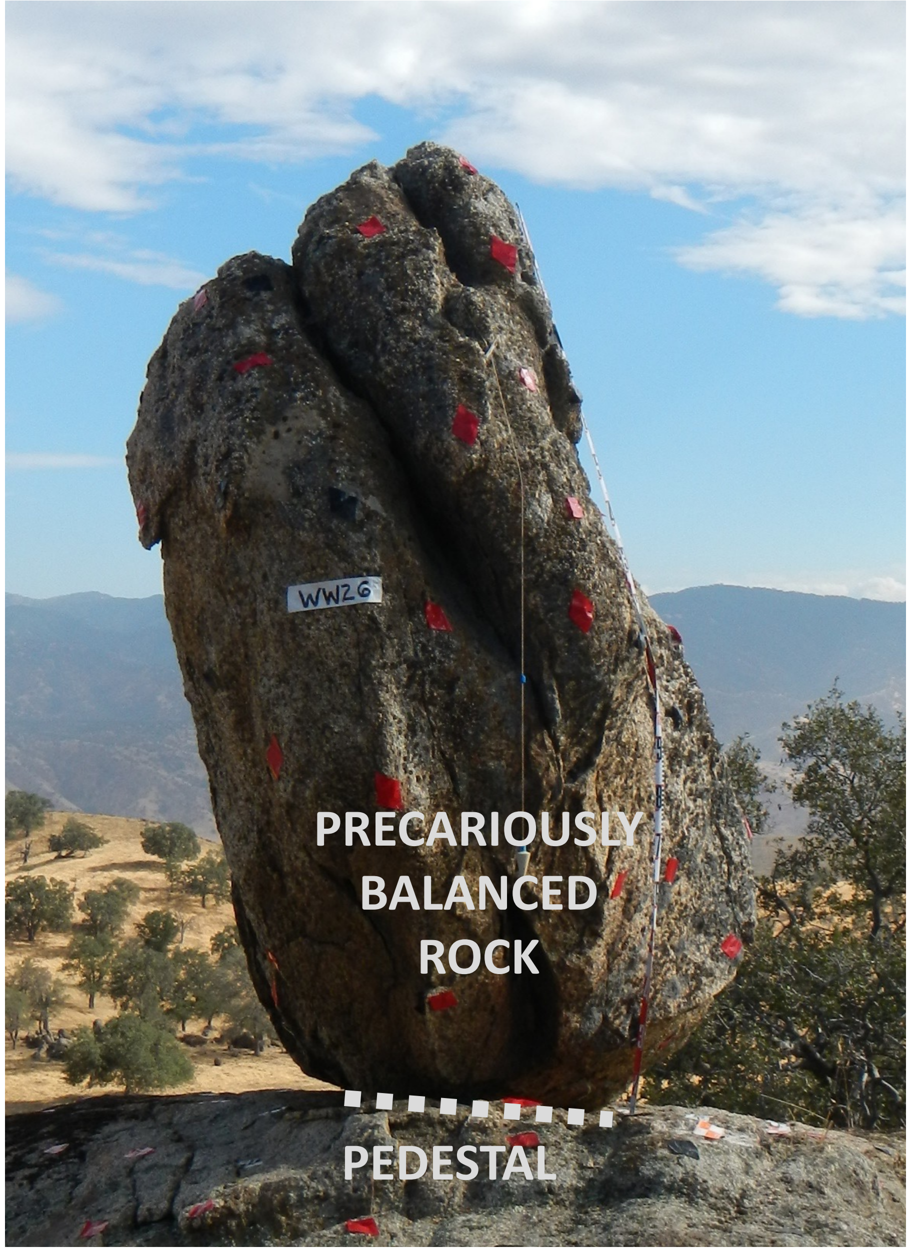
Fragile Geologic Features

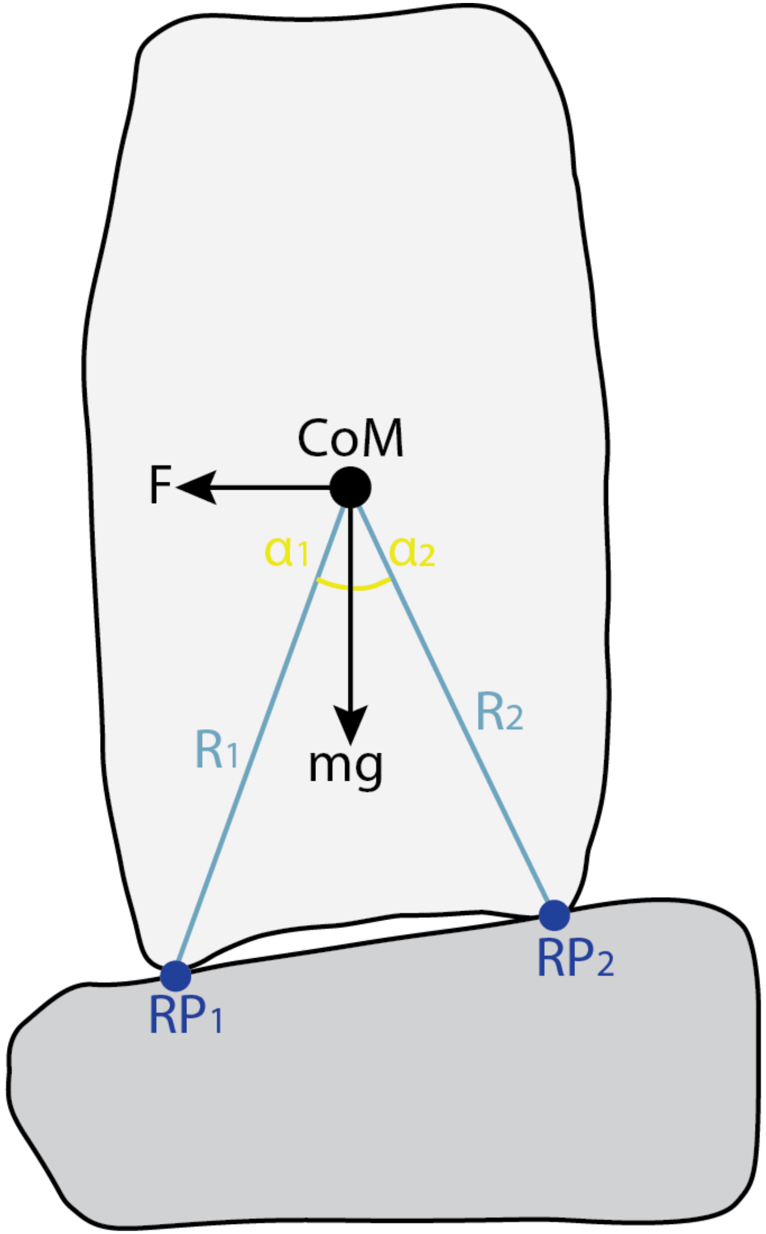


- How fragile is the feature?
- How old is the feature?

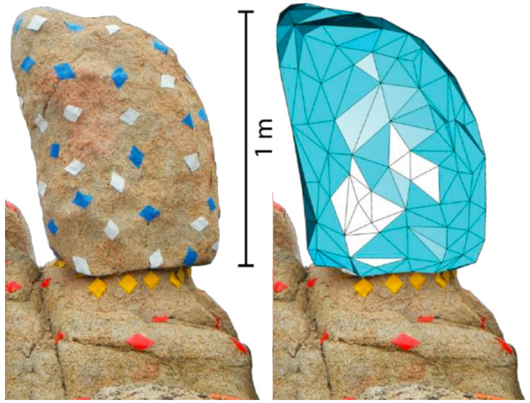
Which ground-motion estimates are consistent vs. inconsistent with the fragile geologic feature?

