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PSHA models for the oceans

Expanding GEM's PSHA models to support remote communities in the Southwest Pacific

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For the Global Earthquake Model (GEM) Foundation Hazard Team

October 23, 2024

working together
to assess risk

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Webinar outline

- Introduction to GEM Foundation and GEM's Global Seismic Hazard Mosaic
- Brief summary of the Southwest Pacific Islands (PAC) model
  - Main qualities of the PSHA input model
  - Hazard results for major cities
- The FORCE project: activities in the southwest Pacific region
- New models for the oceans: focus on the Pacific Ocean model
  - Additional coverage for remote communities
  - Addressing major modelling challenges in the region
  - Results
- Next steps
  - Integrating new oceans models into the Mosaic
  - Upcoming FORCE activities in the southwest Pacific region

GEM Foundation

- Non-profit NGO, founded in 2009
- Global, public-private partnership
- Develop software, tools, data and models for earthquake risk assessment worldwide

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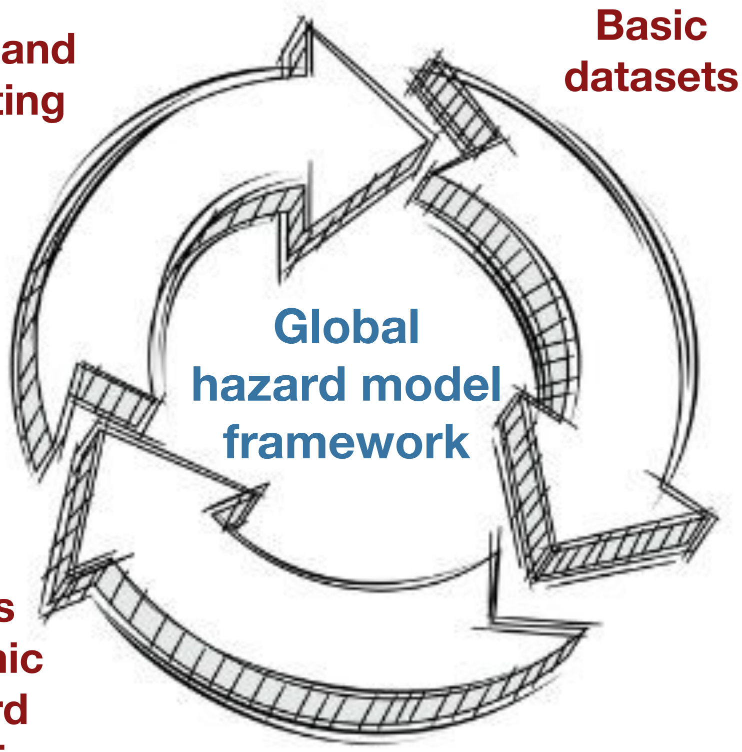
- Promote and foster applications to disaster risk reduction



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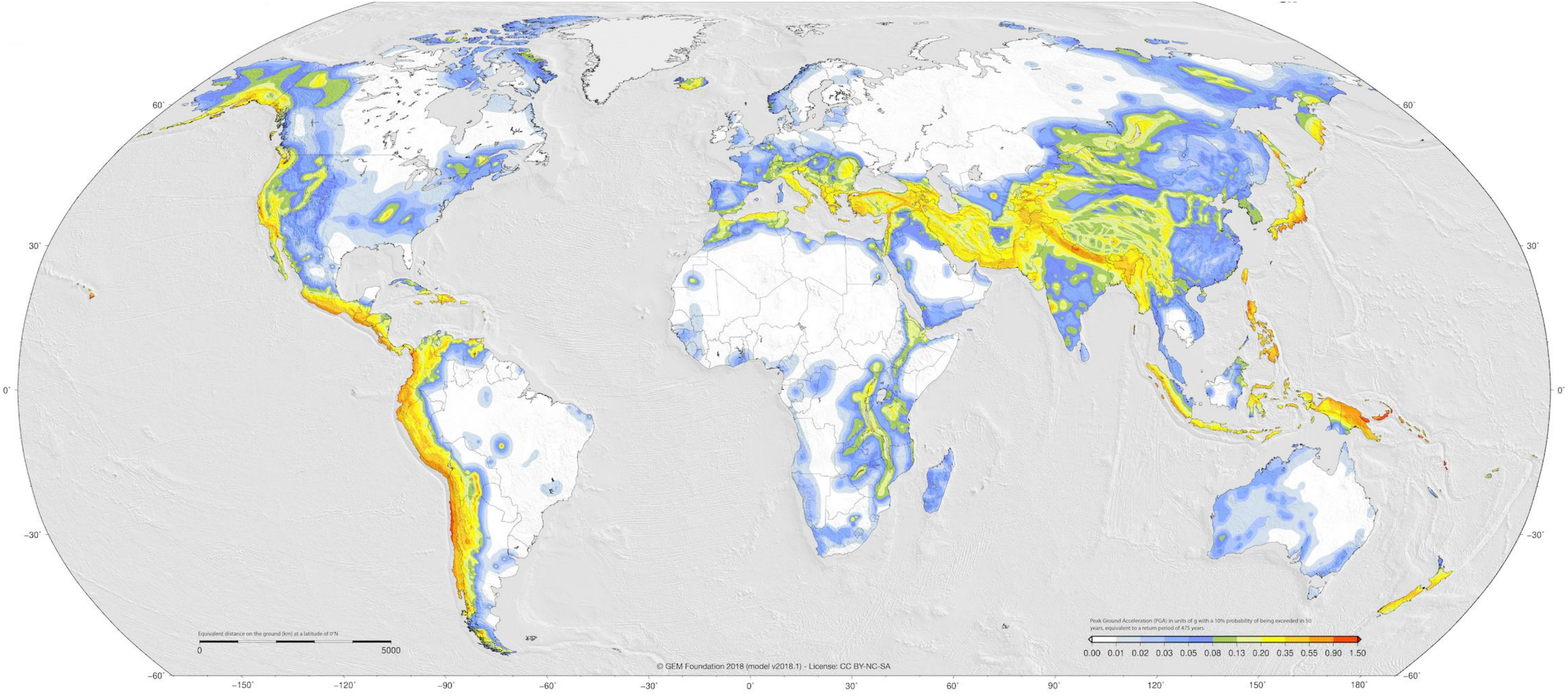
Global Seismic Hazard Map

PGA on rock, 10% POE in 50 years



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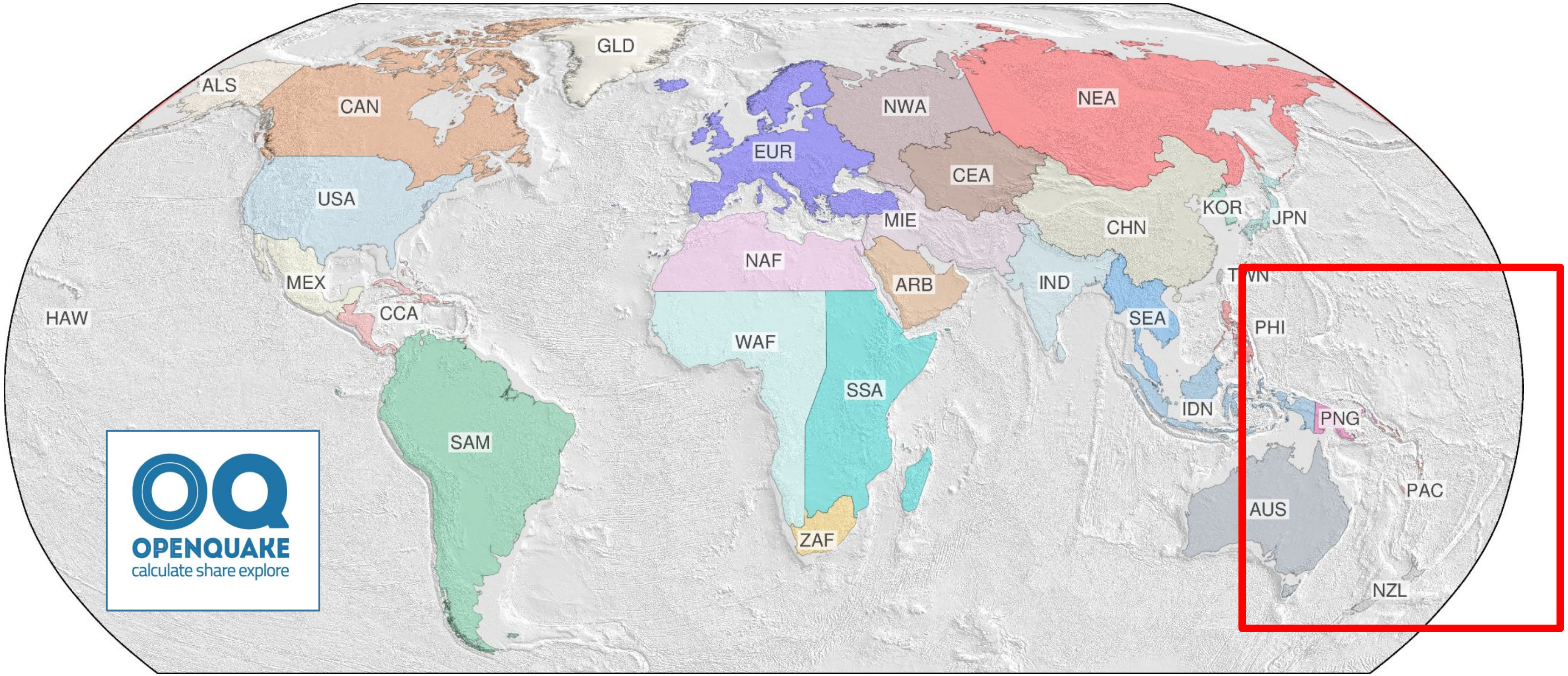
Global Seismic Hazard Map v.2023.1 (https://www.globalquakemodel.org/gem)

Global Seismic Hazard Mosaic: a database of models for probabilistic seismic hazard analysis (PSHA)

https://hazard.openquake.org/gem/models/



Global Mosaic of Seismic Hazard Models

Global Seismic Hazard Map v.2023.1 (https://www.globalquakemodel.org/gem)

PSHA of the Southern Pacific Islands (PAC)

Developed by GEM hazard team* in 2018 to complete the global hazard mosaic; updated in 2019 to include epistemic uncertainties in the seismic source characterization

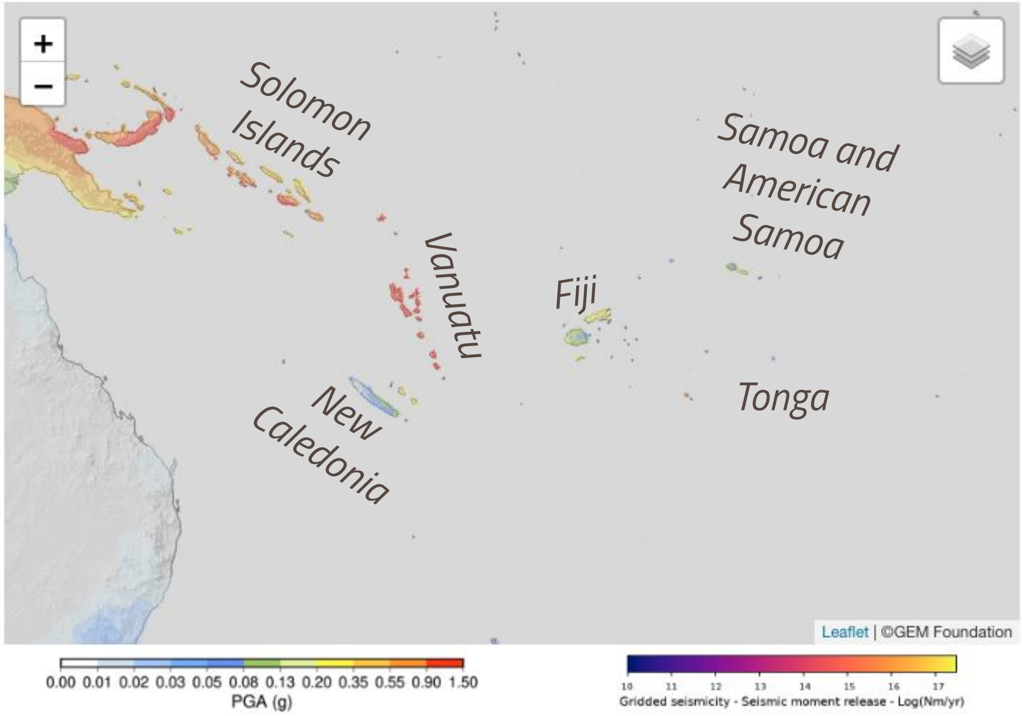
Based on global datasets:

- active faults database
- ISC-GEM extended catalogue (classified to the tectonic regions; declustered)

*At the time, we did not manage to build a project with local experts

Interactive Viewer

The viewer below depicts the seismic sources and hazard results in terms of PGA for a return period of 475 years. Click on the menu in the upper right corner to select the layer.



https://hazard.openquake.org/gem/models/PAC/

Johnson, K. L., M. Pagani, and R. H. Styron. "PSHA of the southern Pacific Islands." Geophysical Journal International 224.3 (2021): 2149-2172., https://doi.org/10.1093/gji/ggaa530

