WP5 Simulation Platform

Overview of Earthquake Rupture Simulators and Their Uses for Seismic Hazard Assessment

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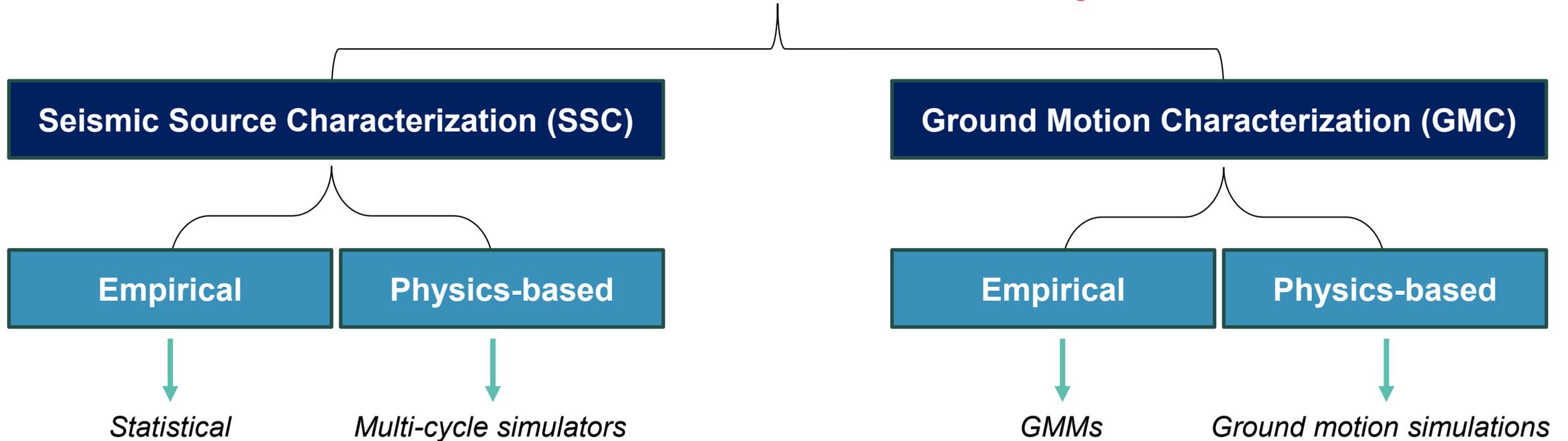
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What do we have?

Probabilistic Seismic Hazard Analysis

Seismic Source Characterization (SSC)	Ground Motion Characterization (GMC)

Empirical	Physics-based		Empirical	Physics-based

*Statistical* — *Multi-cycle simulators* — *GMMs* — *Ground motion simulations*

Field, 2024; Jordan et al., 2024; Gerstenberger et al., 2020

What do we have?

- **Paleoseismology** and **archaeoseismology** provide insights over thousands of years.
- **Historical** and **written records** extend back at most one to two millennia in certain regions.
- **Instrumental** catalogues span only about the past 100–150 years.