Precariously Balanced Rocks: Fragility

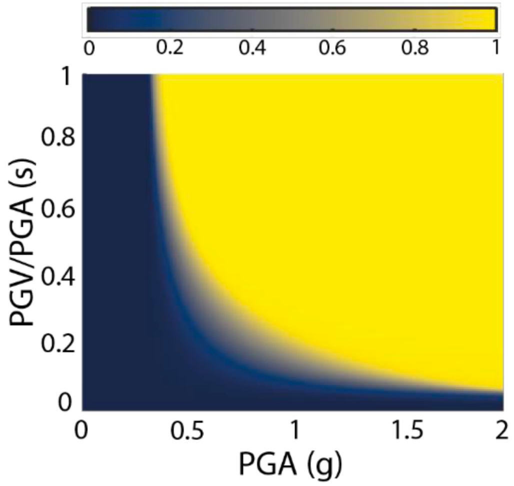




Precariously Balanced Rocks: Fragility

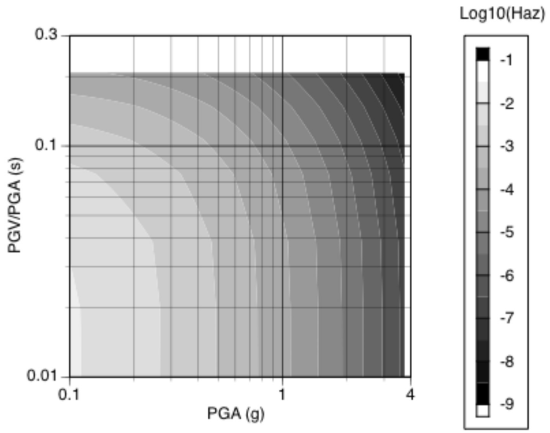


3D model & 2D geometry

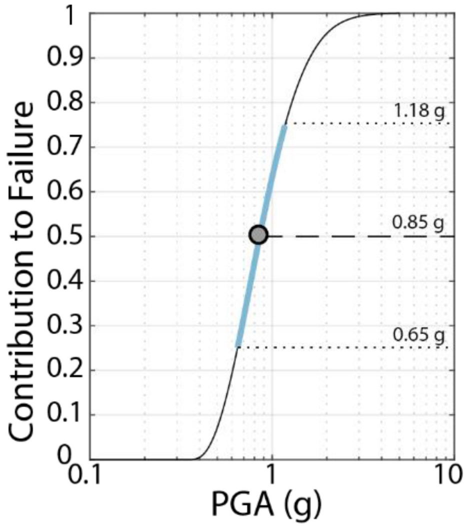


(Purvance et al. 2008)

PGA – PGV/PGA probability of toppling

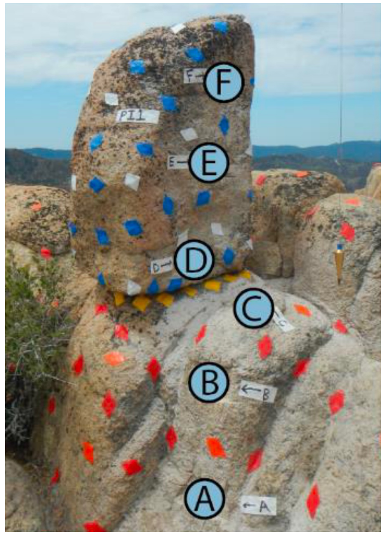


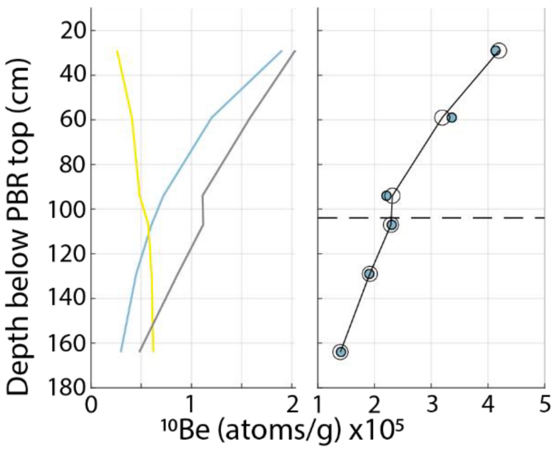
PGA – PGV/PGA rate of occurrence

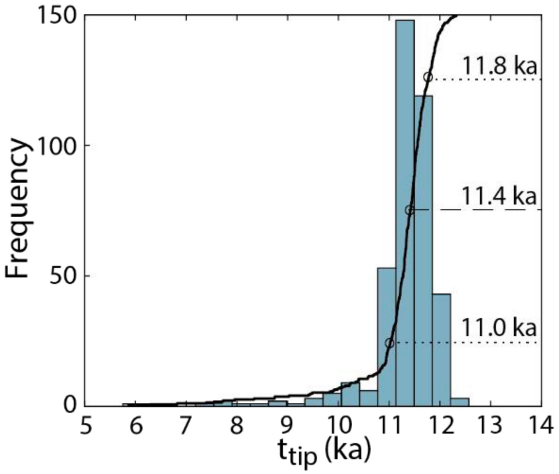


Fragility function

Precariously Balanced Rocks: Fragility Age







(Balco et al., 2011)

Samples for cosmogenic dating	Modelling of geomorphic history	Fragility age and uncertainty

Precariously Balanced Rocks: Hazard Validation

Fragility function

Hazard curve

$$\lambda_{Failure} = \int P\left(Failure|PGA = a;\ PBR_j\right) . \left|\frac{d\lambda_i(a)}{da}\right| da$$