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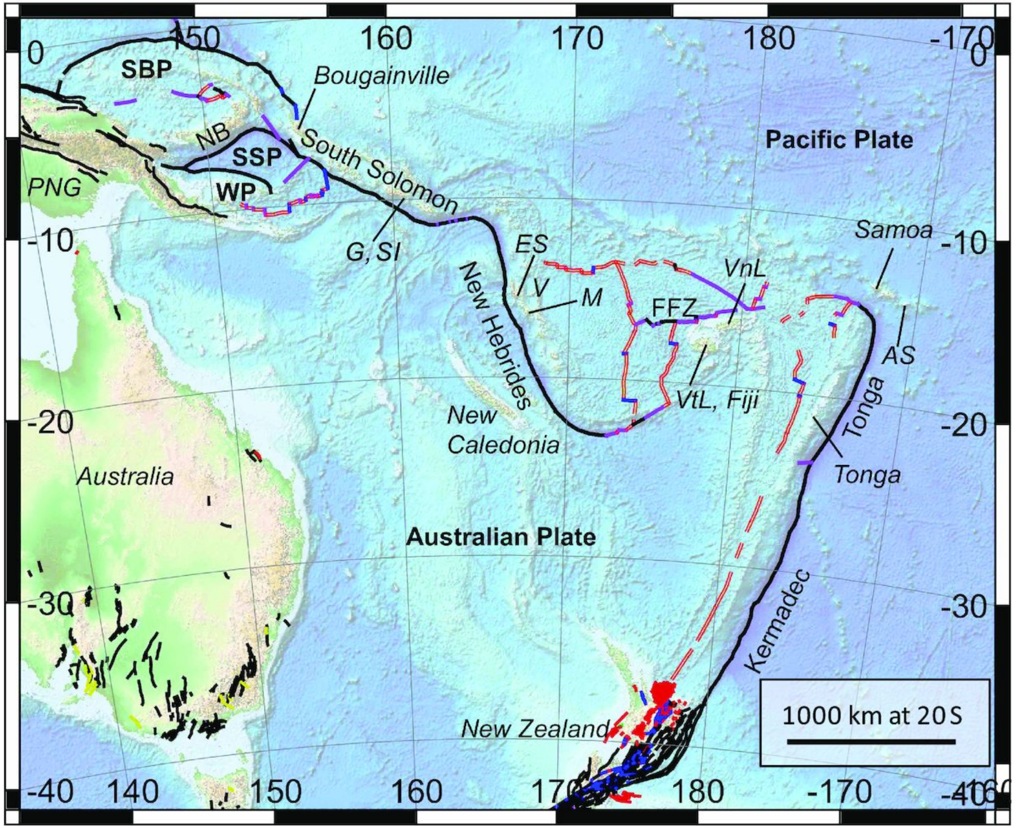

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PSHA of the Southern Pacific Islands

Seismic source characterization

Four subduction zones (W to E):

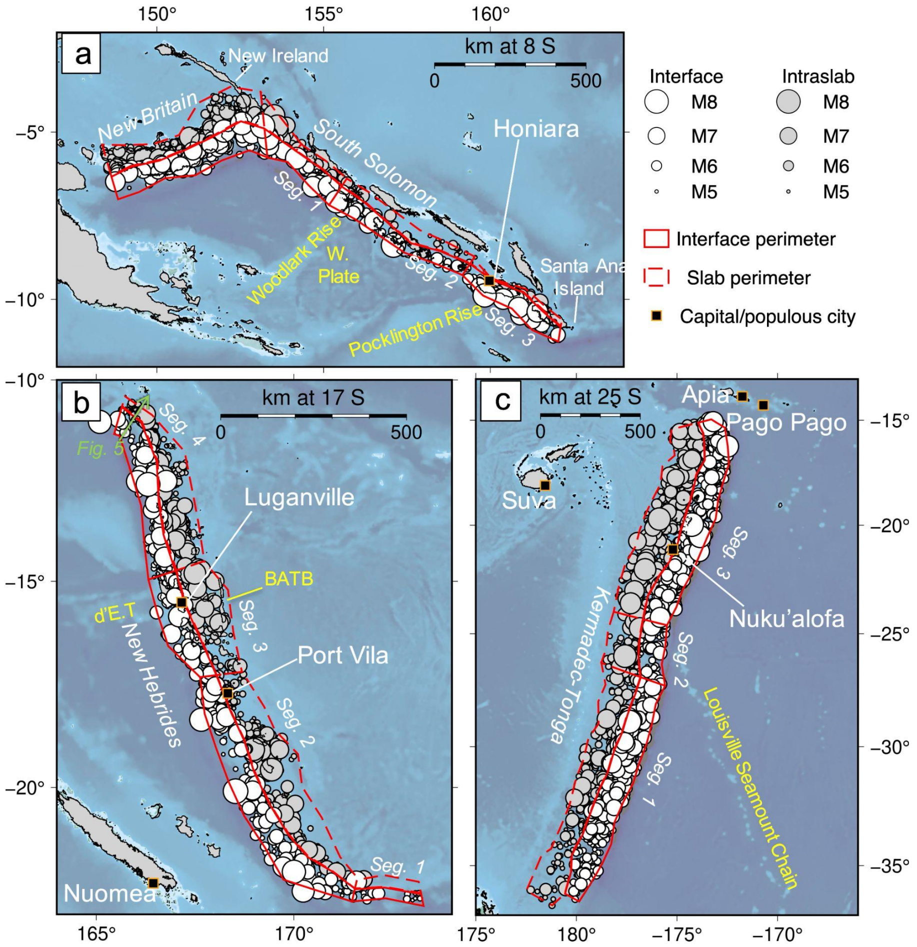
- New Britain
- South Solomon
- New Hebrides/Vanuatu
- Tonga/Kermadec

Subduction interface:

- faults with 3D geometries; occurrence rates from tectonics and seismicity as in Pagani et al (2021)

Subduction Intraslab:

- gridded ruptures constrained to the slab volume



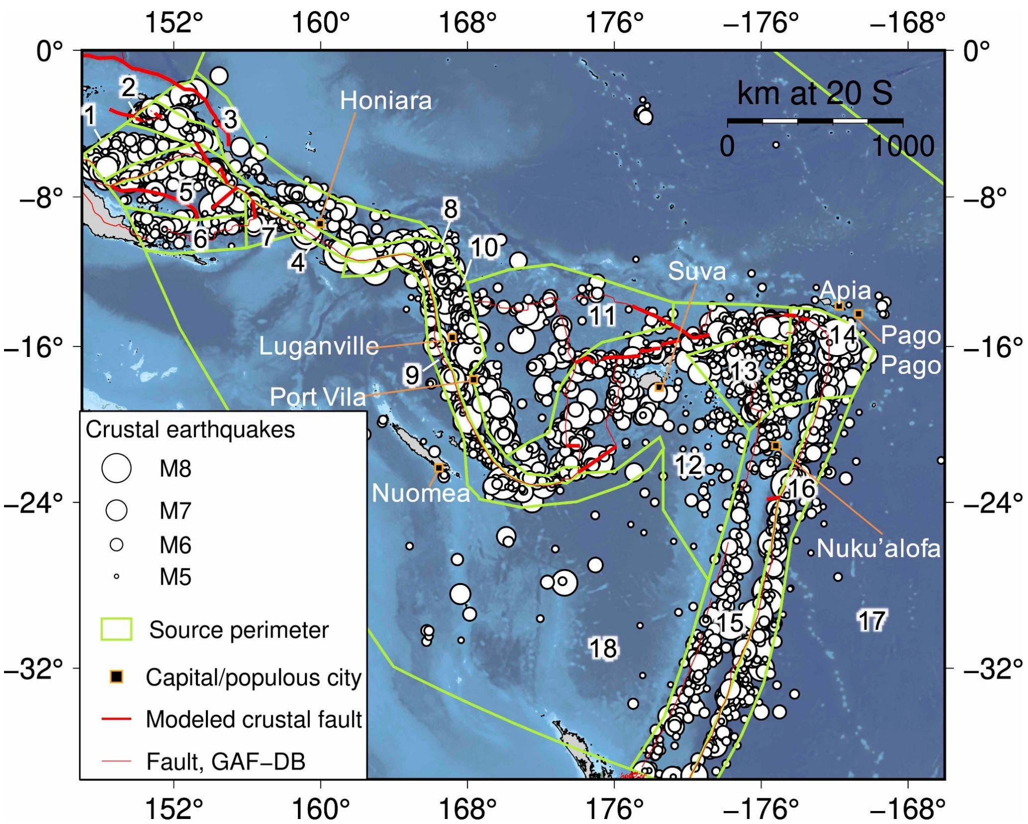
Johnson et al. (2021)

PSHA of the Southern Pacific Islands

Seismic source characterization

Active shallow crustal sources:

- fault sources for the larger and faster moving seafloor faults
- distributed seismicity to account for earthquakes not modelled by these faults; source zones with occurrence rates smoothed according to past seismicity



Johnson et al. (2021)

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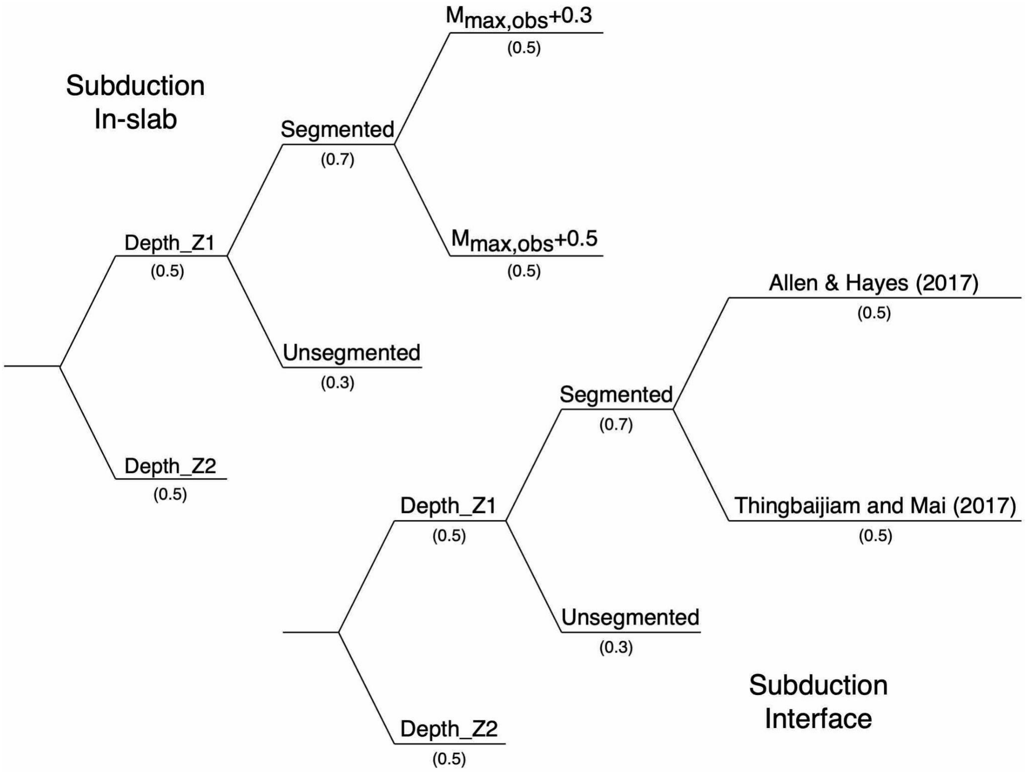
PSHA of the Southern Pacific Islands

Epistemic uncertainties in subduction sources

- Locking depth
- Segmented vs unsegmented
- Maximum magnitude delta (inslab)
- Magnitude scaling relationship (affects rates and M_{max} for the interface sources)

Ground motion characterization

- Logic tree using globally applicable GMPEs for each tectonic region



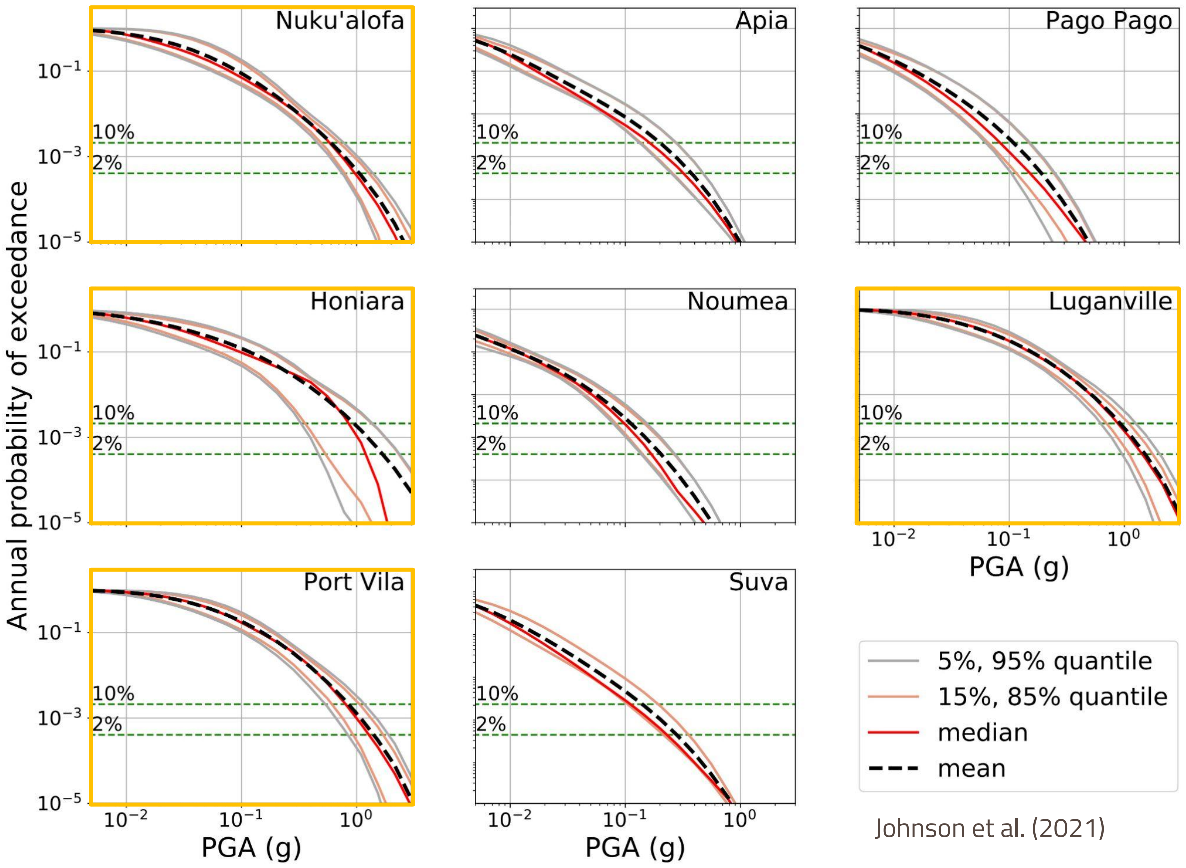
Johnson et al. (2021)