Are these enough?
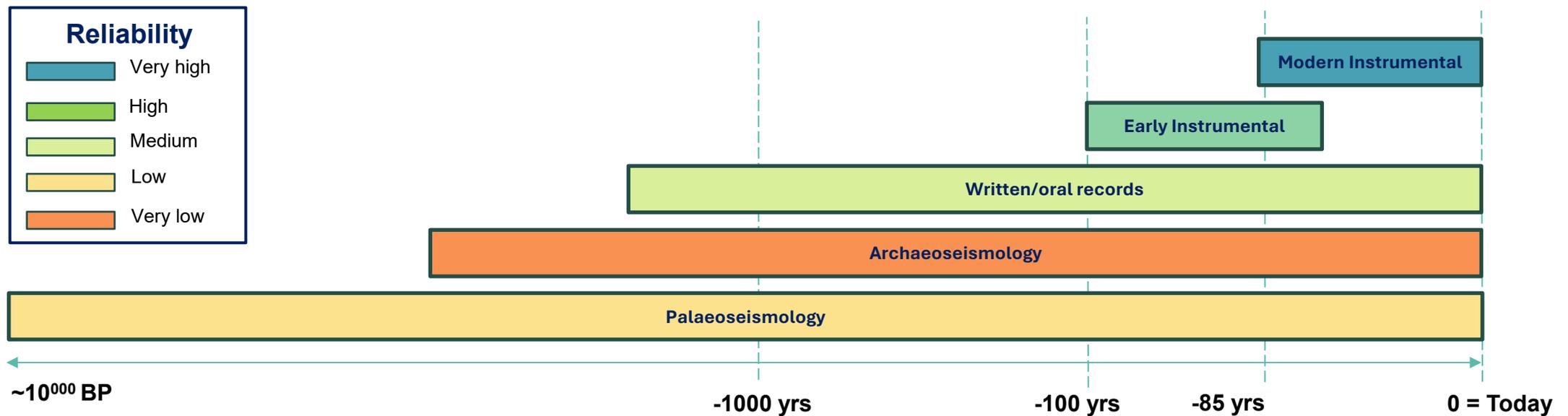
IAEA, 2015; Hinzen 2010; McCalpin, 2009
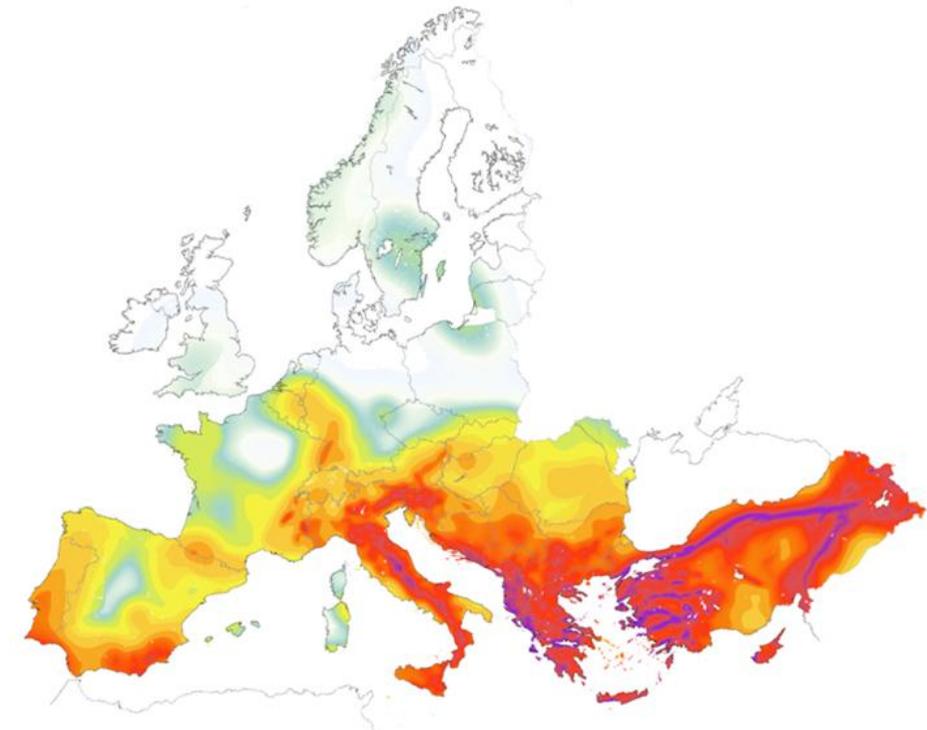
What do we have?

2020 European Seismic Hazard Model (ESHM20)
Danciu et al., 2021; 2024)

- Time-independent - Poisson model
- PGA, Sa(0.05 to 5s), 5% damping
- Hybrid source models

Return Periods (years)	APE (%)
50	1.98%
475	0.21%
975	0.10%
2475	0.04%
5000	0.02%

	(1) Historical: EPICA v1.1	(2) Instrumental: EMEC v20190218	(1)+(2): Unified ESHM20	Compare Unified ESHM13
Time span	1000/1899	1900/31-12-2014	1000/31-12-2014	1000/31-12-2006
Magnitude span	1.9/8.5	3.49/8.3	1.7/8.5	1.7/8.5
Longitude span	-23.5°/32.4°	-37.0°/51.9°	-37.0°/51.9°	-31.65°/45.0°
Latitude span	35.0°/69.4°	26.9°/73.0°	26.9°/73.0°	33.2°/73.32°
# Total Number	5703	55411	61127	30012
# magnitude ≥ 4.5	2337	20388	22728	13284
# magnitude ≥ 5.0	1550	6013	7565	5585
# magnitude ≥ 5.5	885	1920	2805	2066
# NaN depth	4965	9451	14422	10616
# NaN magnitudes	282	0	282	303
# depth < 40km	5355	49436	54791	25666