$$P\left(PBR_{s,j}|\lambda_i\right) = e^{-\lambda_{Failure}.T}$$

Probability of survival

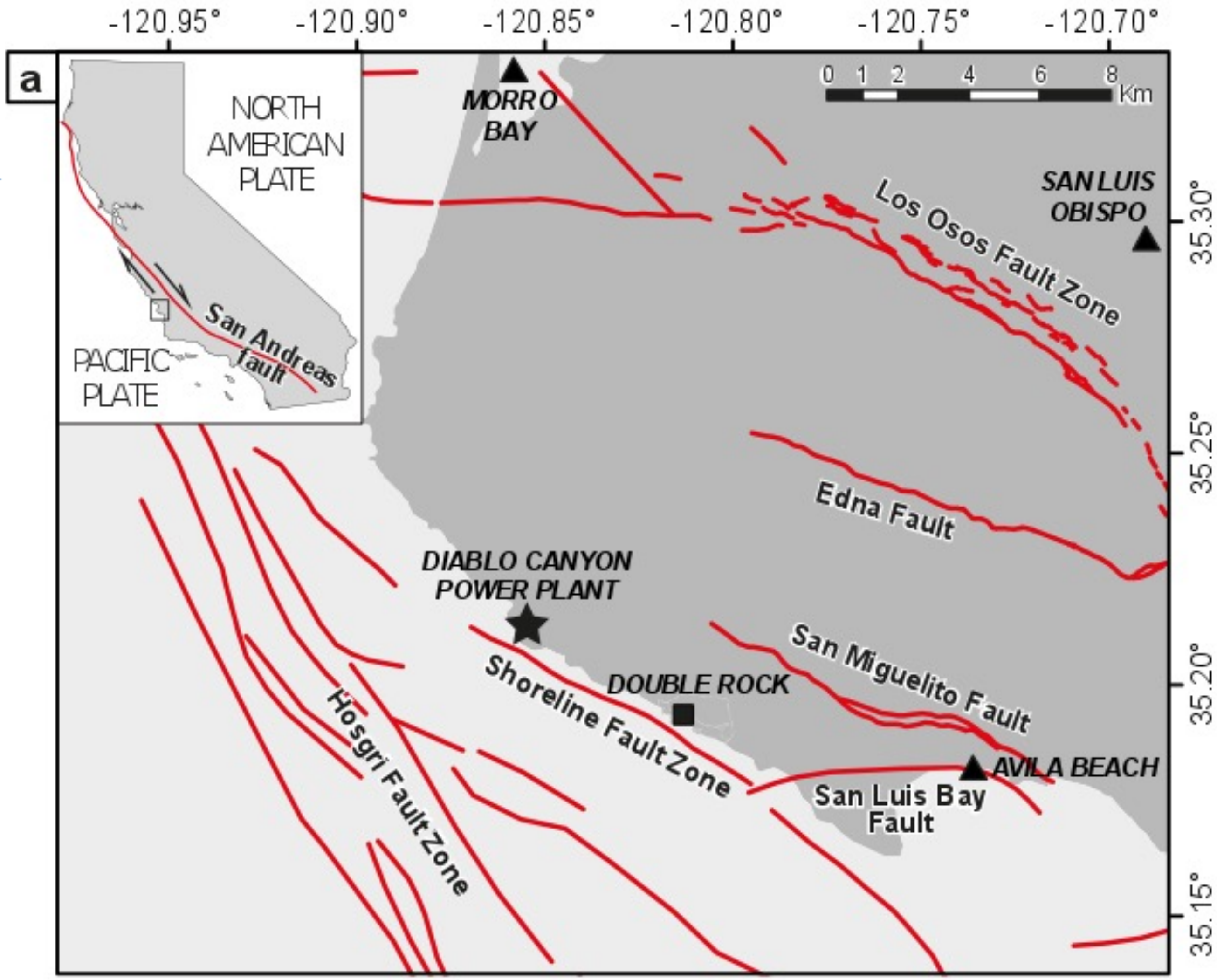
Fragility age

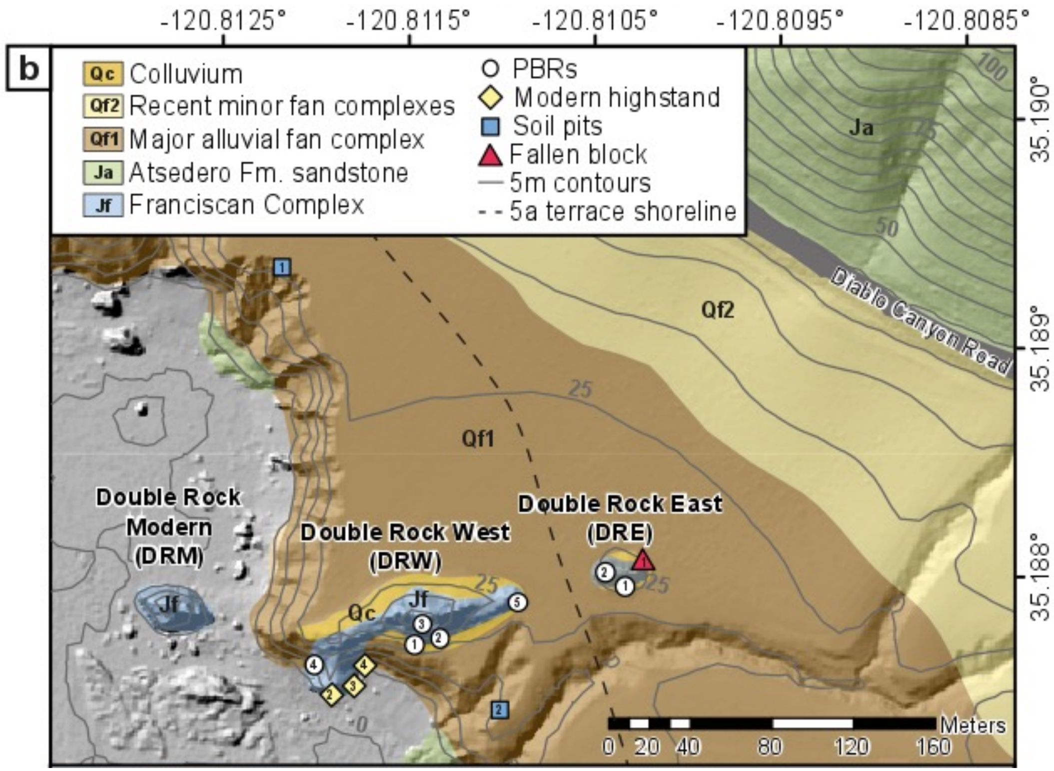
Case Study: The Diablo Canyon Nuclear Power Plant

AGU Advances

Earthquake Hazard Uncertainties Improved Using Precariously Balanced Rocks

A. H. Rood[1], D. H. Rood[2], M. W. Stirling[3], C. M. Madugo[4], N. A. Abrahamson[5], K. M. Wilcken[6], T. Gonzalez[7], A. Kottke[4], A. C. Whittaker[2], W. D. Page[4], and P. J. Stafford[1]





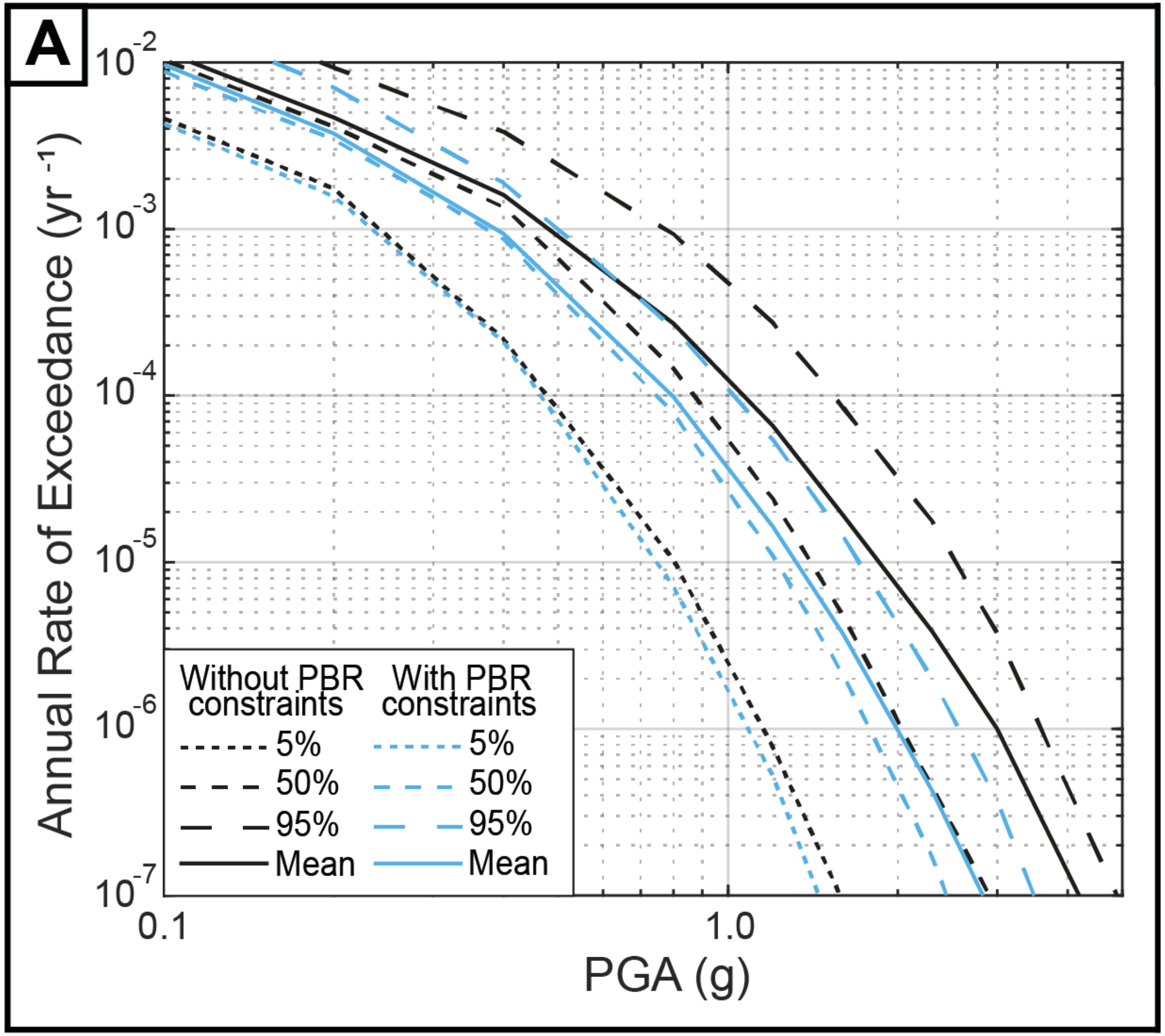
Case Study: The Diablo Canyon Nuclear Power Plant

Reject hazard curve from the model results if <5% probability of survival of the most fragile PBR.

At the hazard level of 10^{-4} yr^{-1} (10,000 yr mean return period):