PSHA of the Southern Pacific Islands

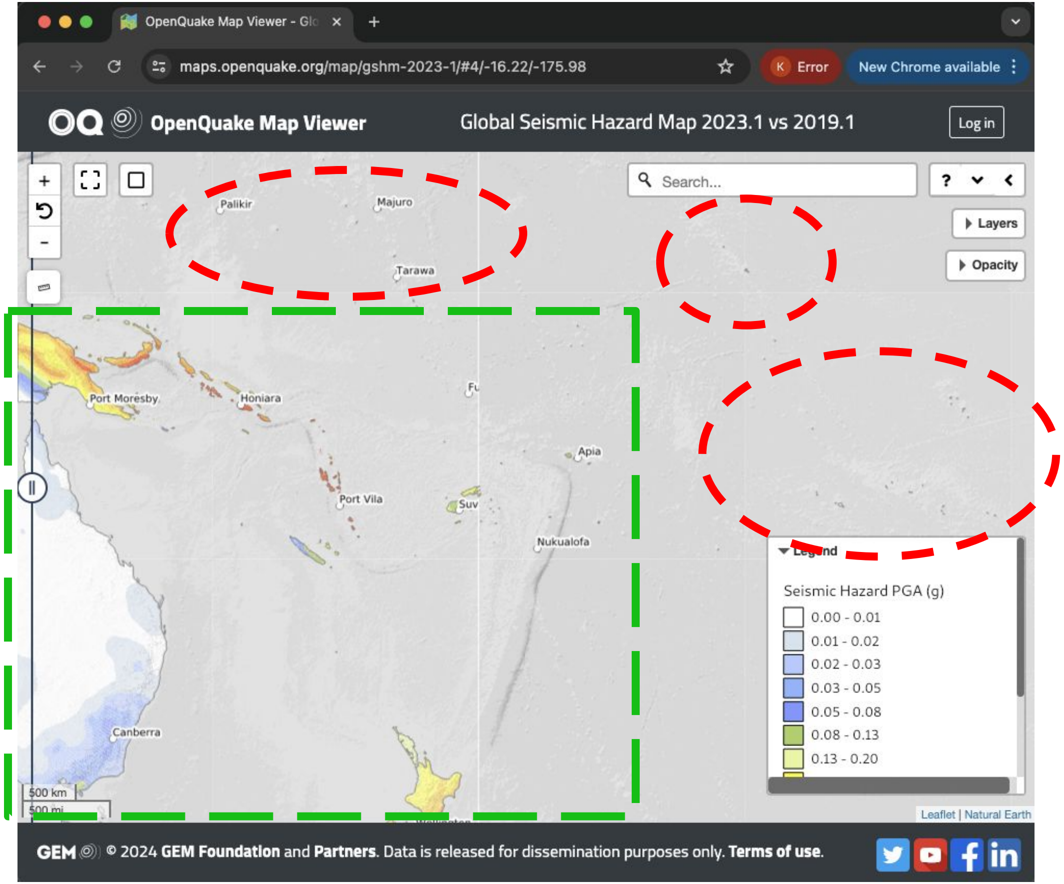
Example results:
mean and quantile hazard curves for capital cities; PGA on rock

Other results possible with the model and OQ:

- hazard maps
- uniform hazard spectra
- disaggregation (by position, magnitude, tectonic region, GMPE uncertainty, source)
- stochastic event sets; ground motion fields



Johnson et al. (2021)



Territories already covered by the Southern Pacific Islands (PAC) hazard and risk models

- Fiji
- Vanuatu
- Tonga
- New Caledonia
- Niue
- Solomon Islands
- Samoa
- American Samoa

Other models in the SW Pacific region:

- Papua New Guinea (PNG)
- Australia (AUS)
- New Zealand (NZL)

Global Seismic Hazard Map v.2023.1 (https://maps.openquake.org/map/global-seismic-hazard-map)

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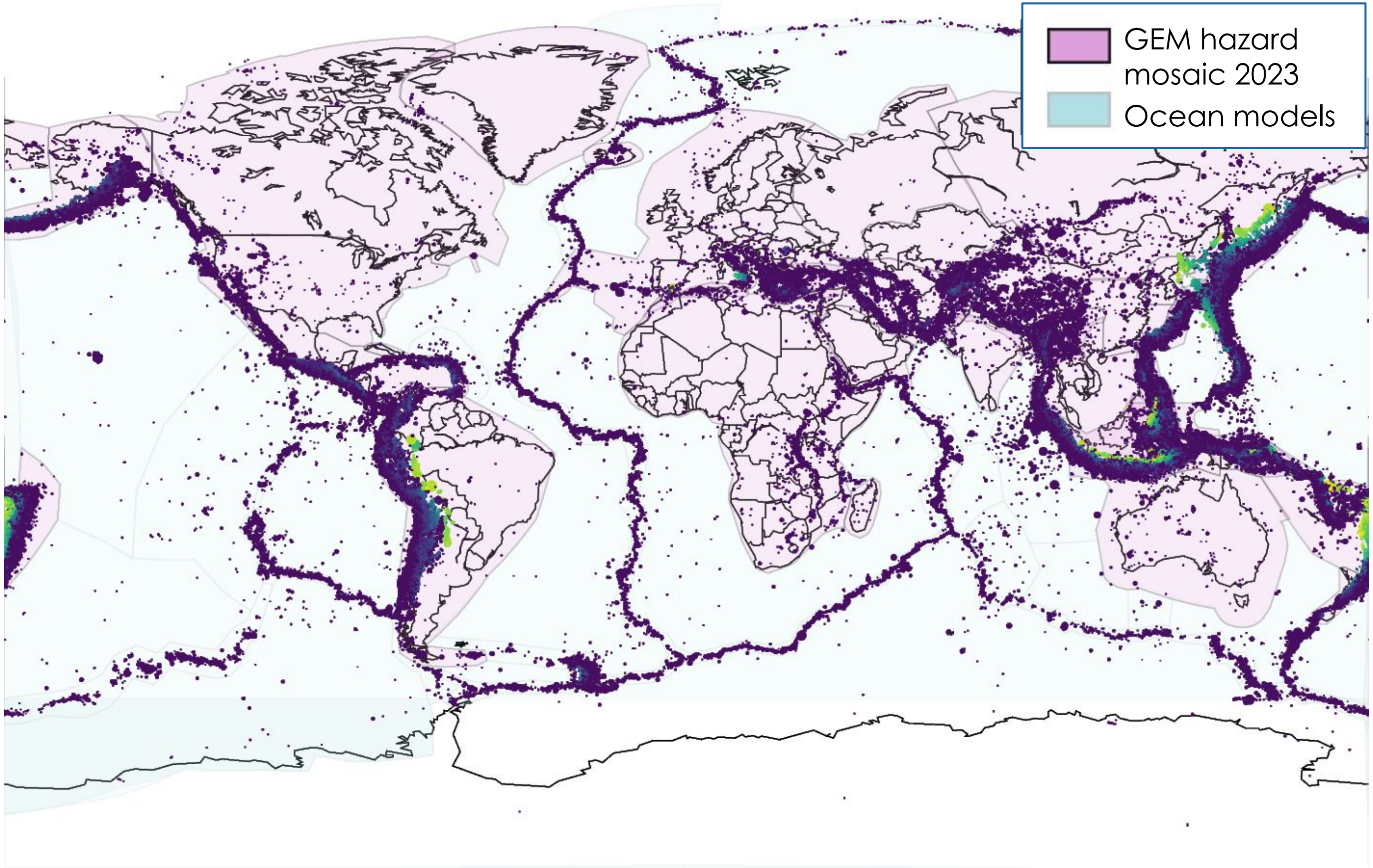
GEM's Global Earthquake Models



2023 GEM seismic hazard mosaic covers continents, but not remote island communities.

Oceans models extend coverage to the rest of the globe for a fully global model

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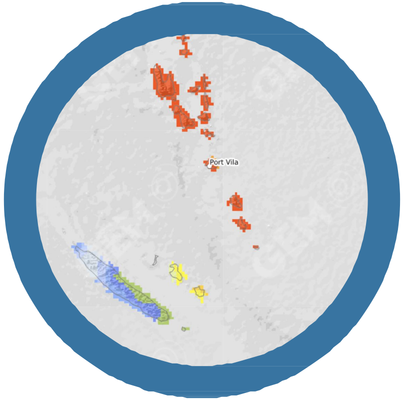
Forecasting and Communicating Earthquake Risk



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Hazard and risk assessment in small communities

Cover islands located in the Pacific, Indian, and Atlantic Oceans with seismic hazard and risk models

Training

Strengthening local capacities and consolidating a technical community network

Communication

Usable information for stakeholders and decision making authorities

https://www.globalquakemodel.org/proj/force

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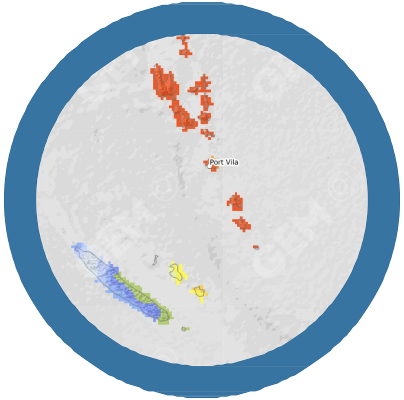

Hazard and risk assessment in small communities

Covered islands in the GRM located in the Pacific, Indian, and Atlantic Oceans.

New models: Pacific Ocean

Territories covered during FORCE

- Nauru
- Tuvalu
- Marshall Islands
- Kiribati
- Palau
- Northern Mariana Islands
- Cook Islands
- Federated states of Micronesia
- French Polynesia
- Easter Island

Collaborations and training

Workshop co-hosted by SPC and UNESCO to be held in Suva, Fiji in November.

- Training on seismic hazard and risk and the OpenQuake Engine
- Dissemination of models to local experts

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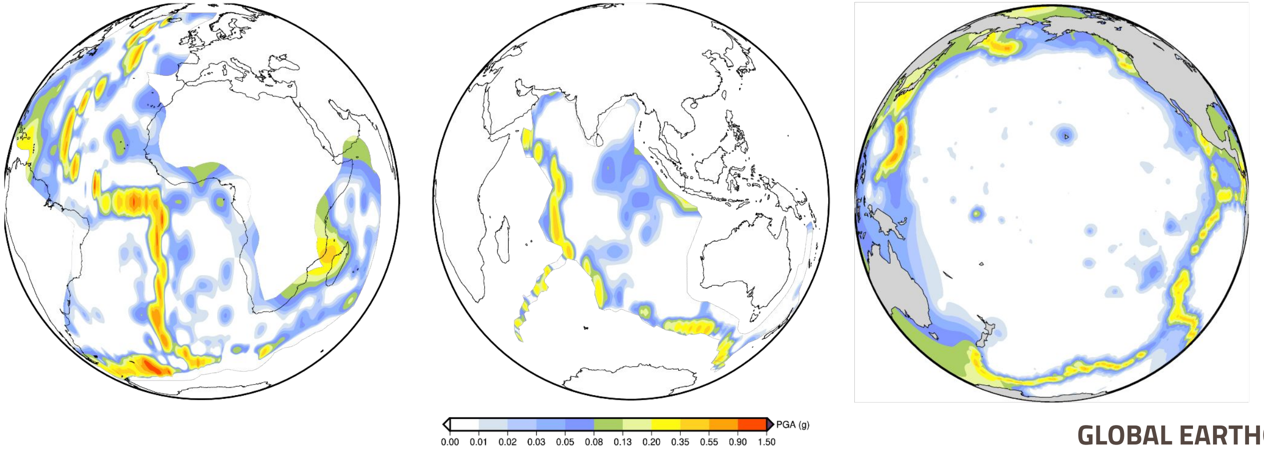
PSHA models for the Oceans

Motivation: Improve coverage of the globe in the Mosaic for both disaster risk reduction and scientific applications

- Hazard and risk assessments for small remote communities
- Creation of truly global products such as hazard maps and stochastic event sets

Approach: three models divided by ocean - **Pacific (OPA)**, Atlantic (OAT), and Indian (OIN)