PGA – Hybrid Shallow Faults and Background Seismicity

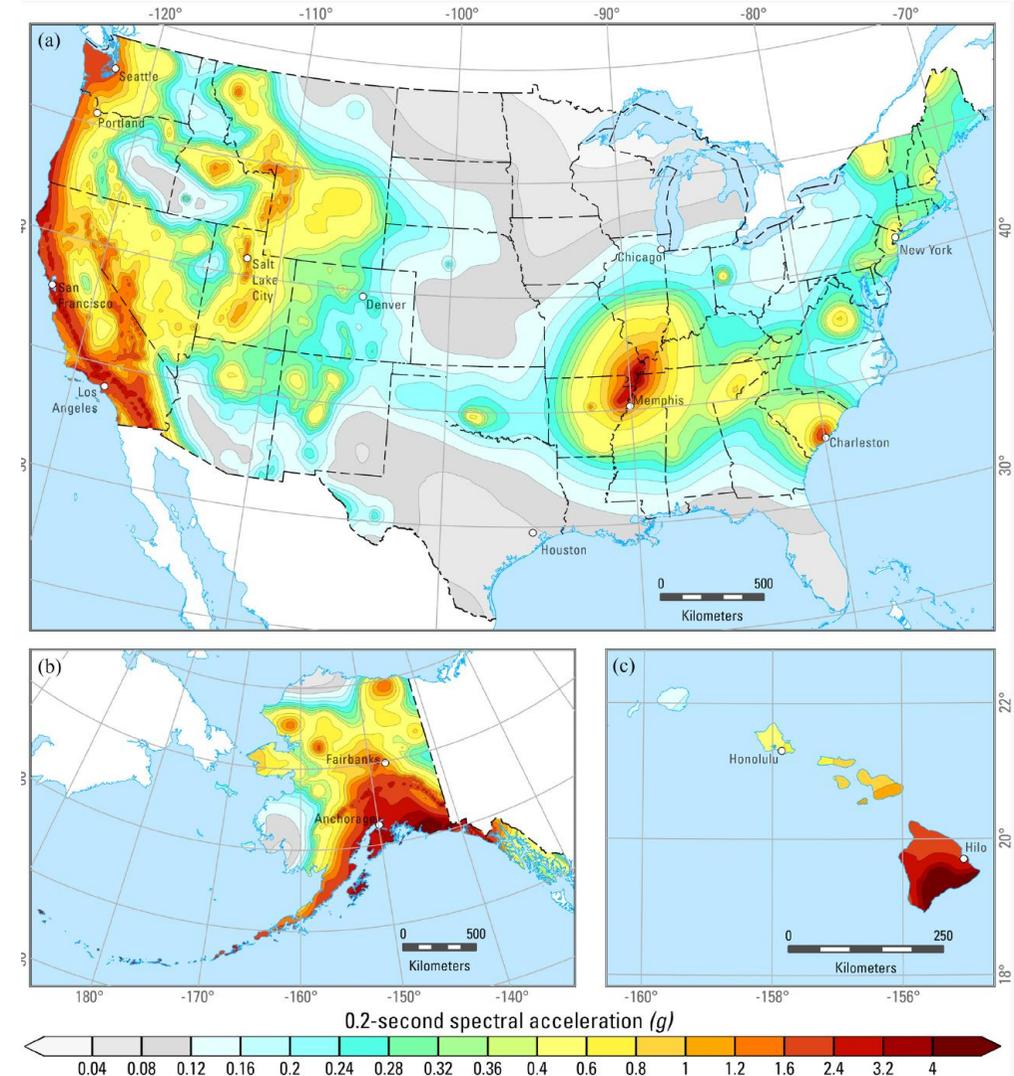# What do we have?

2023 US National Seismic Hazard Model
Petersen et al., 2024; Field et al., 2024)

- Time-independent - Poisson model
- PGA, PGV, MMI, Sa, PoE=2% and 10% in 50 years
- Hybrid source models

<u>**Catalogues**</u>:
CEUS: *since* <u>**1568**</u> *(26,145 events with M1-7.5)*
WUS: *since* <u>**1700**</u> *(60,214 events with M3-9)*

0.2-second spectral acceleration *(g)*

| 0.04 | 0.08 | 0.12 | 0.16 | 0.2 | 0.24 | 0.28 | 0.32 | 0.36 | 0.4 | 0.6 | 0.8 | 1 | 1.2 | 1.6 | 2.4 | 3.2 | 4 |

What do we have?

PSHA studies have come a long way from the past (Cornell, 1960,1968; Esteva, 1966) to the present.

But …

We **lack sufficient earthquake data**, particularly in regions with **low to moderate** seismicity, such as France.	**Time span of earthquake catalogues is too short to capture the full variability** of earthquake recurrence, rupture complexity, and clustering behavior.	**Time-dependent models** require detailed rupture histories and fault-specific parameters which are unavailable or highly uncertain for most faults, making them less reliable for hazard studies.	Even if models have become more **advanced**, their underlying **assumptions** and **data limitations** remain.

Our goal is to make our model **more precise** in describing the earthquake process while also **reducing epistemic uncertainty**.
How could we achieve this?

Rupture Simulation Approaches

We categorized the existing simulation approaches for generating long-term synthetic earthquake catalogues in PSHA into three overarching groups: **statistical**, **hybrid**, and **physics-based** frameworks.

Statistical	**Hybrid**	**Physics-based**
Follows **statistical principles**	Follows **kinematic modelling of rupture process**	Follows **physical laws and rupture dynamics**
Based on: • *MFDs* • *recurrence rates* • *probability laws*	**Based on:** • Slip duration • Rupture velocity • Direction • Predefined empirical rules	**Based on:** • Stress accumulation, slip • Fault interactions • Rupture dynamics • Friction laws
e.g., *Monte-Carlo*	**e.g.,** SKIES	**e.g.,** MCQsim, RSQSim

STATISTICAL APPROACHES

Monte-Carlo Simulation
(Musson, 1999)

France model
(…in publication process)

- Generates **thousands of years of earthquake ruptures**

- Enables sampling **many possible earthquake sequences** consistent with fault parameters to estimate **hazard** and understand **variability in rupture occurrence** over geological timescales.

- Employed in **global** *(Silva et al., 2020)* and **regional** *(Mistry and Lombardi, 2023; Crowley and Bommer, 2006)* seismic risk analyses.

Statistical Simulation of Rupture Sequences

Pros

- **Simple** but **computationally** efficient
- **Works well with limited data**, relying on observed seismicity, MFDs..