Mean ground-motion estimate **reduced by 27%.**

Range of estimated 5th–95th fractile ground motions **reduced by 49%.**

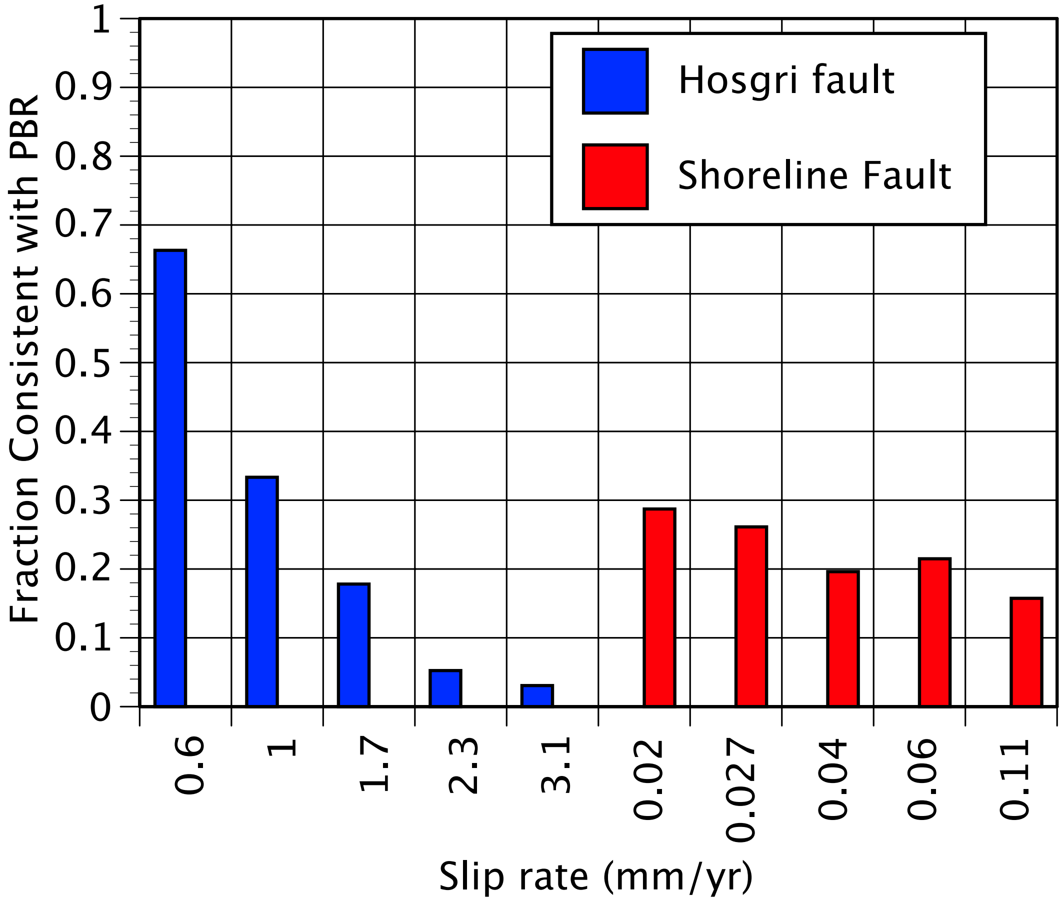


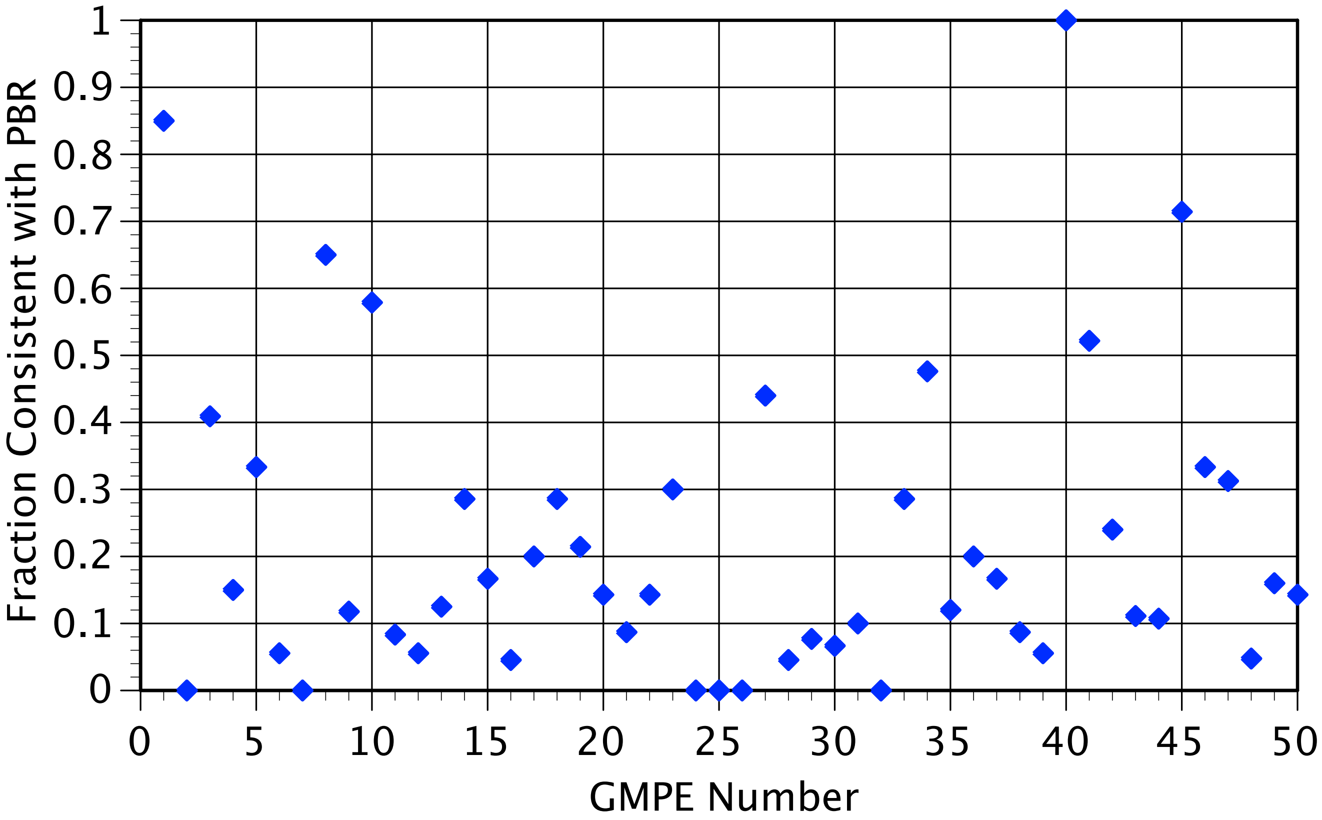
(Rood et al. 2020, AGU Advances)

Case Study: The Diablo Canyon Nuclear Power Plant

For each node in the logic tree, investigate the fraction of realizations that are consistent with the PBR for each branch at that node, i.e., number that pass / total number of sample for a given branch.

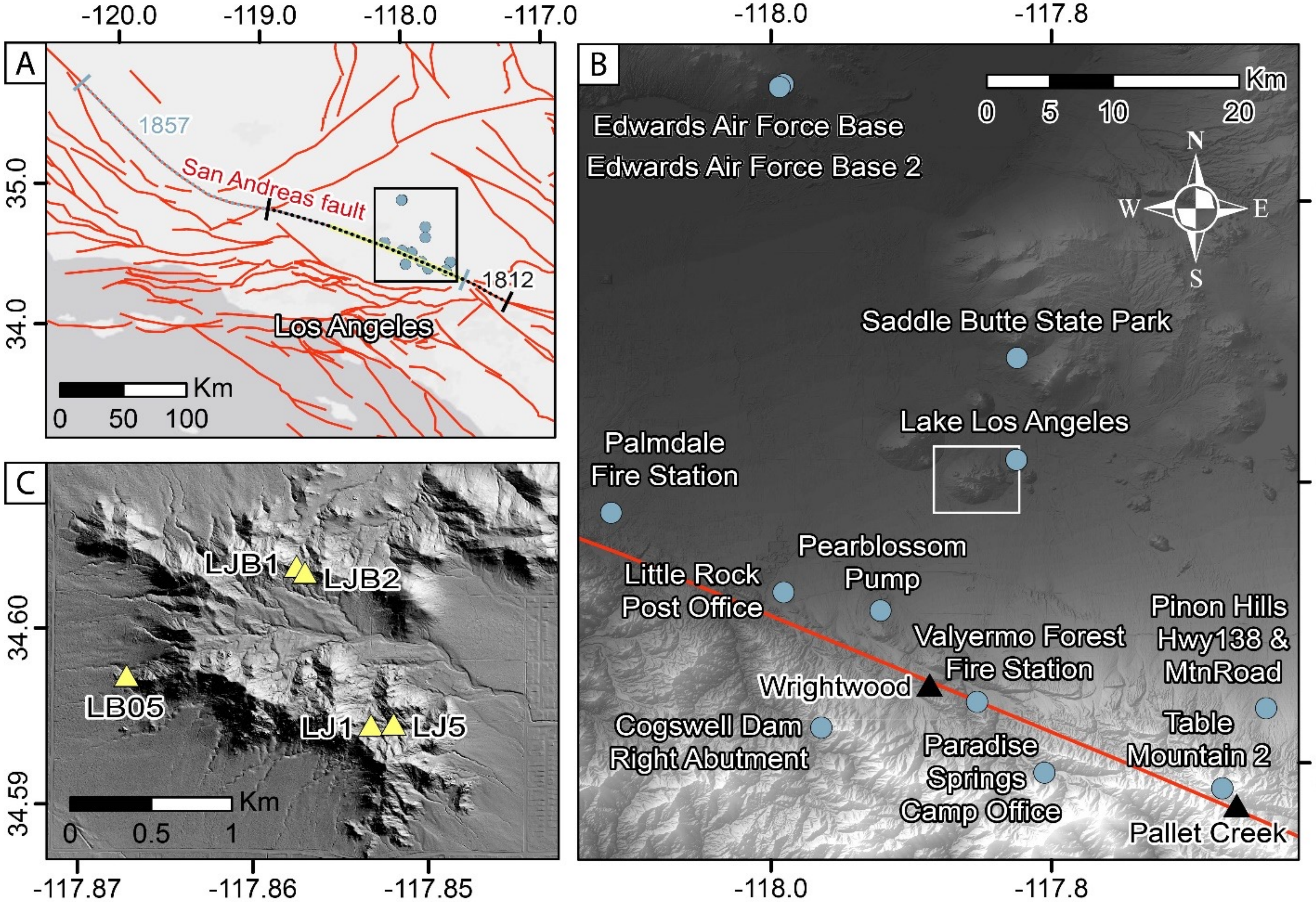
DRW1 PBR, 1% survival





(Courtesy of N. Abrahamson)