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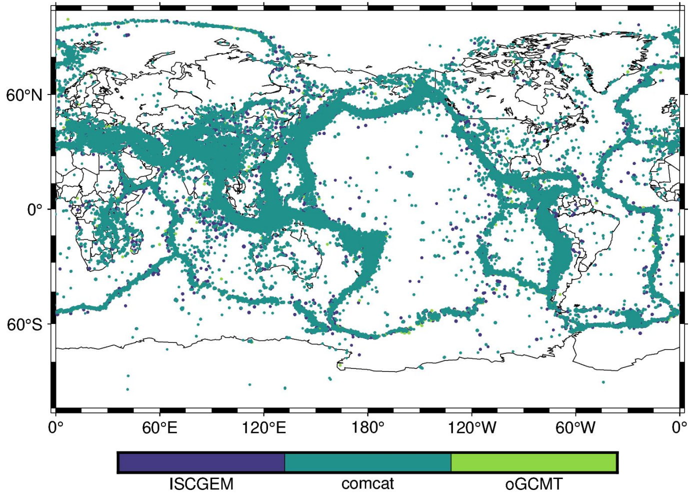
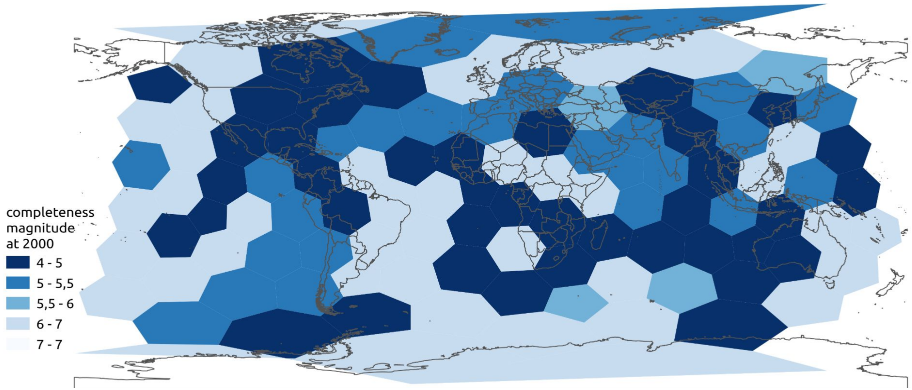
PSHA for the Pacific Ocean (OPA)

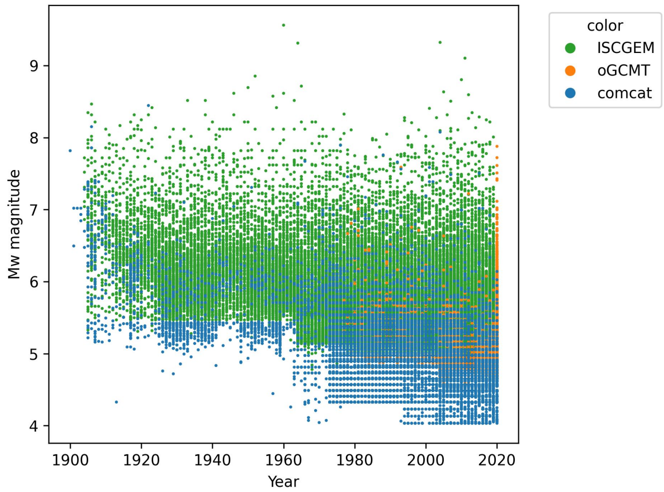
- Required update to underlying datasets/models
    - Global homogenized earthquake catalogue
    - Seismic zonation for the oceans
- Developed as much as possible following GEM's state of practice for building hazard input models
    - Seismic source characterisation based on tectonics and declustered catalogue classified to the main tectonic units
    - Ground motion characterisation uses multi-model approach to overcome lack of data
- More recent methods implemented as needed
    - new algorithm jointly solves for catalogue completeness and occurrence model
    - adaptive smoothing for distributed seismicity

Global catalogue

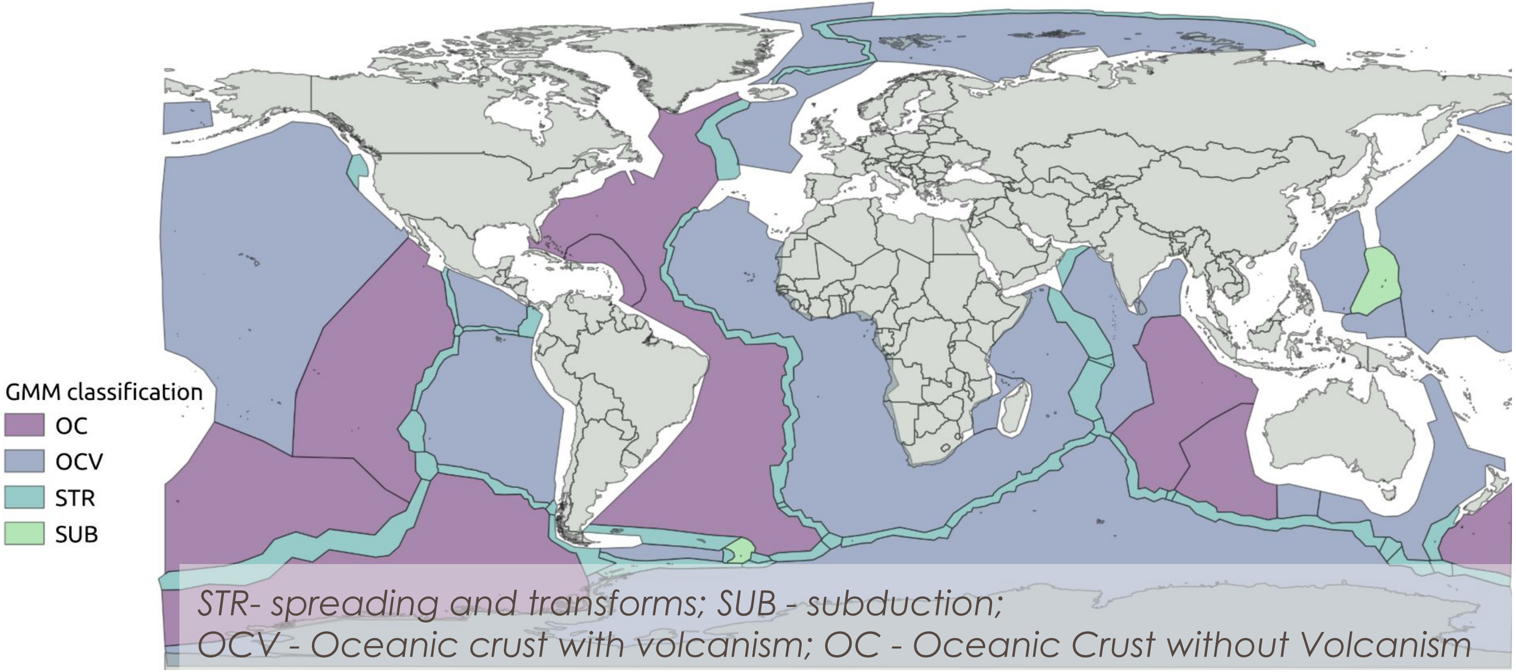
- Developed a new global catalogue merging ISCGEM with comcat and GCMT for better ocean coverage
- Reduced completeness in recent time periods to M_w~5 in some ocean regions, though magnitude completeness threshold remains high especially in the southern ocean







GEM global oceans zonation, coloured by tectonic region



- Ocean zones determined by geology (tectonic regionalisations, fault models) and by observed seismicity
- Narrow zones covering MOR and transform areas
- Subduction zones from Slab2.0 (Hayes et al, 2018) geometry

Seismic source characterisation (SSC)

SSC constructed using the Model Building Toolkit (mbtk). Main aspects:

- Includes sources for **shallow crust** (oceanic mid-ocean ridge and transform zones), **subduction** (interface and intraslab) based on tectonic information and seismicity (a catalogue classified to the main tectonic units)
- Subduction sources modelled as 3D faults for the interface and ruptures that sample the slab volume
- Crustal sources modelled as distributed seismicity (multipoint sources) with spatially-varying rates
- For sources based on catalogue: occurrence model derived using automated method that jointly determines completeness and FMD Gutenberg-Richter (GR; negative exponential) parameters

This is GEM's first model covering the oceans, so we generally aim to keep the logic trees simple but account for some epistemic uncertainties

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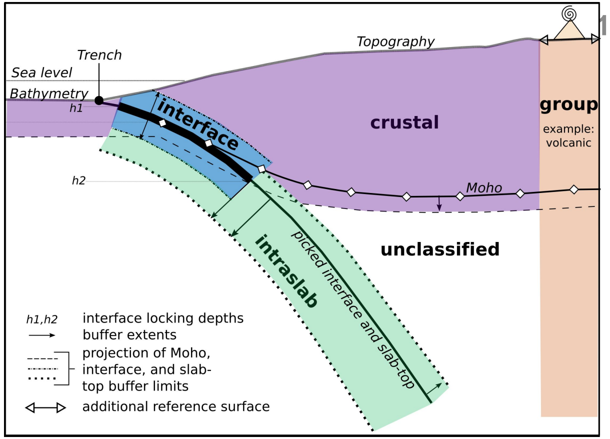
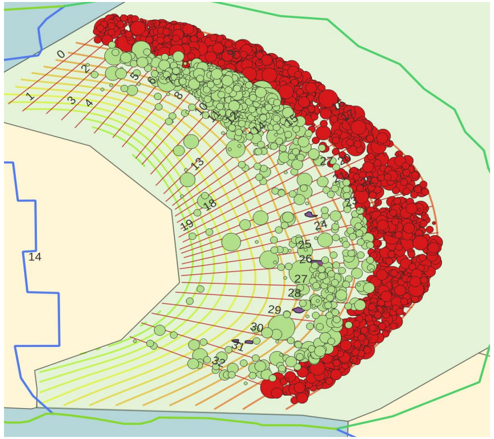
SSC: subduction zones

Subduction sources modelled as in Pagani et al. (2021):

- Classify catalogue based on event locations and subduction geometry
- Decluster crustal and interface sub-catalogues jointly, intraslab separately
- Use interface geometry to identify M_{max} and define magnitude frequency distribution (FMD). Two versions: (1) based purely on seismicity and (2) hybrid version that considers tectonics
- Model interface as an OpenQuake fault source with 3D geometry
- Model slab events as precomputed ruptures that sample the slab volume; distribute occurrences evenly or using smoothing according to positions of past earthquakes





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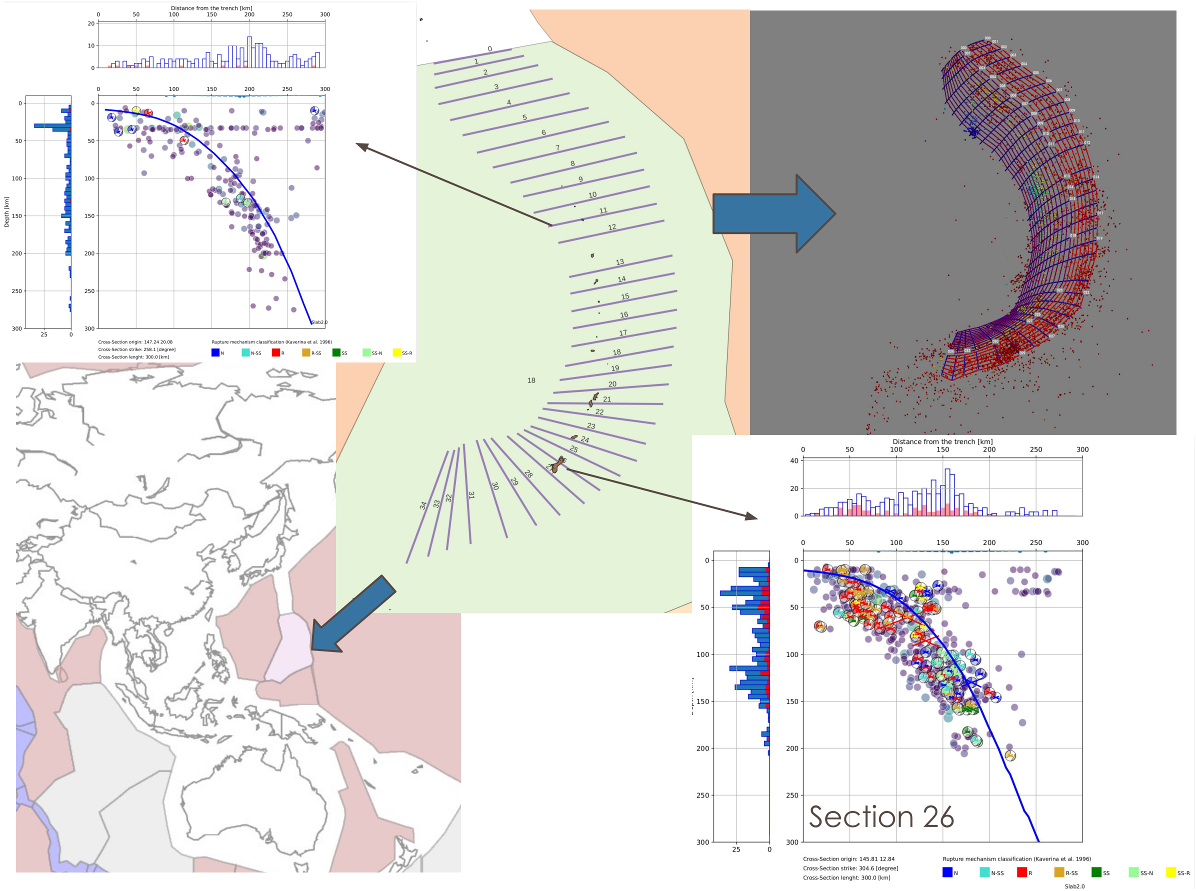
SSC: Mariana subduction zone