Cons

- Stochastic simulations **do not reproduce the real earthquake sequence**; they statistically emulate its long-term characteristics. Therefore, long sequences are **required** for it (This is general to approaches based on simulation catalogues of ruptures), particularly if hazard at long return periods is required (i.e., we need a sufficient sampling of large events). NOTE: In PSHA, we compute the mean rate (or probability of exceedance).
- **Transients of seismicity** (e.g., foreshocks and aftershocks can be added a posteriori) to a stochastic event set of mainshocks
- In some models, **grid-dependent** stochastic ruptures might constrain the randomization of seismicity.
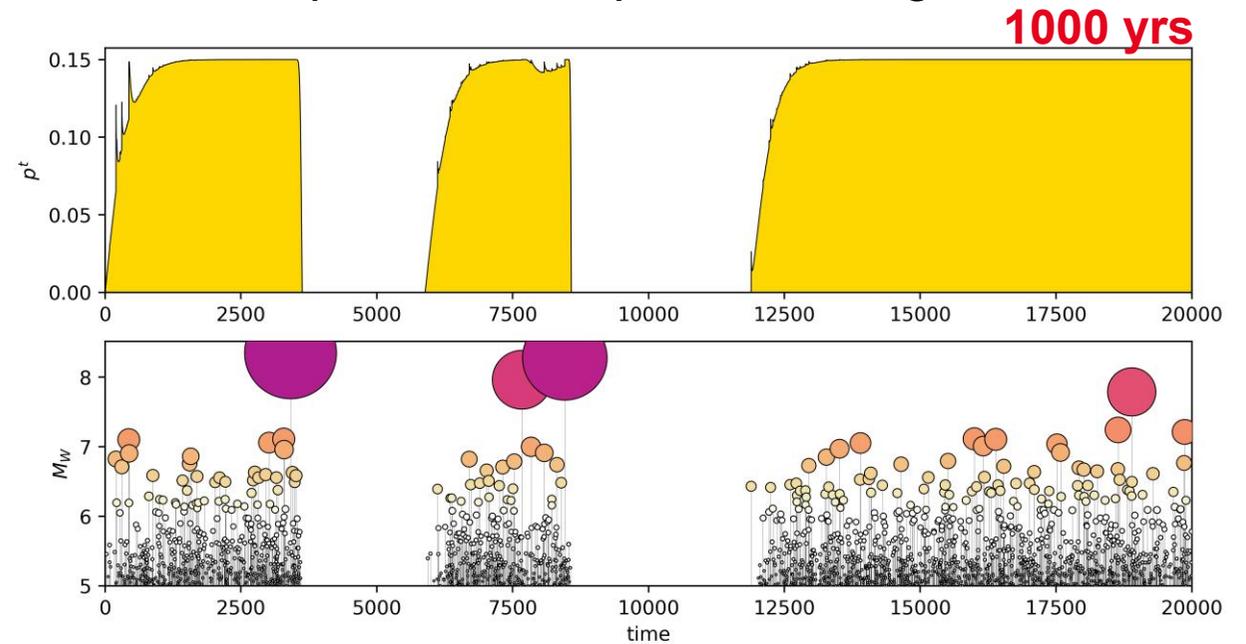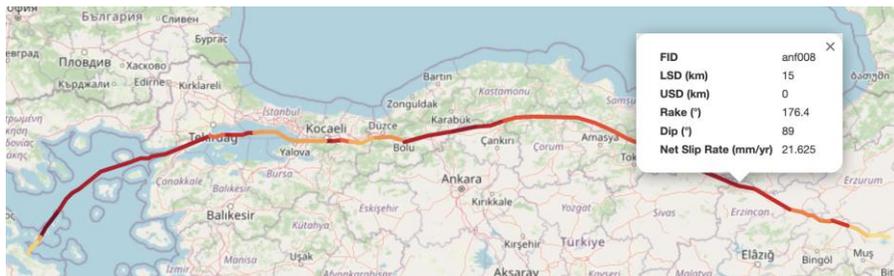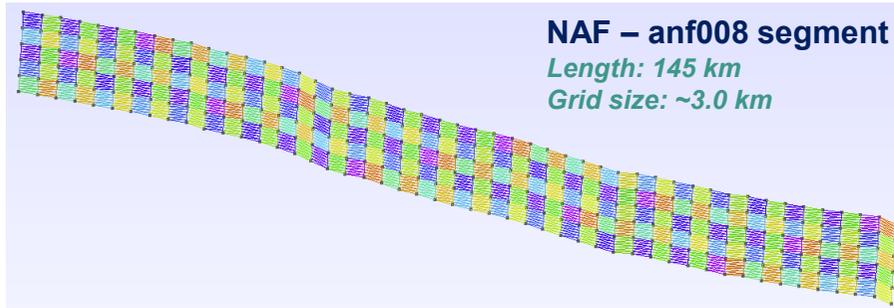
KINEMATIC APPROACHES

Hybrid (Kinematic + Stochastic)

SKIES - Stochastic Kinematically Informed Earthquake Sequences *(Meade, 2024)*

$$m_i(t) = \int_{t_0}^{t} v_i a_i v_i^{sd}(t')dt' - \sum_{j}^{N_{eq}(t_j \leq t)} a_i s_{i,j}(t_j)$$

- The model **probabilistically generates earthquakes** when enough moment builds up.
- Earthquake **timing** includes **short-term clustering** (aftershocks) via an **Omori-style decay.**
- Slip distribution is **spatially variable** and stochastic but respects the empirical scaling laws.