Case Study: Mojave Section of the San Andreas Fault



(Rood et al., 2024, SRL)

San Andreas Fault Earthquake Hazard Model Validation Using Probabilistic Analysis of Precariously Balanced Rocks and Bayesian Updating Seismological Research Letters

Anna H. Rood; Peter J. Stafford; Dylan H. Rood

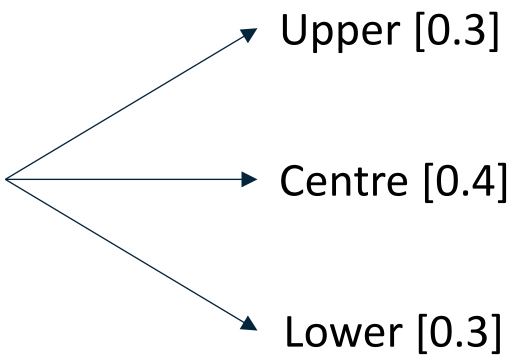
Case Study: Mojave Section of the San Andreas Fault

$$\prod_j P\left(PBR_{s,j} \middle| \lambda_i\right)$$

Joint probability of survival of all 5 PBRs

$$\frac{1}{n_t}\sum_k e^{-P_{Failure} \cdot t_k}$$

Full fragility age epistemic uncertainty



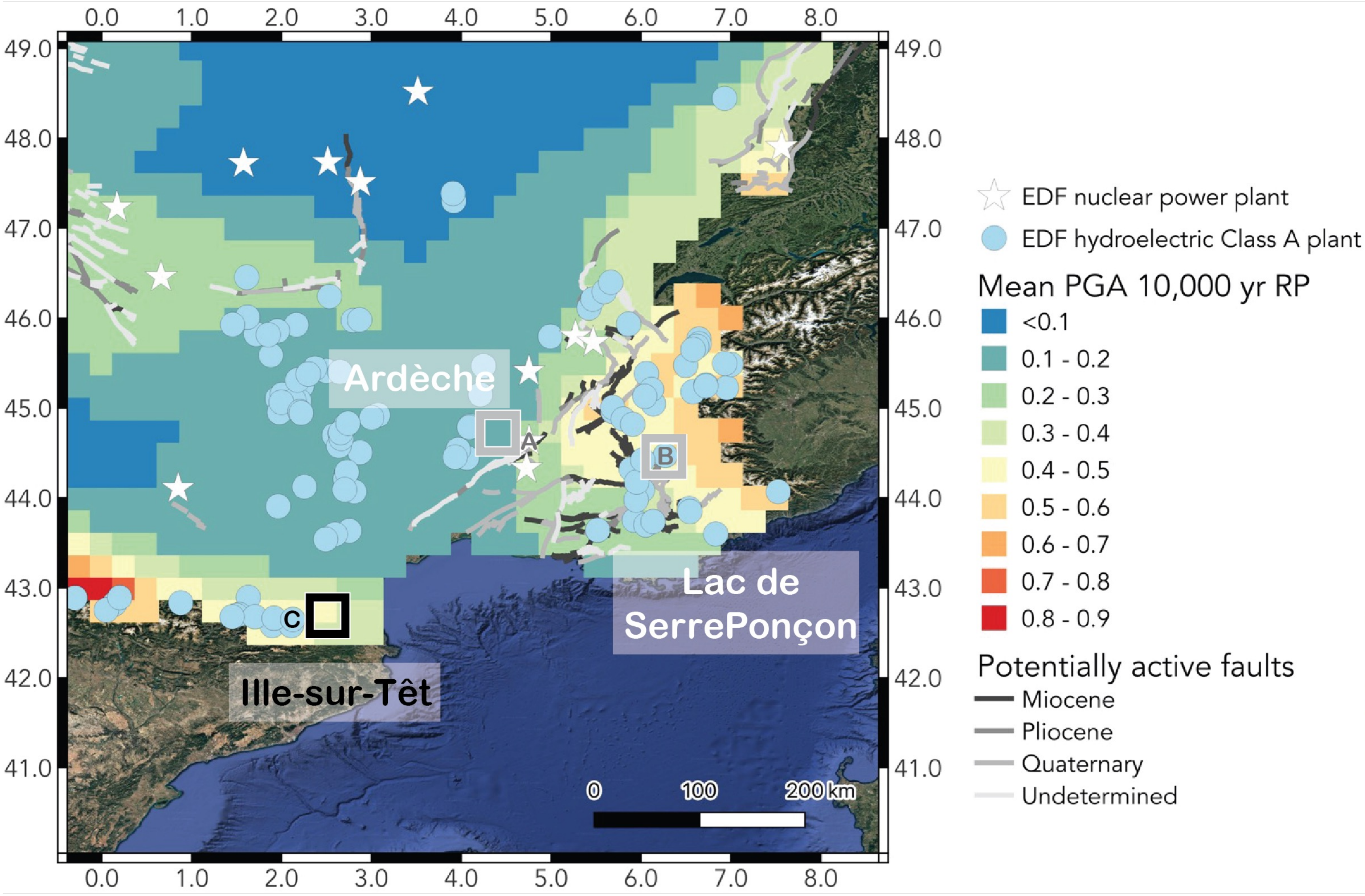
Fragility uncertainty 0.2/0.3 log units

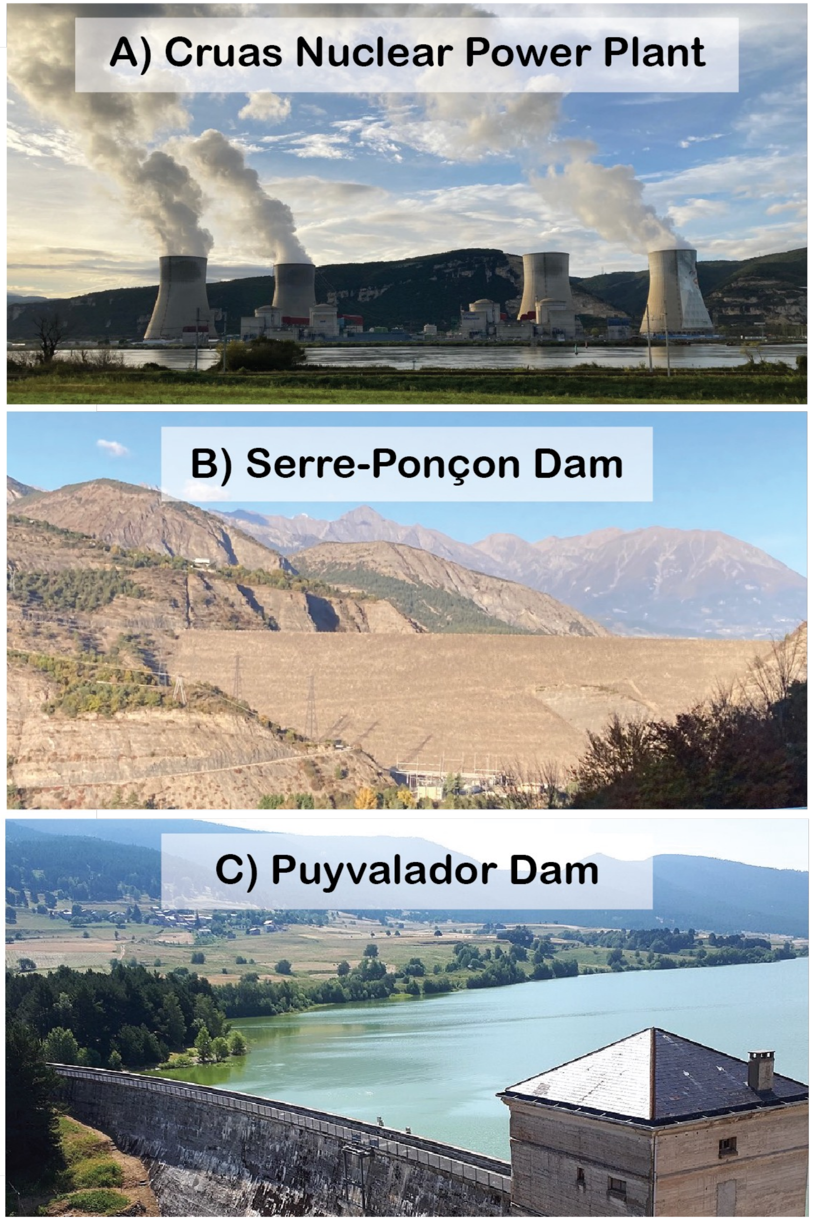
$$\frac{\left[\prod_j P\left(PBR_{s,j} \middle| \lambda_i\right) P(\lambda_i)\right]}{\sum_j\left[\prod_j P\left(PBR_{s,j} \middle| \lambda_i\right) P(\lambda_i)\right]}$$