- Low observed seismicity compared to neighbouring subductions
- Event classification more difficult, some controversy with large events in the literature
- Historically believed to have very low coupling, though recently some authors dispute this, favouring a spatially-varying coupling

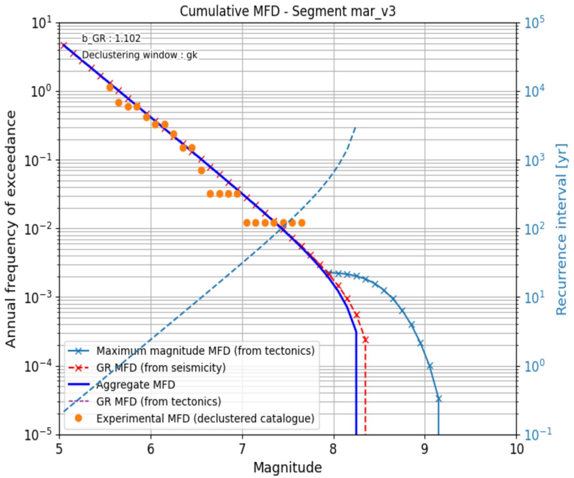
SSC: Mariana subduction zone

Subduction interface FMDs

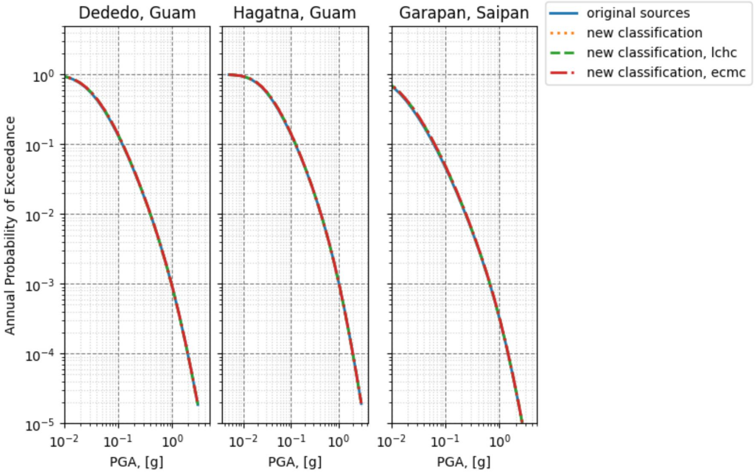
(1) GR FMD derived from seismicity

(2) Gaussian based on tectonics (convergence and coupling) and M_{max} from fault area and magnitude scaling

(3) Hybrid model joining (1) and (2)



Computed M_{max} exceeds observed and Gaussian rates are higher at high M regardless of coupling and convergence choices **->** three versions in the logic tree



Subduction intraslab FMDs: two branches (more smoothed vs more uniform) to reflect spatially non-uniform rupture history

Source models: distributed crustal seismicity

Distributed seismicity in the shallow crust modelled with the OpenQuake model building toolkit (mbtk). Main steps:

- Events classified to the crust are further divided into large zones with ~consistent tectonic properties
- Completeness and FMD parameters jointly calculated for each zone
- M_{max}, hypocentral depths and nodal plane distributions determined for each zone using catalogues and historical information
- Declustered catalogue smoothed for spatially-varying rates
- Spatial distribution scaled by FMD parameters
- Multipoint source written for OQ

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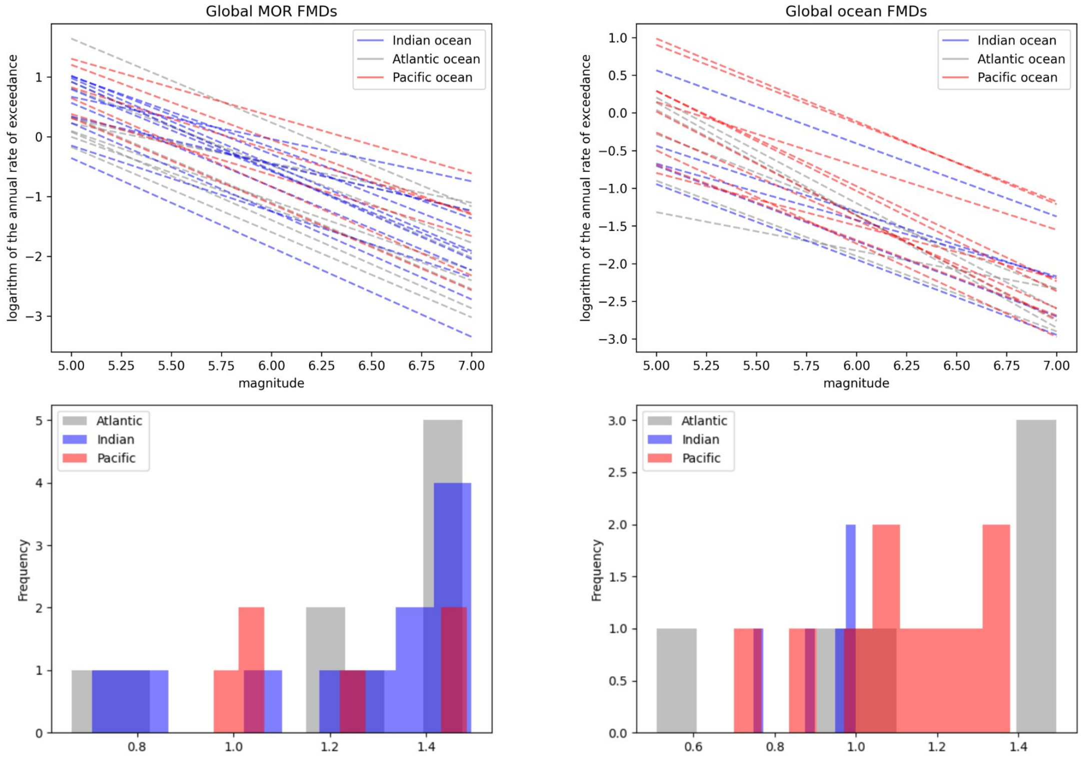
Source models: FMDs for the Oceans



- Parameters such as FMD calculated for each zone and then compared for a global picture
- b-values high in MOR regions and lower in quiet ocean zones
- Zones with more data used to constrain FMD parameters in quieter zones based on global trends

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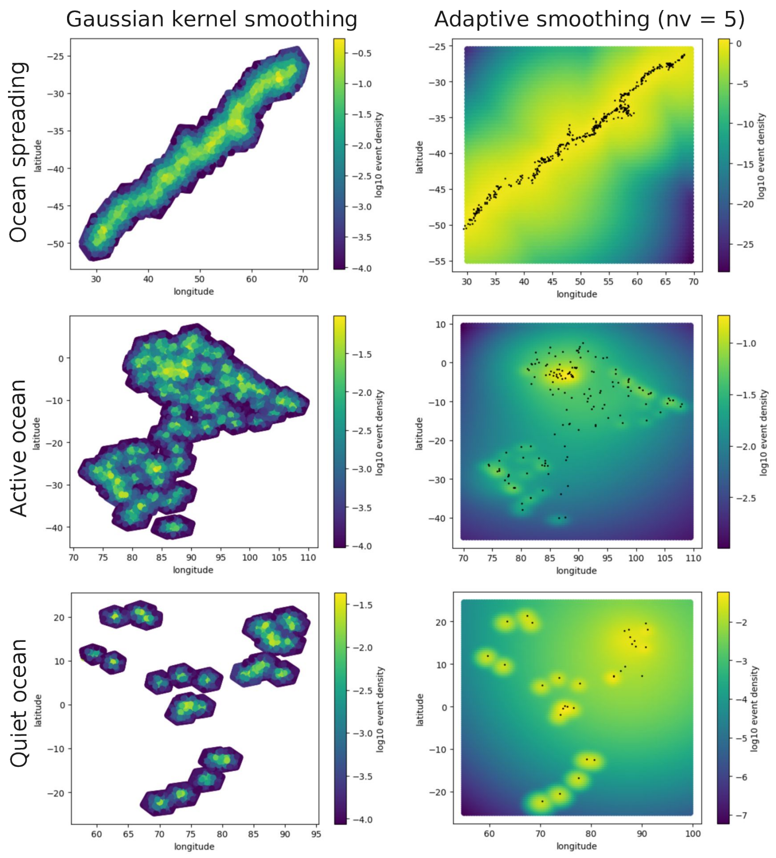
SSC: shallow crust smoothed seismicity models



Example: Gaussian kernel and adaptive smoothing results for three zones in the Indian Ocean model.

- Overall patterns are similar, with the adaptive smoothing giving ‘smoother’ densities.
- Adaptive smoothing approaches are more sensitive to declustering choices due to dependence on neighbouring events

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SSC: additional notes

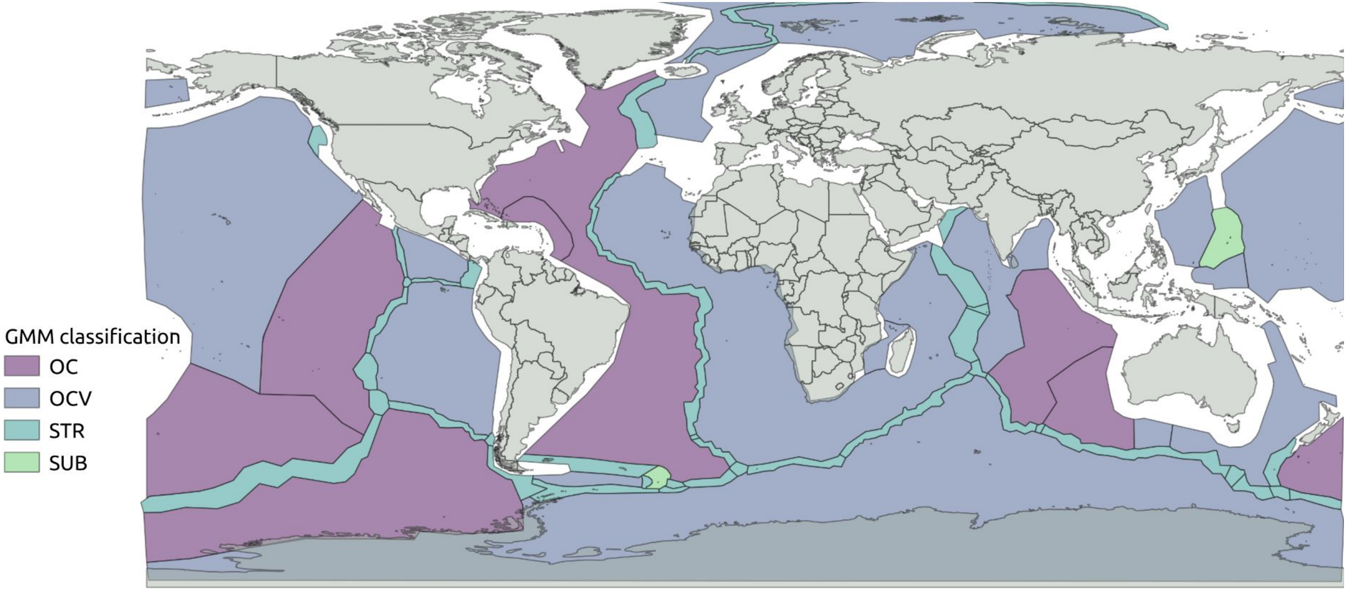
Other modelling parameters

- M_{max} in MOR regions kept low: largest events M_w~6 more likely on transform fault segments
- Leonard et al (2010) rupture scaling - for consistency with PAC
- Nodal plane distributions very uncertain, but effect expected to be small given rupture sizes (small M_{max})

Sensitivity analysis

- Tested two declustering approaches (Uhrammer and Zaliapin and Ben-Zion); limited effect on hazard in the Pacific due to locations of islands
- Changing M_{max} for oceanic regions generally very small effect on hazard
- **Depth distributions had largest impact** - expect events in oceanic crust to be shallow, but depths are highly uncertainty and catalogues often use fixed values

Ground motion characterisation (GMC)

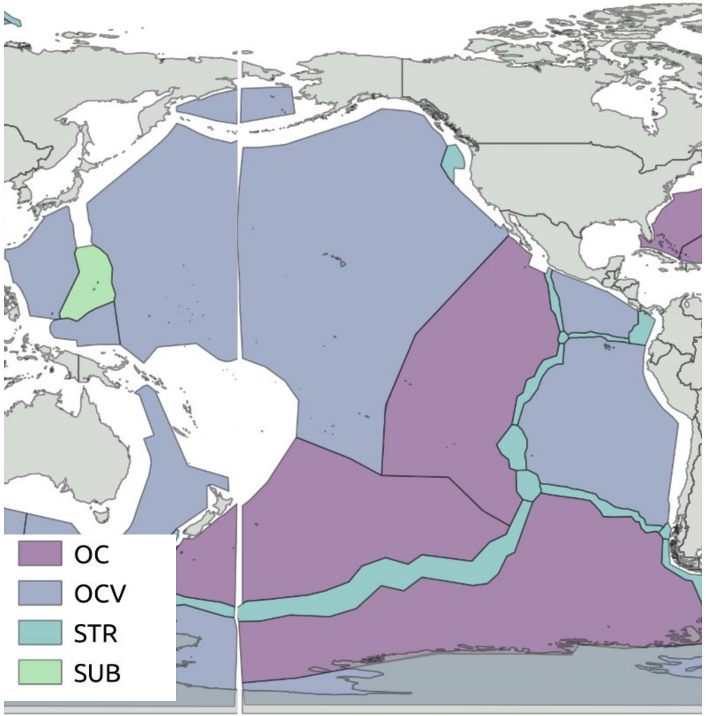


- Extremely challenging to define GMC due to limited ground motion records
- Thin oceanic crust is warm -> lower stress drops near MOR and (possibly) higher in oceanic transform, but very limited data
- Presence of volcanism increases apparent attenuation