NAF – anf008 segment
Length: 145 km
Grid size: ~3.0 km

FID	anf008
LSD (km)	15
USD (km)	0
Rake (°)	176.4
Dip (°)	89
Net Slip Rate (mm/yr)	21.625

1000 yrs

Hybrid (Kinematic + Stochastic) Simulation of Rupture Sequences

Pros

- Combines physical constraints with statistical flexibility
- Still **computationally efficient**

Cons

- **Limited by the simplicity of kinematic assumption(e.g.,** no stress evolution, no true earthquake cycles, no dynamic triggering)
- Ruptures still contain **randomness**
- **Limited use** so far (only a few papers in international scientific literature discuss this approach)
- Does **not cover diffuse seismicity** → cannot be used as-is for simulating earthquake occurrence in low- to moderate-seismicity areas
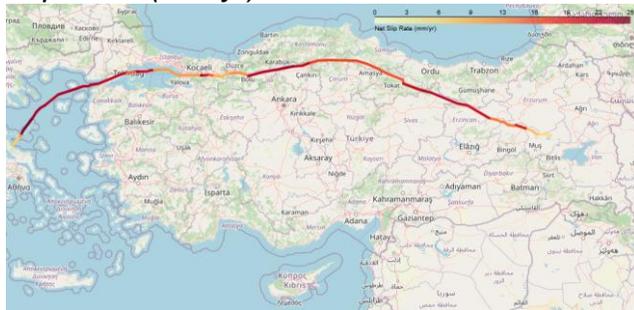
DYNAMIC (PHYSICS-BASED) APPROACHES

In a nutshell ..

- Primary inputs are **fault geometry** and **slip rate.**
- Physical processes are introduced through friction laws, stress transfer, and nucleation criteria.
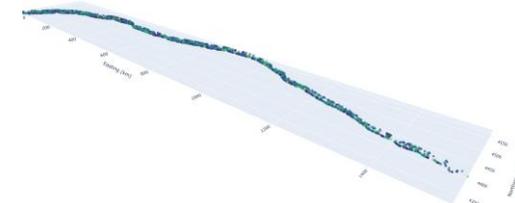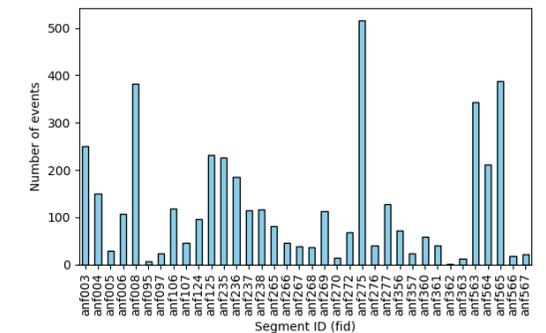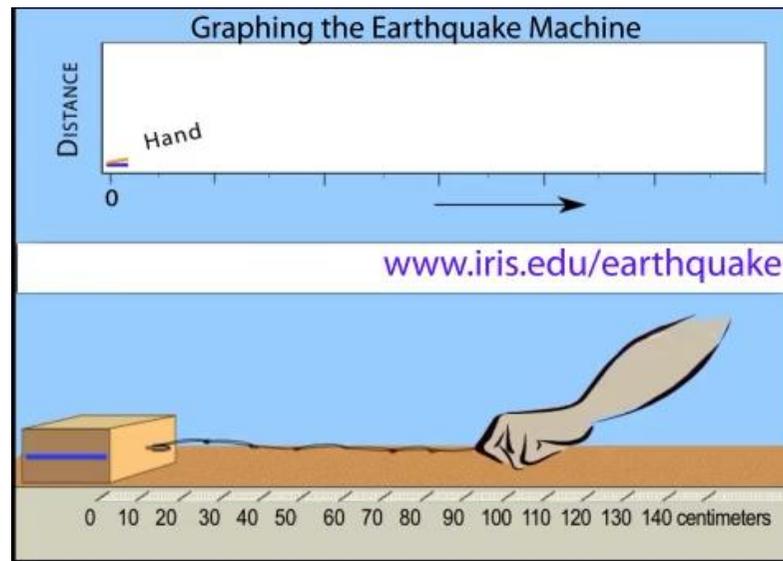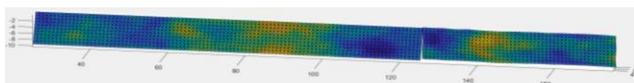- Output is a **long-term synthetic earthquake catalogue.**

Fault system (geometry)
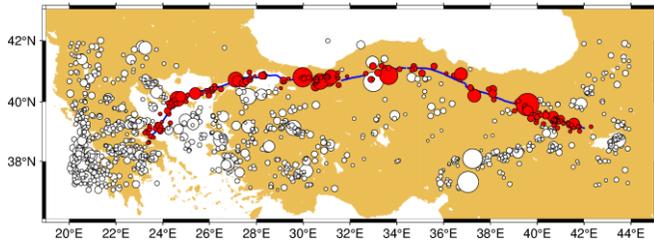
Slip rates (mm/yr)