Bayesian updating of logic tree end branch weights

(Rood et al., 2024, SRL)

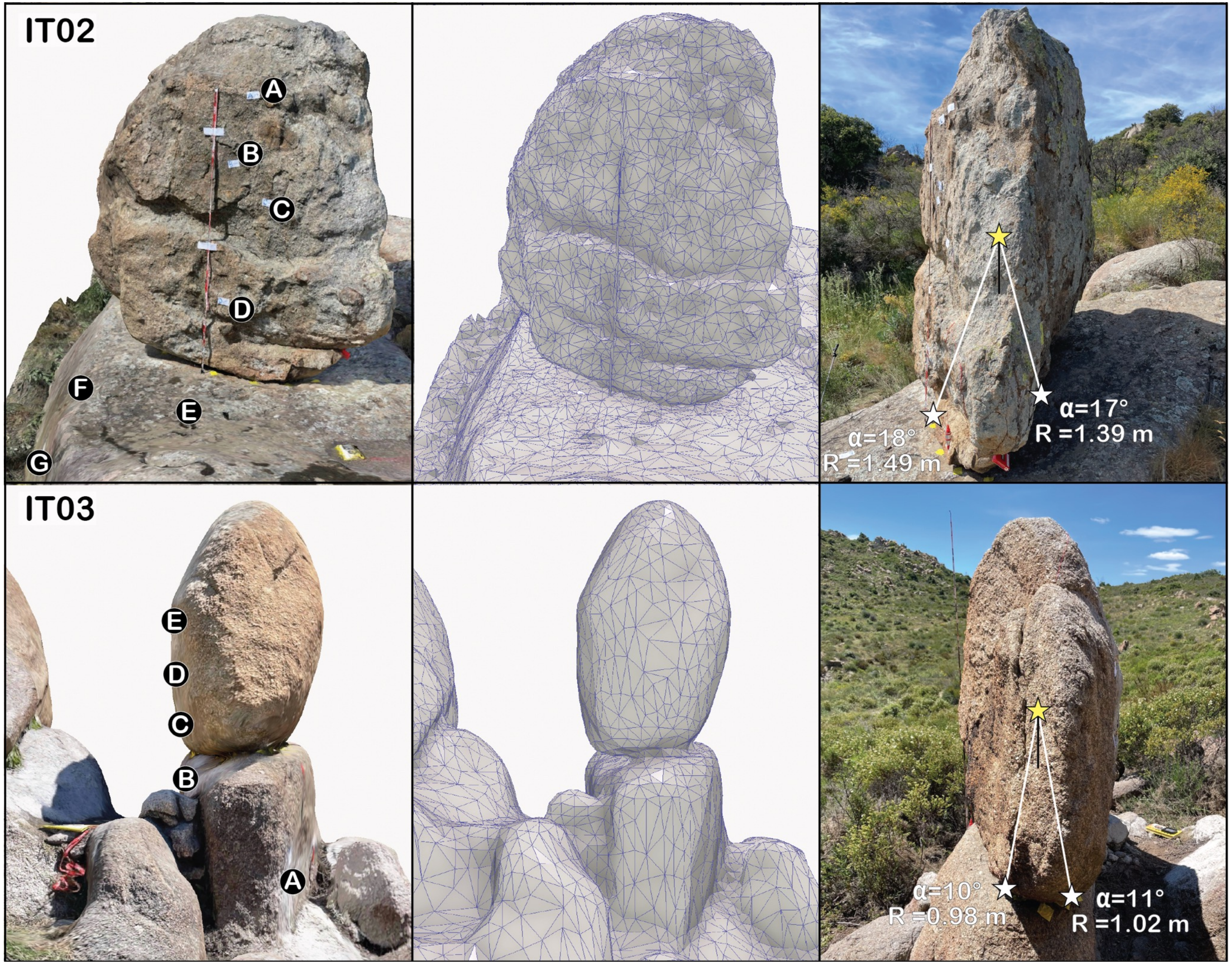
SIGMA 3: France



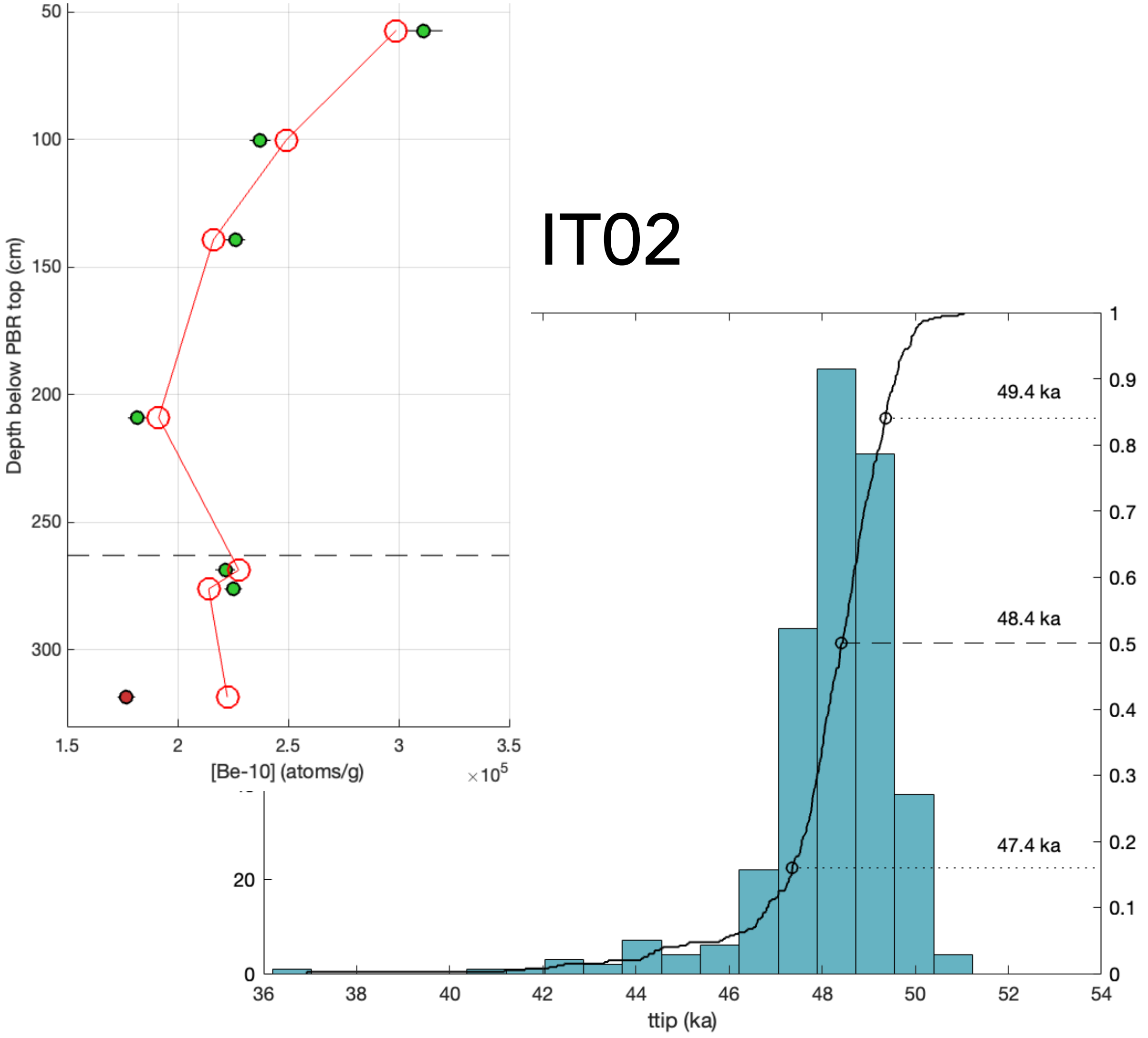


Weatherill et al. (2022) OpenQuake implementation of Drouet et al., (2020)