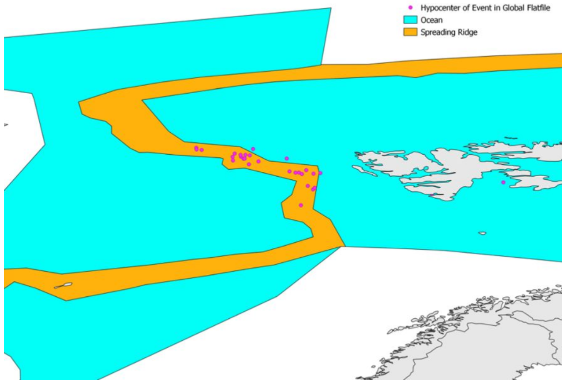
Ground motion characterisation (GMC)

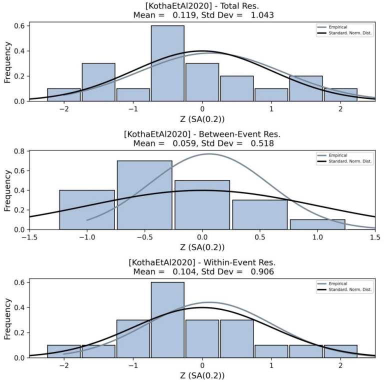
Approach: Use multi-model GMC for each tectonic region type (TRT)

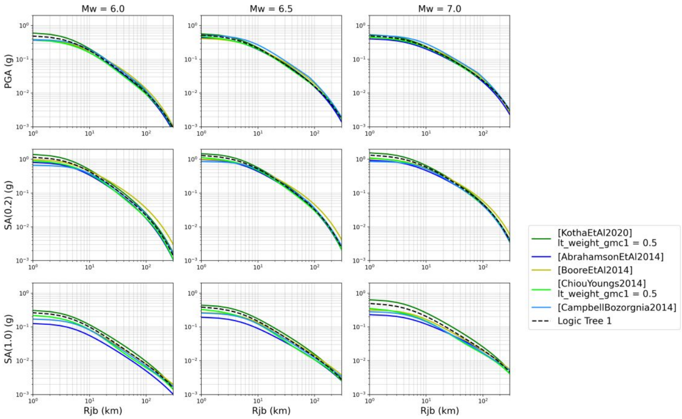
- Choose small set of ground motion models (GMMs) for each TRT using rejection criteria
- Collect strong motion data for each area and tectonic region in the model -> **residual analysis** comparing model-predicted ground motion levels to observations
- Use comparative scaling (trellis plots) to choose GMMs that capture range of possible shaking levels considering all parameters (magnitude, distance, spectral period...)



GMC: spreading and transform (STR)

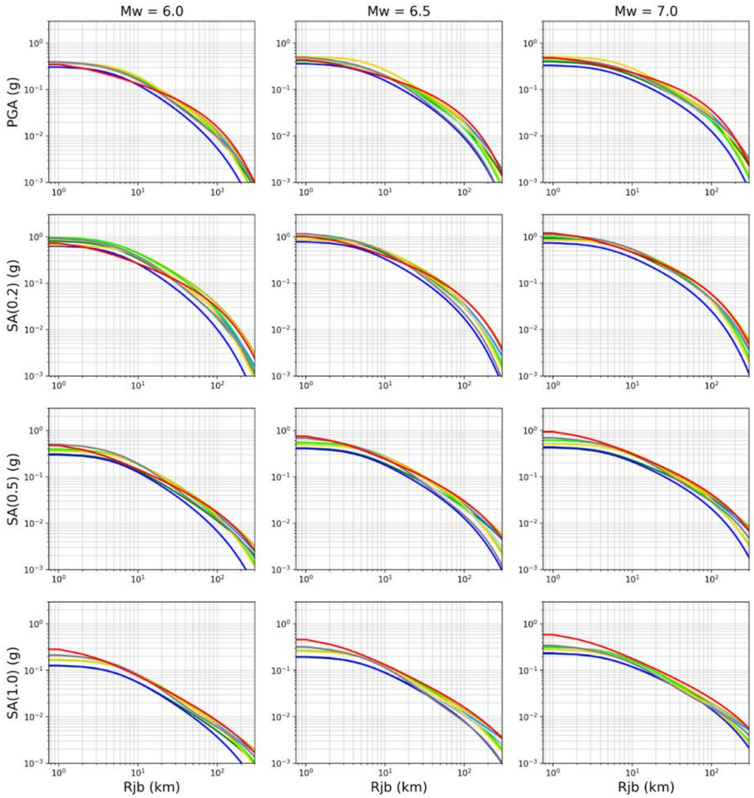






- GMC for STR developed using records from Gakkel ridge in North Atlantic
- Residual analysis shows that ESHM20 ASCR backbone model is suitable, but it predicts high ground motions at shallow depths for larger magnitudes
- Include Chiou and Youngs (2014) with equal weight to reduce mean

GMC: Oceanic crust



MORs
ESHM20 ASCR Backbone (Iceland) (0.5)
CY14 (0.5)

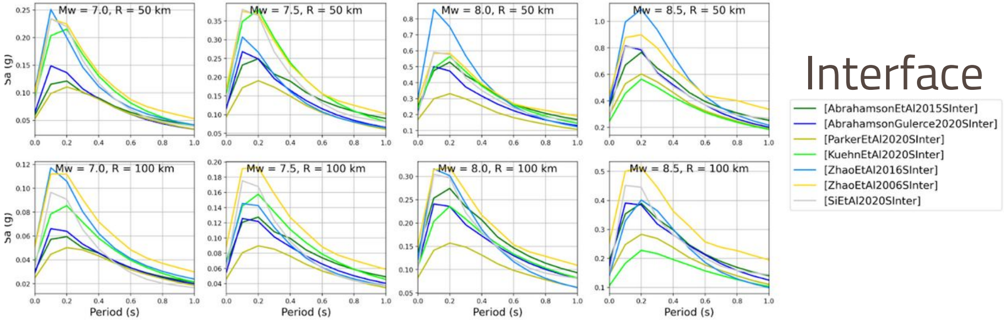
Oceanic Crust (Volcanism) - OCV
Atkinson2010Hawaii (0.20)
ASK14 JPN (0.20)
BSSA14 low Q (0.20)
CB14 (0.20)
CY14 JPN (0.20)

Oceanic Crust (No Volcanism) - OC
ASK14 (0.25)
BSSA14 (0.25)
CB14 (0.25)
CY14 (0.25)

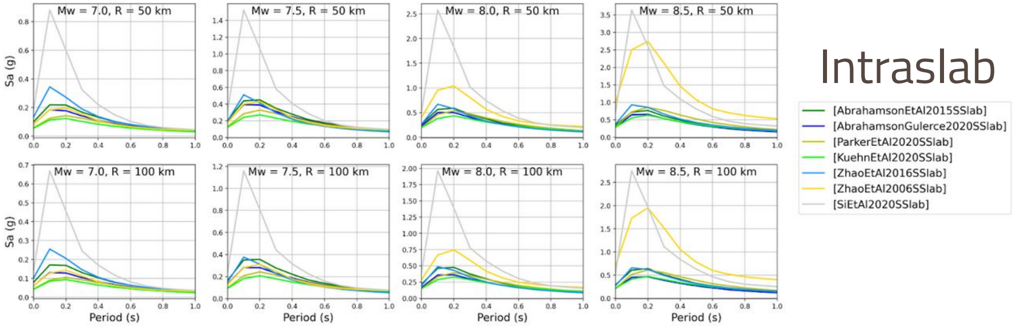
- Presence of volcanism increases apparent attenuation
- With and without volcanism GMMs give broadly similar results below 0.1s but diverge at longer periods
- Use NGAWest GMMs to help capture uncertainty from under-sampled areas

GMC: subduction interface and intraslab

Interface



Intraslab



- For subduction slab and interface sources, the same GMMs are used for both Scotia and Mariana, given limited data in either region
- Tested the GMMs used in USGS Guam and Mariana model (Mueller et al, 2012) - updated GMMs selected

GMC: final selection and logic tree

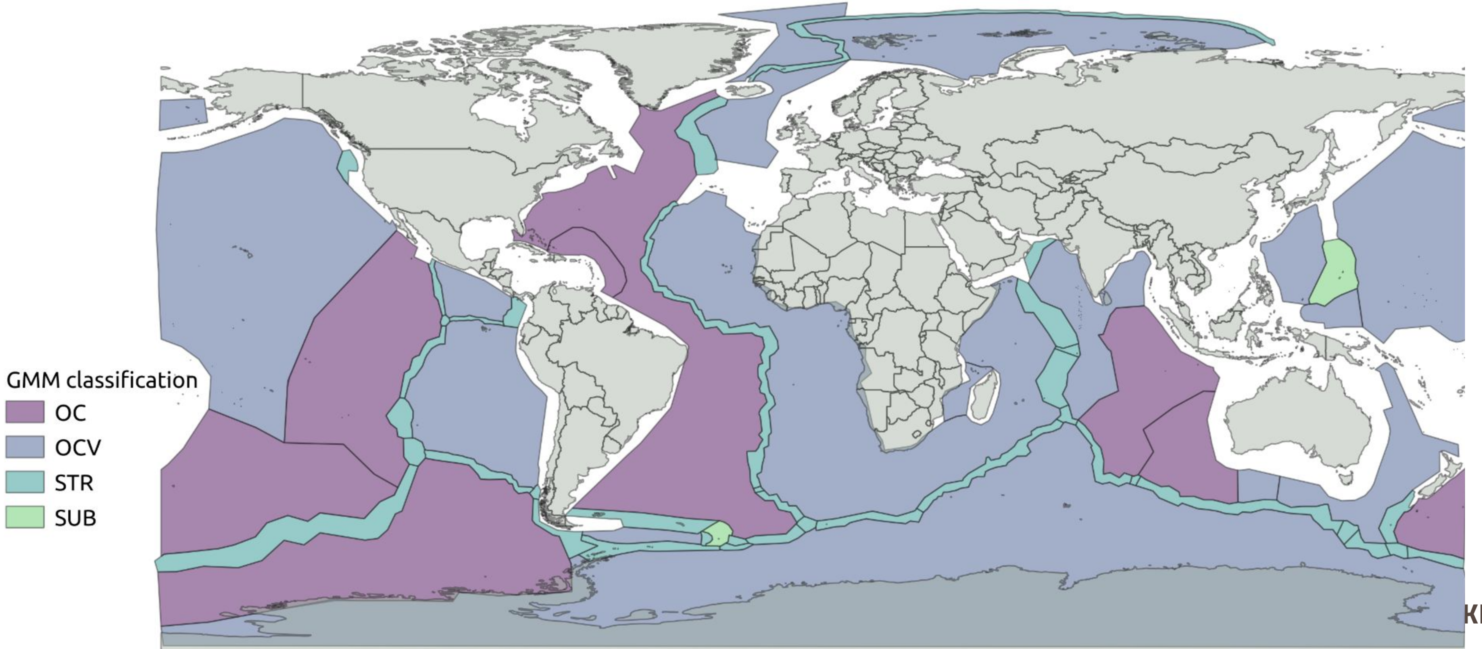
OCV - Oceanic crust with volcanism
Atkinson 2010 Hawaii (0.2)
ASK14 Japan (0.2)
BSSA14 low Q (0.2)
CB14 (0.2)
Chiou and Youngs 2014 Japan (0.2)

SUB - Subduction Interface
BC Hydro Interface (0.2)
Abrahamson & Gulerce 2020 Interface (0.2)
Parker et al 2020 Interface (0.2)
Kuehn et al 2020 Interface (0.2)
Zhao et al 2006 Interface (0.2)

STR - Spreading and transform
ESHM20 ASCR Backbone (Iceland) (0.5)
Chiou and Youngs 2014 (0.5)

OC - Oceanic crust (no volcanism)
ASK14 (0.25)
BSSA14 (0.25)
CB14 (0.25)
Chiou and Youngs 2014 (0.25)

SUB - Subduction InSlab
BC Hydro InSlab (0.25)
Abrahamson & Gulerce 2020 InSlab (0.25)
Parker et al 2020 InSlab (0.25)
Kuehn et al 2020 InSlab (0.25)



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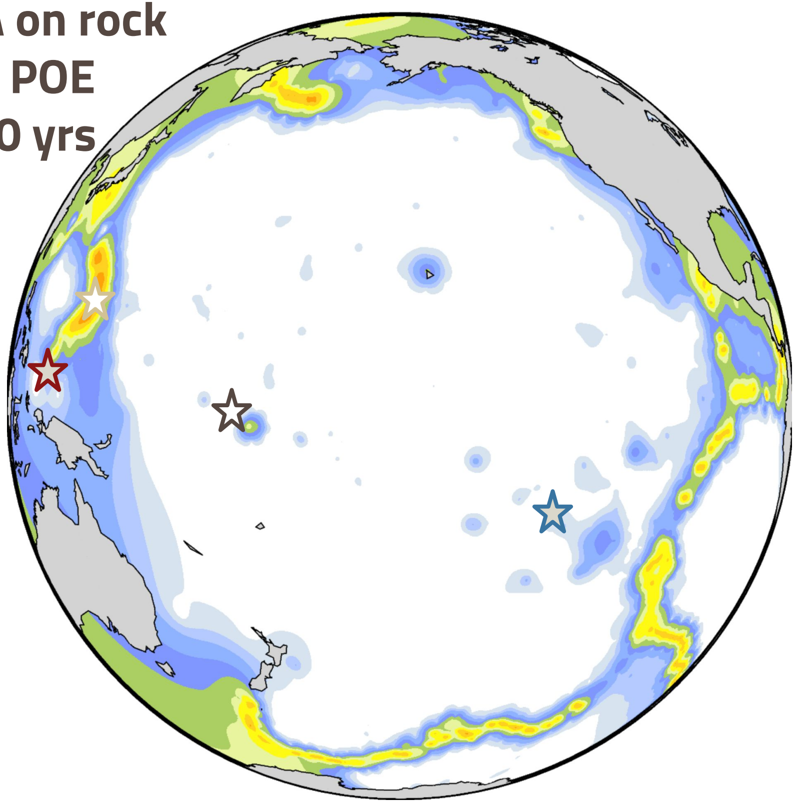
Hazard results - Pacific Ocean