Example of roughness distribution

Physics-based Simulation of Rupture Sequences

How much physics do we want to include, and what is our **goal** and **capacity**? …

Quasi- static/dynamic (hybrid)

- **Quasi-static** loading <u>during the interseismic period</u>
- **Quasi-dynamic** rupture propagation <u>during earthquakes</u>

- **Instantaneous stress equilibrium** between events

- Neglecting **inertial effects** except during rupture

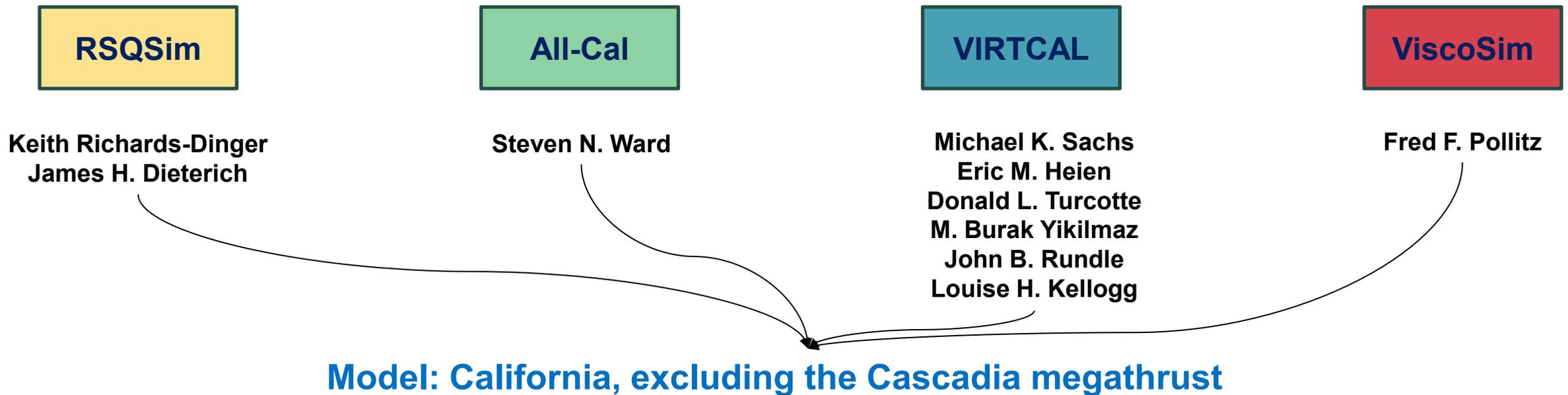- Appropriate for **long-term fault system evaluation**

Quasi-dynamic

- Solves **quasi-dynamic approximation** continuously

- including radiation damping to approximate inertial effects.

- Capture more realistic **rupture propagation and stress transfer dynamics**

- Appropriate for **single-fault** or **simplified fault system** studies

Physics-based Simulation of Rupture Sequences

What happened in 2012 (SRL 83/6)?

The Southern California Earthquake Center (SCEC) Earthquake Simulator Comparison Project

RSQSim	All-Cal	VIRTCAL	ViscoSim

Keith Richards-Dinger
James H. Dieterich

Steven N. Ward

Michael K. Sachs
Eric M. Heien
Donald L. Turcotte
M. Burak Yikilmaz
John B. Rundle
Louise H. Kellogg

Fred F. Pollitz

Model: California, excluding the Cascadia megathrust

Physics-based Simulation of Rupture Sequences

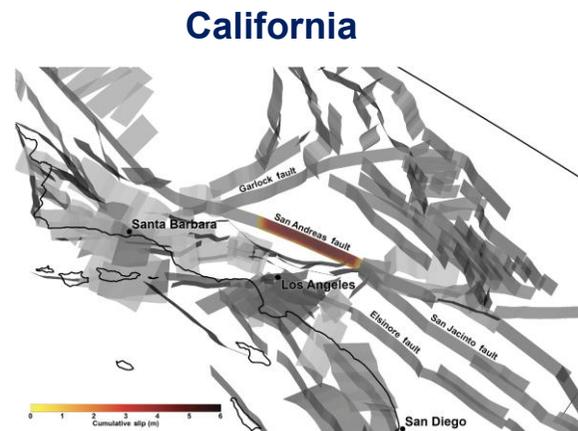## RSQSim – Earthquake simulator

Richards-Dinger and Dieterich, 2012

- RSQSim results **fit observed seismicity** in California marginally better than the other simulators *(Tullis et al., 2012)*.