SIGMA 3: France PBRs

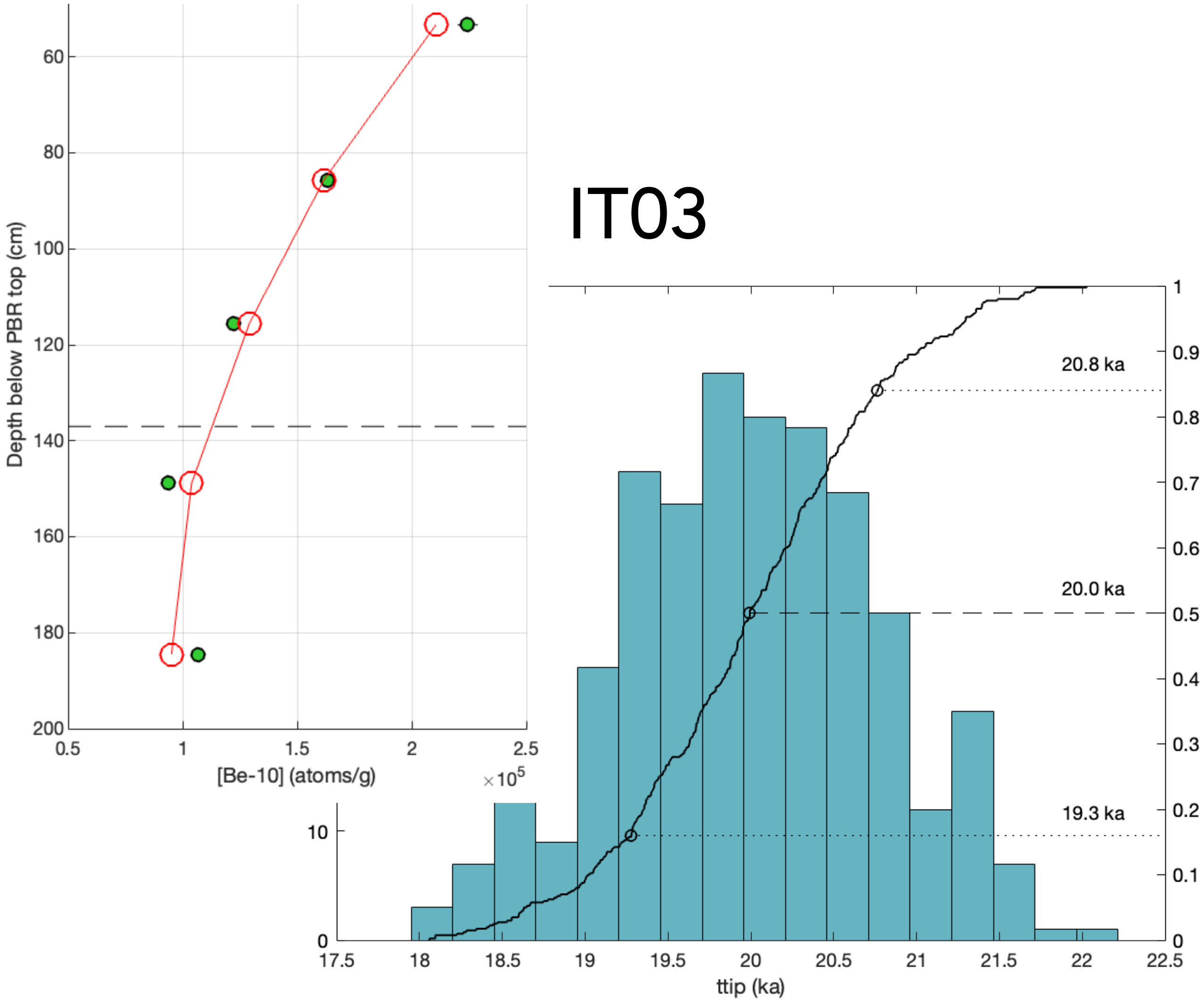


SIGMA 3: France PBR Fragility Age



48.4 ka

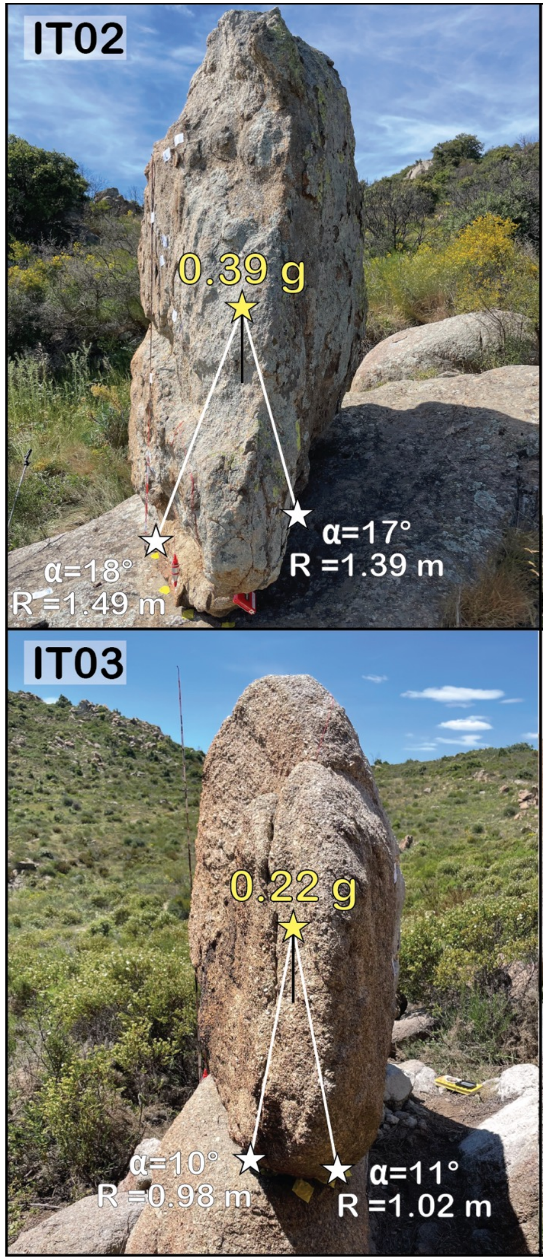
(47.4 – 49.4 ka 16 – 84th)



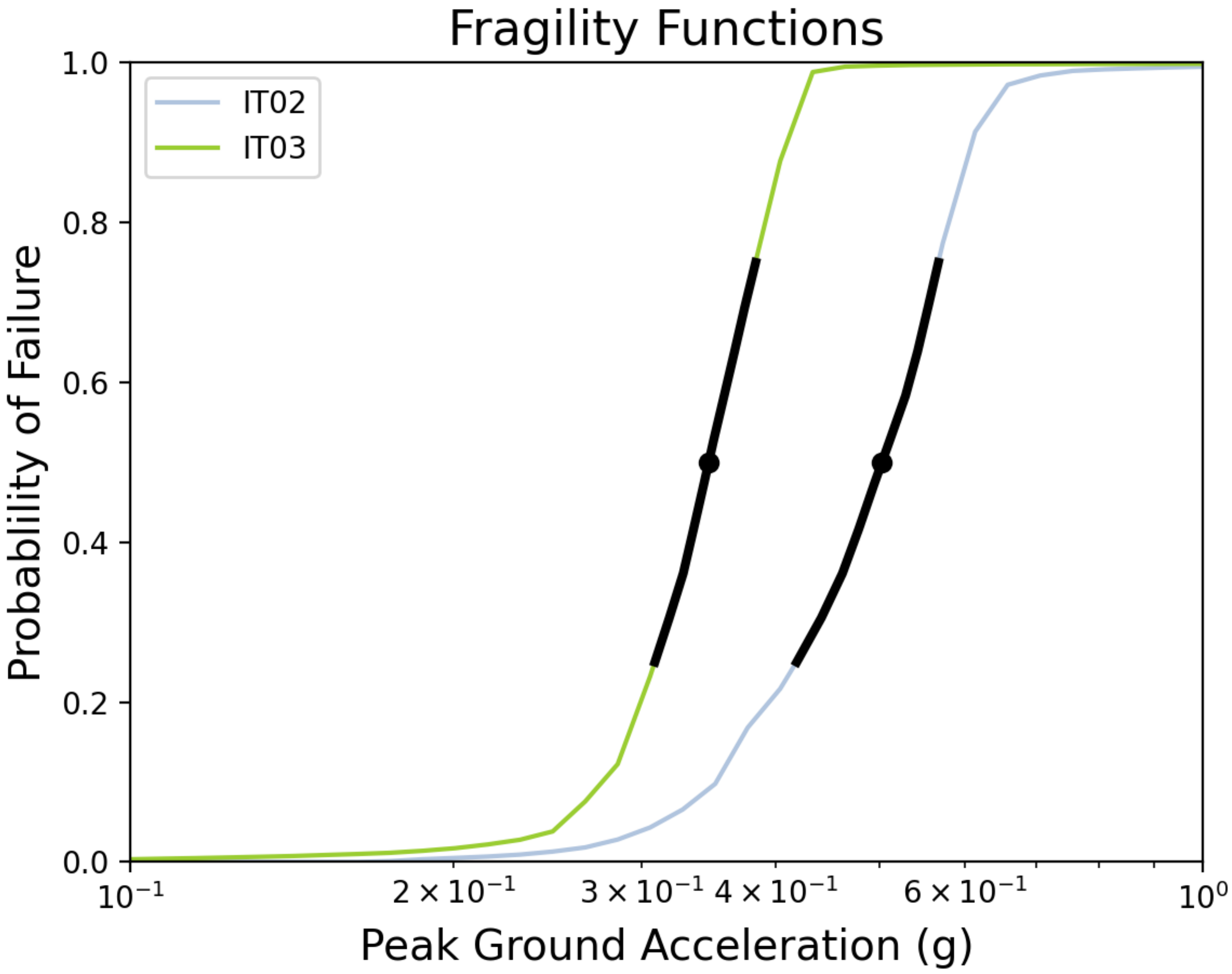
20.0 ka

(19.3 – 20.8 ka 16 – 84th)