PGA on rock 10% POE in 50 yrs



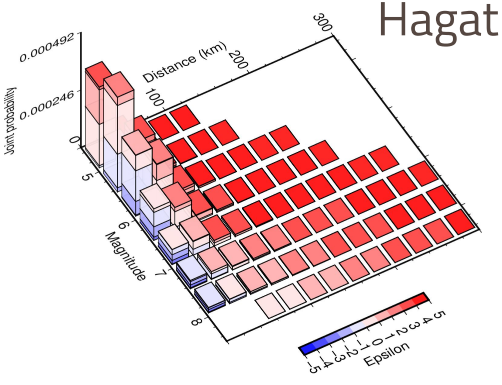
- Highest hazard in Mariana subduction, MOR zones. Small patches of higher hazard linked to clusters of seismicity within the oceanic plates.
- Most island nations in extremely remote Pacific ocean (i.e. Cook islands, Kiribati, French Polynesia, Marshall Islands, Nauru) have very low seismic hazard.
- Closer to Mariana and Caroline plate, the islands have a higher seismic hazard

NB: Pacific ocean model result only; Hawaii and Aleutians subduction not included; Mosaic will use USGS models for these areas.

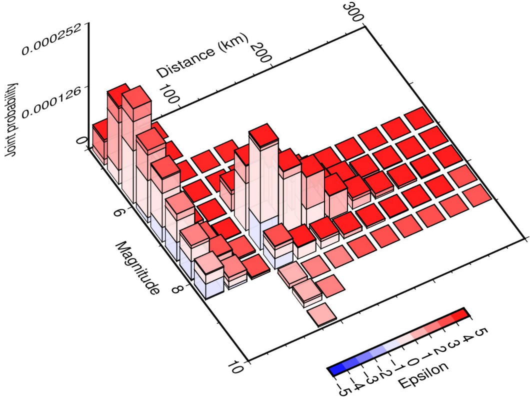
Guam and Northern Mariana

Site	PGA (g) 2%/10% GEM 2024	PGA (g) 2%/10% USGS 2012
Hagatna, Guam	1.14/0.63	*0.94/0.49*
Saipan, N Mariana	0.86/0.45	*0.57/0.29*

Hagatna

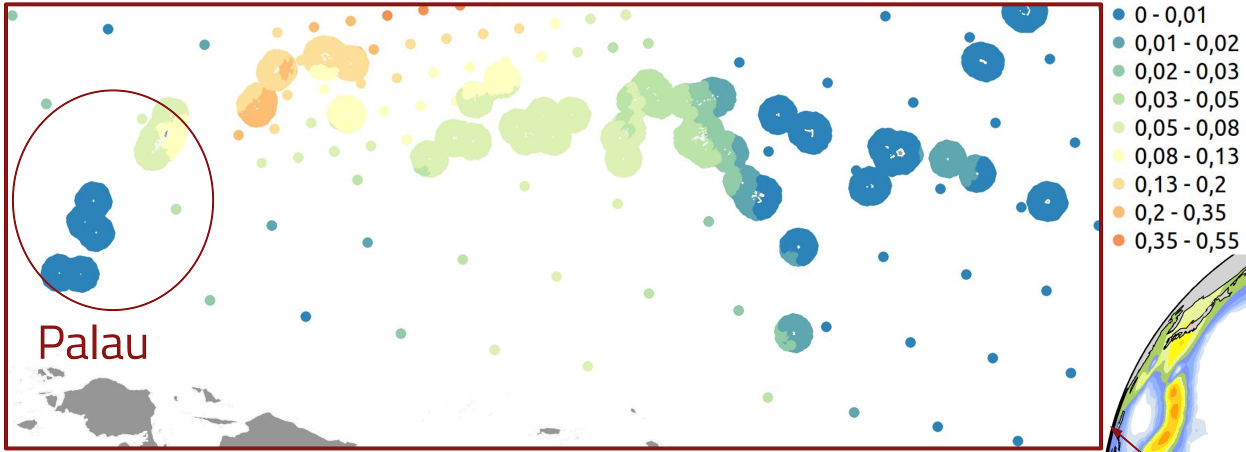


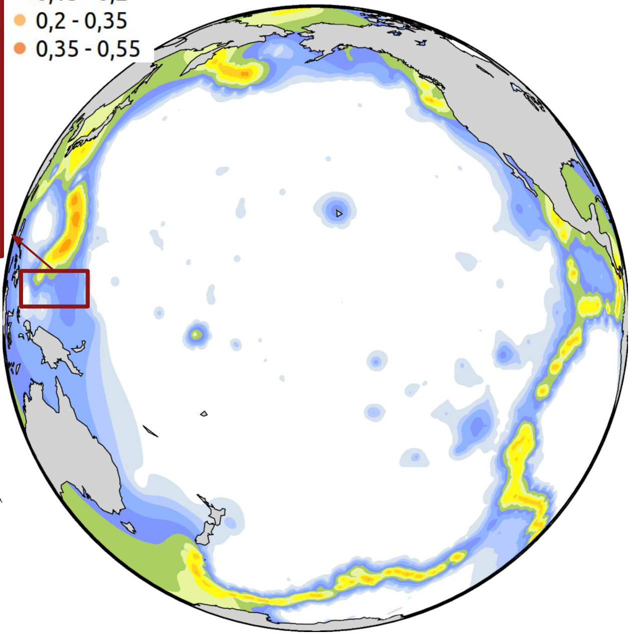
Saipan



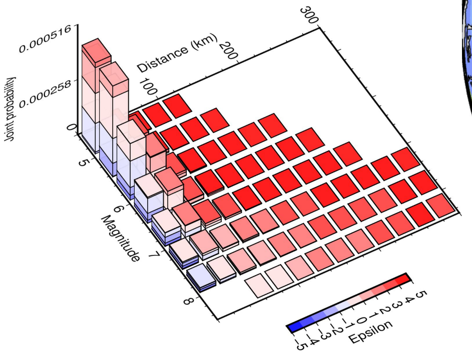
Guam and Northern Mariana regions have higher hazard due to their location above the Mariana subduction zone. We calculate higher PGA and SA results for Guam and N. Mariana than 2012 USGS model, which includes local faults but does not model subduction interface.
Disaggregation shows that this is partly from moderate shallow events

Micronesia and Palau



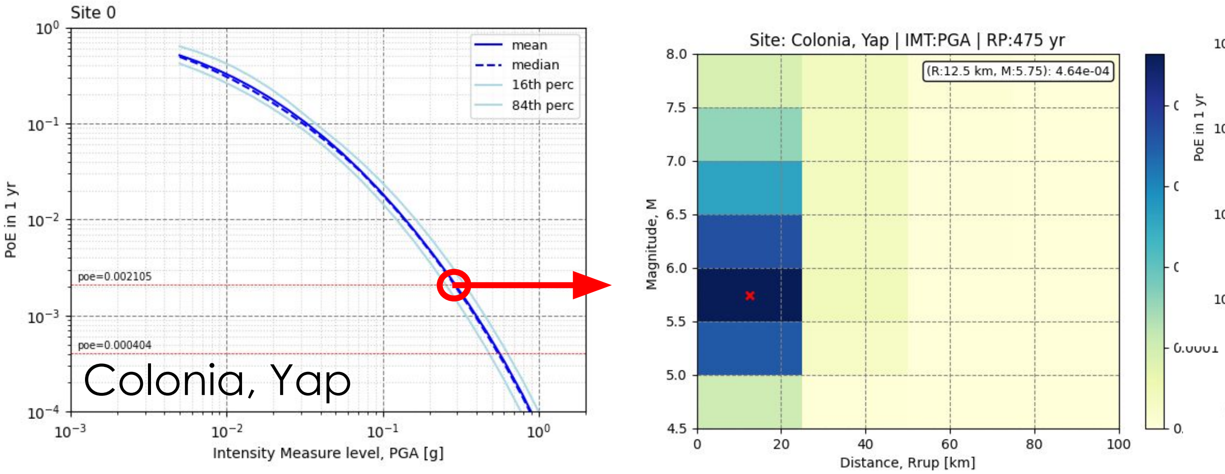


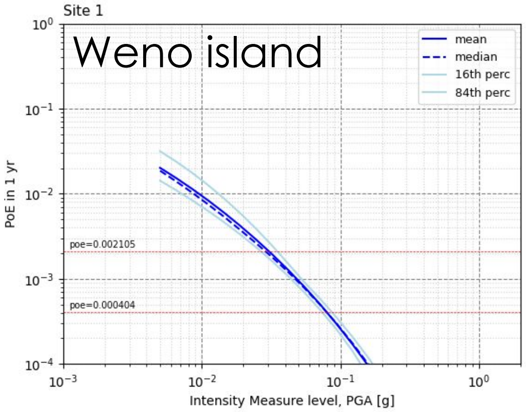
location	PGA (g) 10% in 50yrs	PGA (g) 2% in 50yrs
Koror (city)	0.2148	0.4296

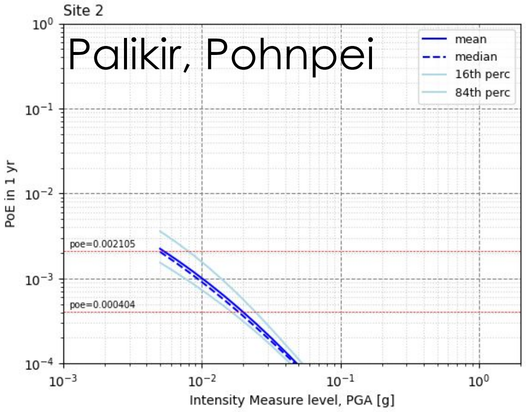


Higher hazard in Koror mostly driven by local crustal seismicity

Federated states of Micronesia







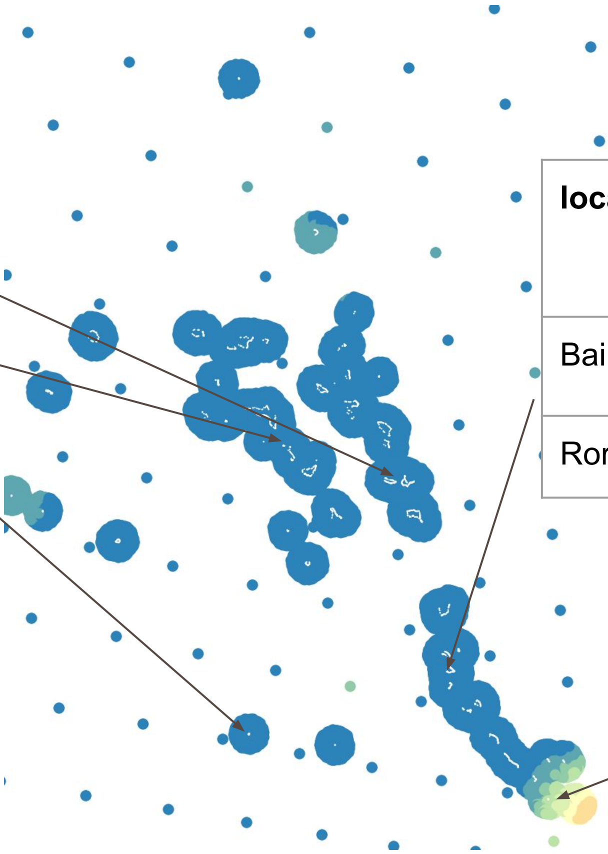
- Hazard is mostly low, with some higher hazard in islands closer to the Mariana subduction zone (i.e. Yap, 0.2g at 10% in 50 years)
- Further from Mariana and Caroline, the hazard drops to very low (PGA 0.01g at 10% in 50 years).

Kiribati, Nauru and Marshall Islands

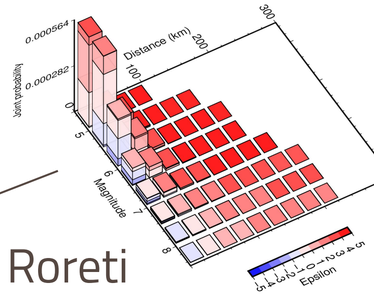
location	PGA (g) 10% in 50 yrs	PGA (g) 2% in 50 yrs
Majuro (MI)	0.00	0.00
Ebeye (MI)	0.00	0.00
Denigomodu (Nauru)	0.00	0.00

Marshall islands, Nauru have very small seismic hazard.