- The only simulator that displays the occurrence of time-dependent increases in the conditional likelihood of neighboring earthquakes after a major earthquake and aftershocks is RSQsim *(Tullis et al., 2012)*.
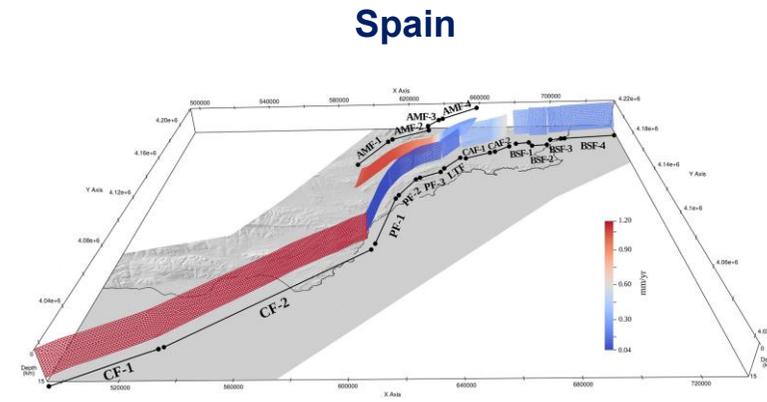
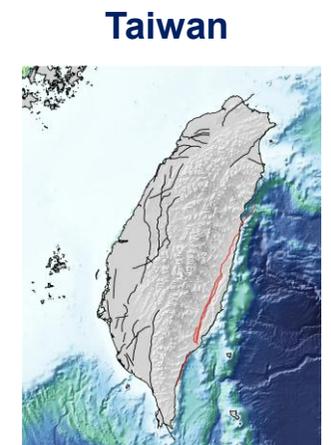Consequently. RSQSim has emerged as the **most widely utilized** physics-based simulator.

New Zealand

(Shaw et al., 2022)

California

(Milner et al., 2021)

Spain
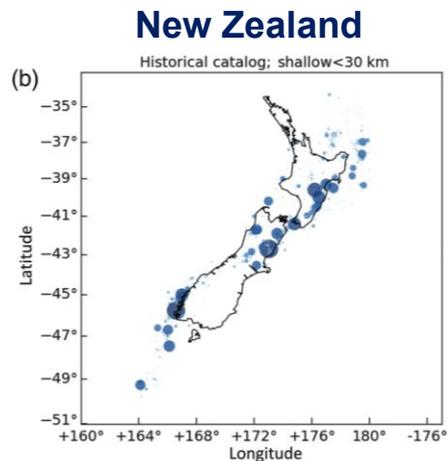
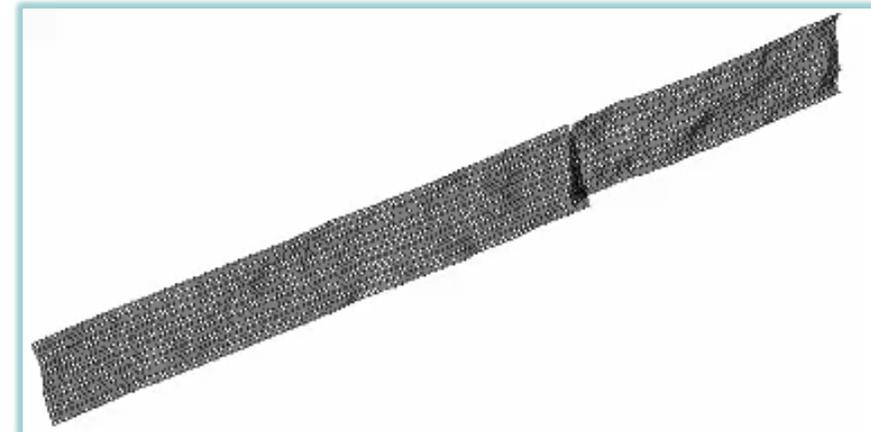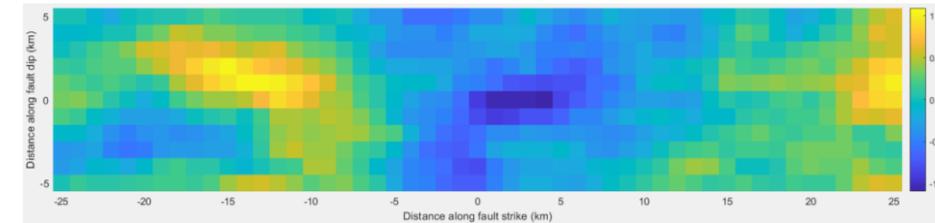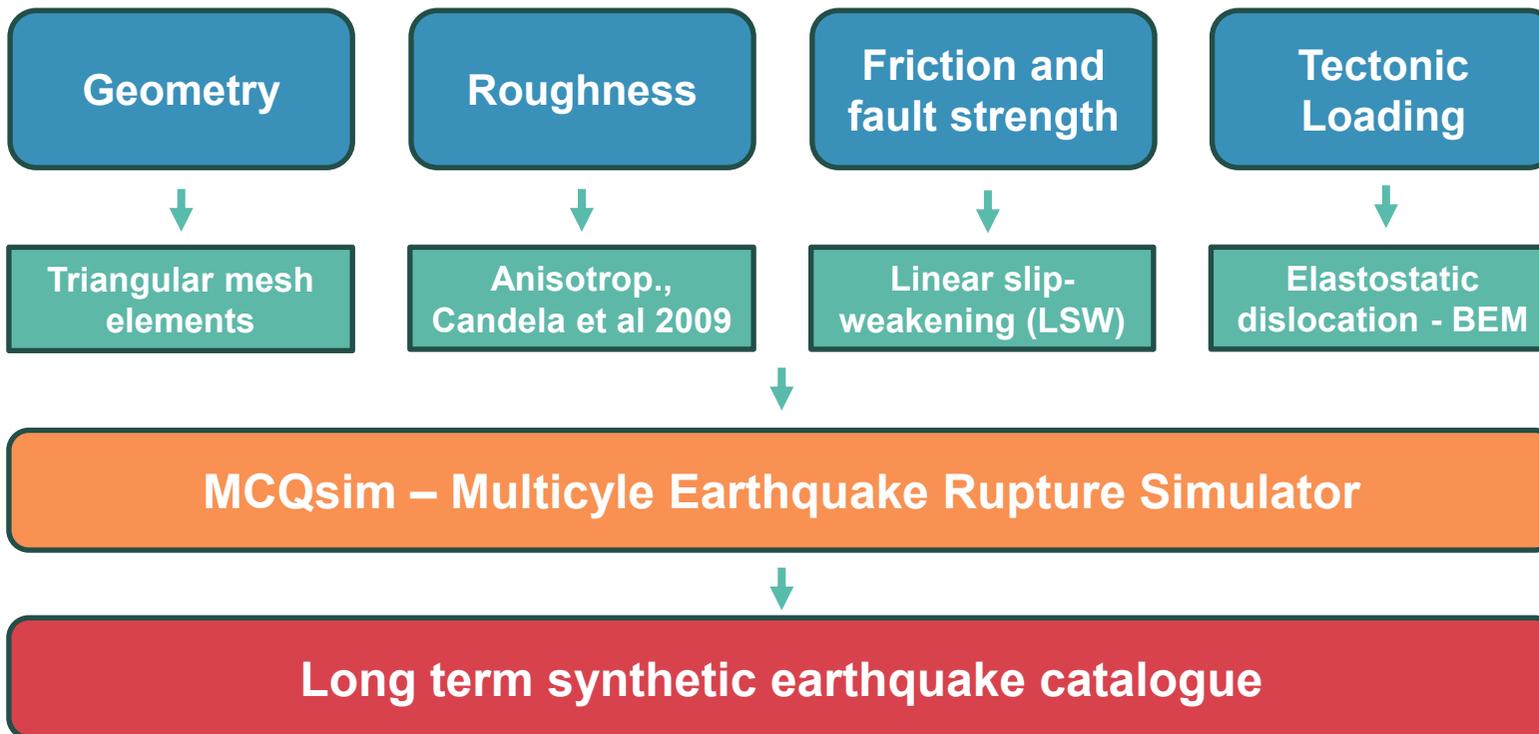*(Herrero-Barbero et al., 2021)*