SIGMA 3: France Fragility



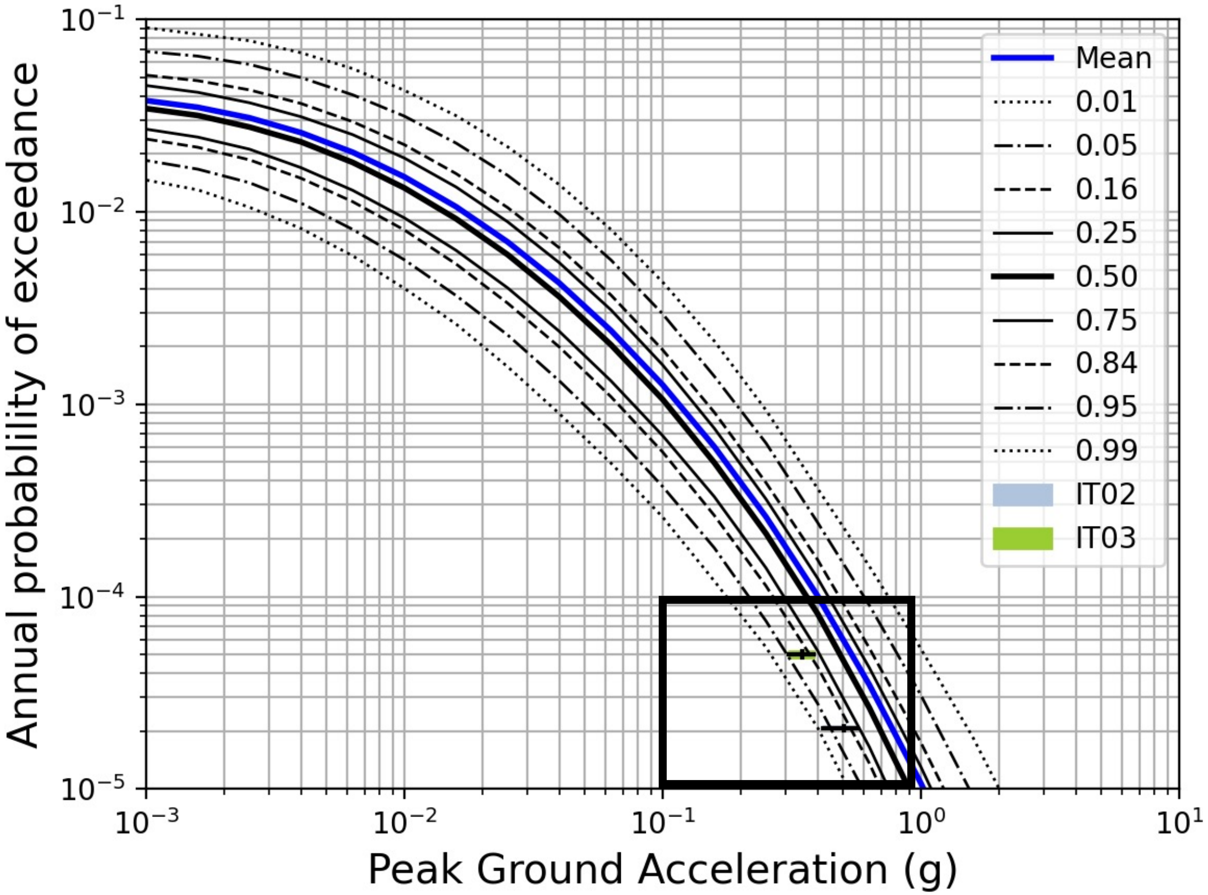
PRELIMINARY (Rood et al., 2023)



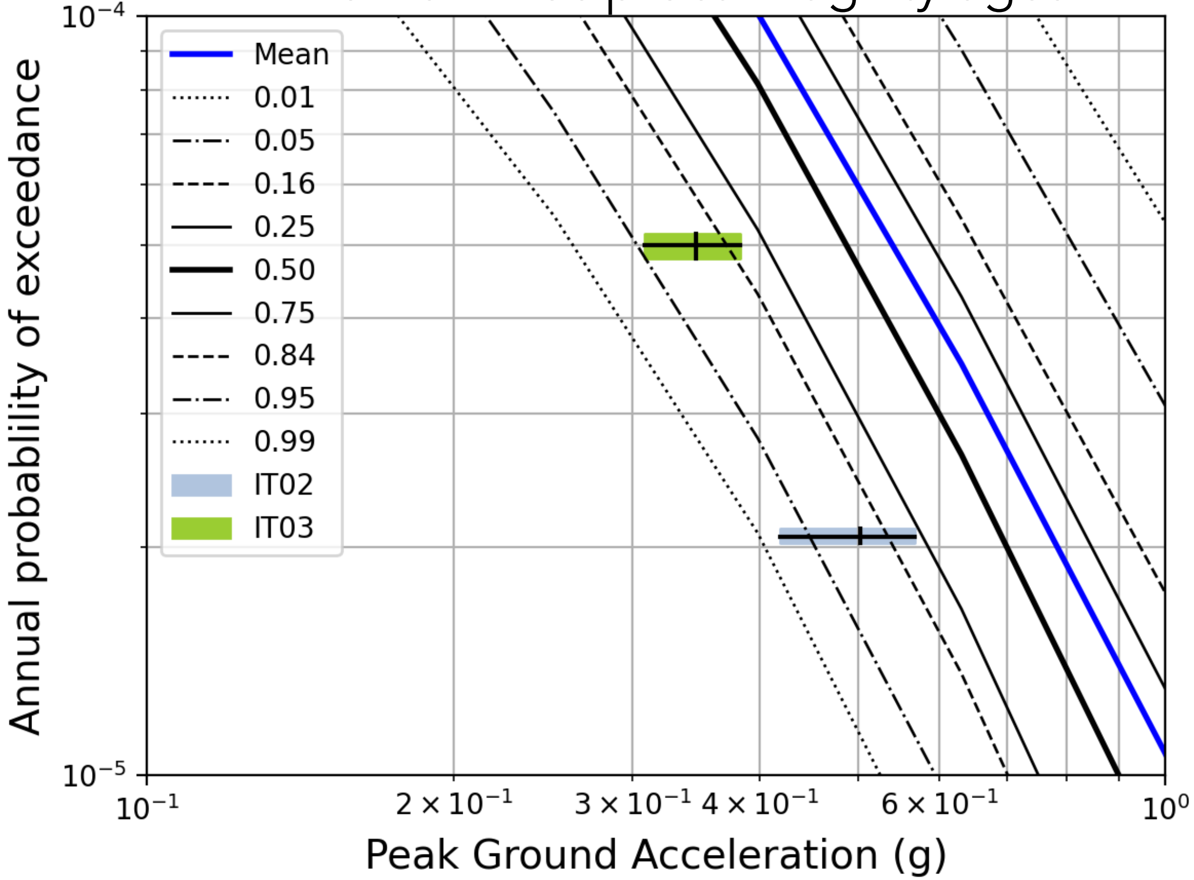
IT02
Median = 0.50 g

IT03
Median = 0.35 g

SIGMA 3: France Hazard Comparison



Features-in-hazard-space:
25th-75th ground motions
16th-84th reciprocal fragility ages



Features-in-hazard-space:
Hazard left of feature = consistent with observed survival
Hazard right of feature = inconsistent with observed survival

SIGMA 3: Future Work

- Full fragility methods of Rood et al., 2020.
- Finite element modelling of fragility.
- Sung et al. (2023) non-ergodic ground-motion model for France.
- Joint probability of survival of multiple features to validate each realization of the PSHA model logic tree to improve the hazard model (Rood et al., 2024).

Ardèche

- Basalt column precariously balanced rocks
- Carbonate speleothems
  - breaking fragilities
  - time-evolving fragilities

Fragile Geologic Features Hazard Model Validation Summary

- Fragile geologic features provide previously unavailable ground-motion constraints over the timescales of 1,000s -10,000s of years.
- Formation is not restricted to a single rock type, tectonic setting, geographic setting, climate, or formation process.
- Include uncertainty in both the fragility and fragility age of each feature.
- Individually validate each realization of the PSHA model logic tree.
- 2 studied PBRs in France are sufficiently old and fragile to provide useful constraints on hazard estimates.

Any Questions?

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