Taiwan

(Chia-Cheng and Hung-Yu, 2024)

Physics-based Simulation of Rupture Sequences

MCQsim - Multi-cycle earthquake simulator   *Zielke and Mai, 2023*

- **Quasi-static/dynamic** earthquake rupture simulation

- **Short-term rupture dynamics** with **long-term crustal deformation** approximations

- Available on **GitHub** as open access. Currently **under renovation**

Geometry	Roughness	Friction and fault strength	Tectonic Loading
Triangular mesh elements	Anisotrop., Candela et al 2009	Linear slip-weakening (LSW)	Elastostatic dislocation - BEM

MCQsim – Multicyle Earthquake Rupture Simulator

Long term synthetic earthquake catalogue

Physics-based Simulation of Rupture Sequences

Pros

- Offer a pathway to **capture complex multi-fault ruptures**, including cascading events that are difficult to infer solely from observed seismicity.

- Provides **a critical tool for exploring the fault interactions** that cannot be directly measured.

- Long-term synthetic catalogs enable us to **explore the largest, potentially most devastating events, and possibly their frequency**.

Cons

- **Software availability** and **high-performance computing** facilities

- Management and processing of **large data sets**

- Representing and propagating **epistemic uncertainties**

- Maintaining **reproducibility**

- Insufficient knowledge of descriptions for **fault friction** and **spatial variations**

- **Off-fault seismicity** is not currently included

Conclusion

"All models are wrong, but some are useful" (Box, 1980)

- **Statistical, hybrid, and physics-based simulators each serve different goals**, and the appropriate choice depends on data availability, spatial scale, and the purpose of the hazard assessment.

- **Statistical approaches** provide an efficient way to generate <u>long-term earthquake rupture forecasts</u> directly from observed seismicity and remain widely used in risk and hazard assessments.

- **Hybrid models** bridge observational constraints and <u>simplified rupture physics</u>, enabling scenario-based ruptures and <u>multi-fault interactions where detailed physical modeling is not feasible</u>.

- **Physics-based simulators** incorporate the underlying <u>frictional</u> and <u>stress-transfer physics</u>, allowing them to reproduce earthquake sequences that closely resemble observed behavior, including fault interactions.

Conclusion

- Ultimately, the goal of physics-based simulation is to achieve the **right balance between empirical realism and physical fidelity**, building hazard models that are both consistent with observations and grounded in the physics of earthquake rupture.

- **We are currently searching/testing suitable open-access, physics-based earthquake simulators** to integrate into the WP5 simulation framework. This would enable the development of more physically grounded and advanced source models by incorporating rupture mechanics and physical laws more directly into the seismic source module.

Invitation

June 23 – 25, 2026
University of Zagreb
GEM CONFERENCE
FROM FAULTS TO FUTURE SCENARIOS

WP5 Simulation Platform

Thank you for your attention!