Gilbert Islands (Kiribati) have higher hazard closer to location of 1981-1983 Gilbert Islands swarm



location	PGA (g) 10% in 50 yrs	PGA (g) 2% in 50 yrs
Bairiki	0.0000	0.0000
Roreti	0.1052	0.2194



Roreti

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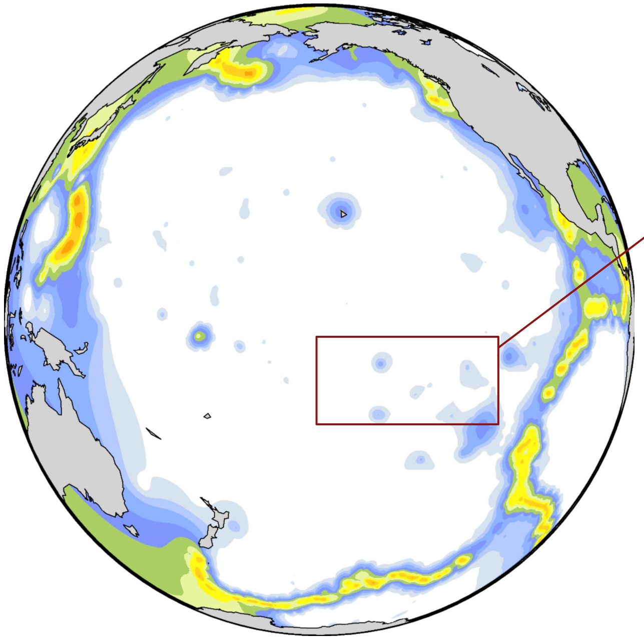
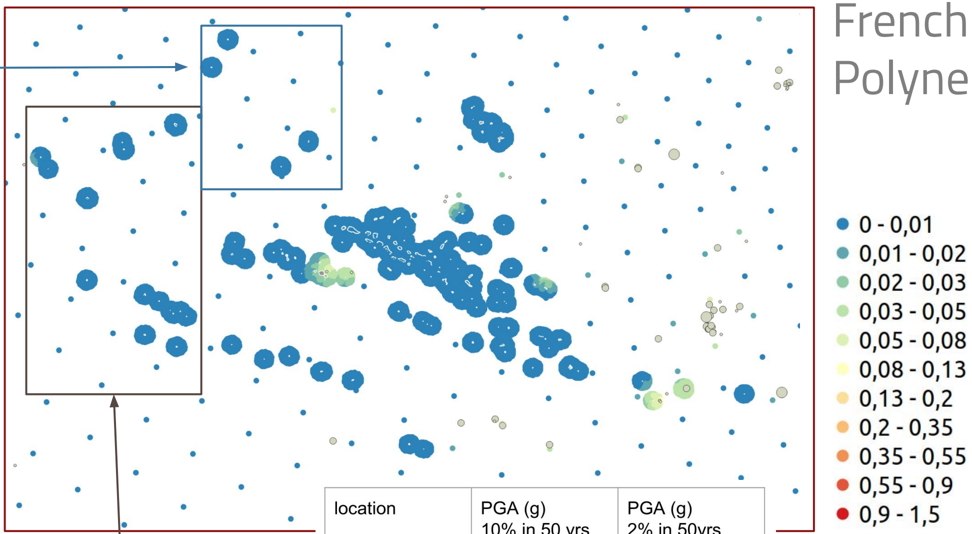
French Polynesia and Cook Islands

Kiribati - Line Islands have very low hazard





French Polynesia

Cook Islands hazard is very low

location	PGA (g) 10% in 50 yrs	PGA (g) 2% in 50yrs
Avarua	0.00	0.00
Aitutaki	0.00	0.00
Mangaia	0.00	0.00
Pukapuka	0.0170965	0.04879174
Aitu	0.00	0.00
Mauke	0.00	0.00
Penrhyn	0.00	0.00
Manihiki	0.00	0.00

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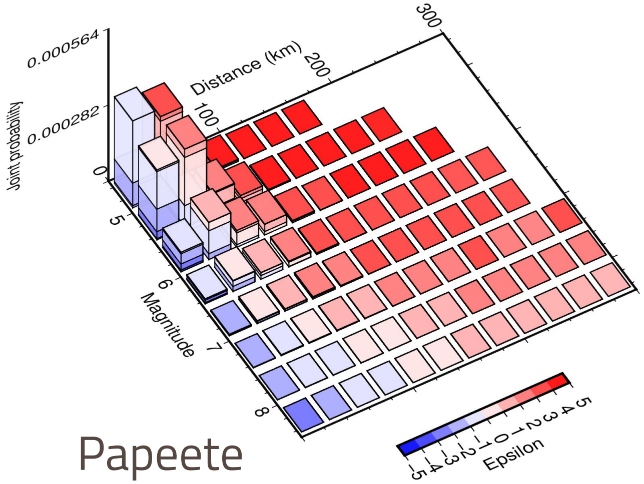
French Polynesia

location	PGA (g) 10% in 50 yrs	PGA (g) 2% in 50 yrs
Pao Pao	0.0319	0.0793
Papeete	0.0428	0.1039
Maiao	0.0165	0.0448
Bora Bora	0.0000	0.0081
Taha'a	0.0000	0.0122
Maupiti	0.0000	0.0000
Ra'iātea	0.0000	0.0141
Hauhine	0.0086	0.0250
Rangiroa	0.0217	0.0601
Magareva	0.0000	0.0000

The hazard in French Polynesia is low, with moderate events at short distances providing the greatest contribution to total hazard



Papeete

Next steps and upcoming activities

- Ocean models to be integrated into Mosaic to produce truly global map
  - Requires homogenisation across the boundaries with other models
  - Scheduled for the first part of 2025; includes making the input models available for certain use cases
- FORCE also has a risk component

- Upcoming workshop! **Understanding earthquake hazard and risk in the southwest Pacific region.**
  - Topics: GEM's hazard and risk models for the southwest Pacific region; introduction to PSHA; introductory level OpenQuake Engine training
  - Suva, Fiji, November 18-19, 2024, during the 2024 STAR conference
  - Free but registration is required
  - Contact **training@openquake.org**

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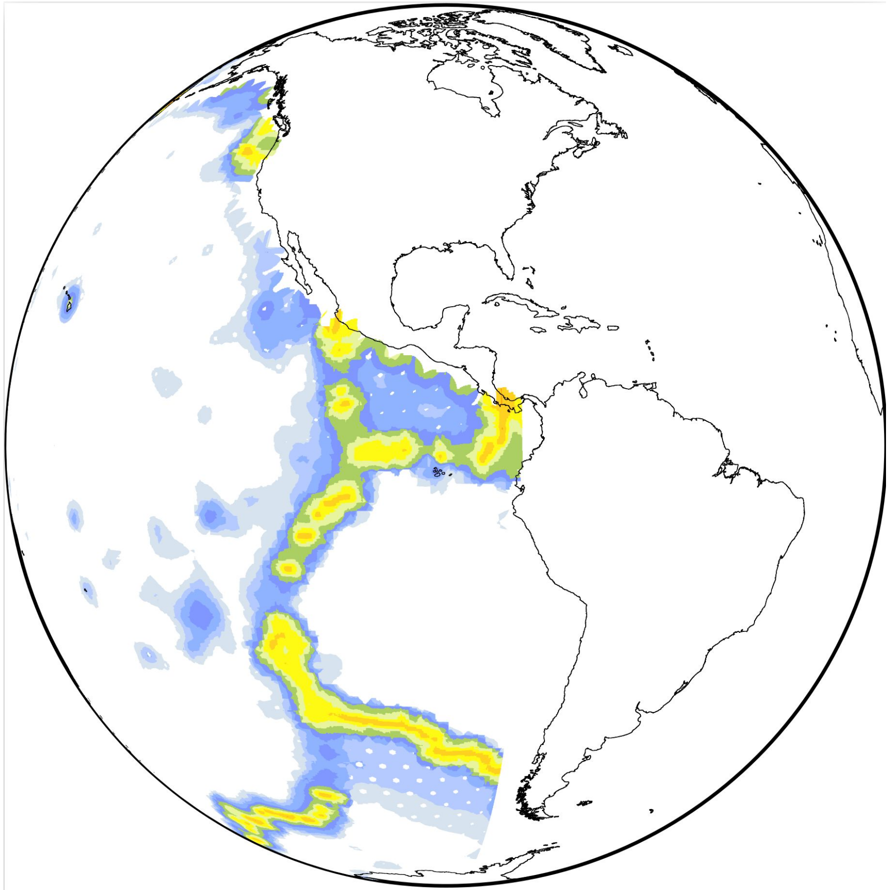
Thank you!

Please attribute to the GEM Foundation with a link to:
https://www.globalquakemodel.org

Hazard results - Pacific Ocean



location	PGA (g) 10% in 50 yrs	PGA (g) 2% in 50 yrs
Hanga Roa (Easter Island)	0.0167	0.04507
Adamstown (Pitcairn islands)	0.0514	0.1211
Isabela Island (Galapagos)	0.0616	0.1362
San Cristobal Is. (Galapagos)	0.0129	0.0359
Santa Cruz Is. (Galapagos)	0.0236	0.0553

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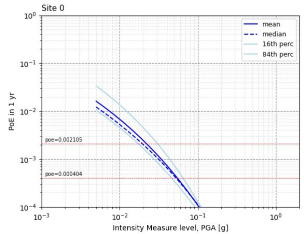
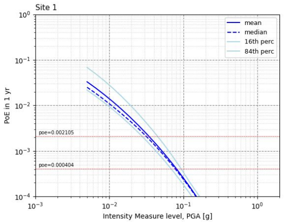
Hazard results - Atlantic Ocean

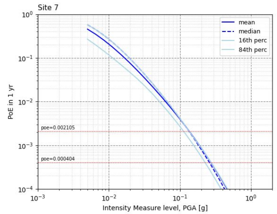
Cabo Verde

Praia



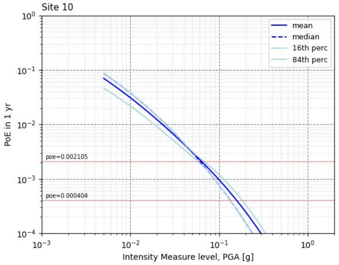
Sao Vicente

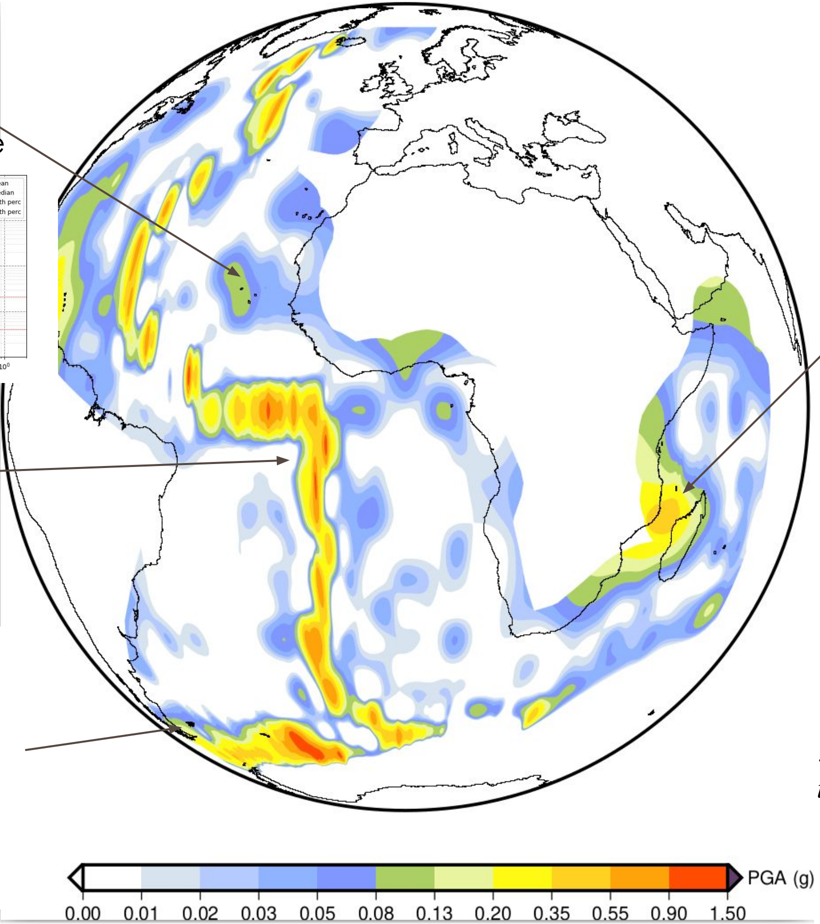




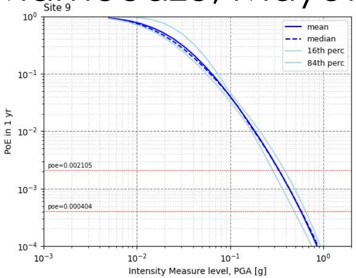
Ascension

Stanley

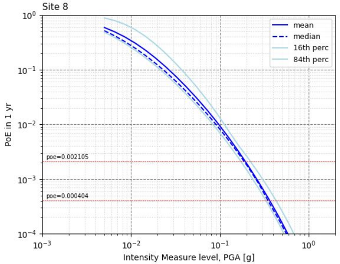




Mamoudzu, Mayotte



Moroni, Comoros



PGA on reference rock for 10% in 50 years for the Atlantic ocean model, with the colour scale consistent with the 2023 seismic hazard model.

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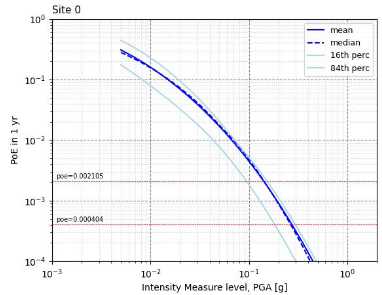
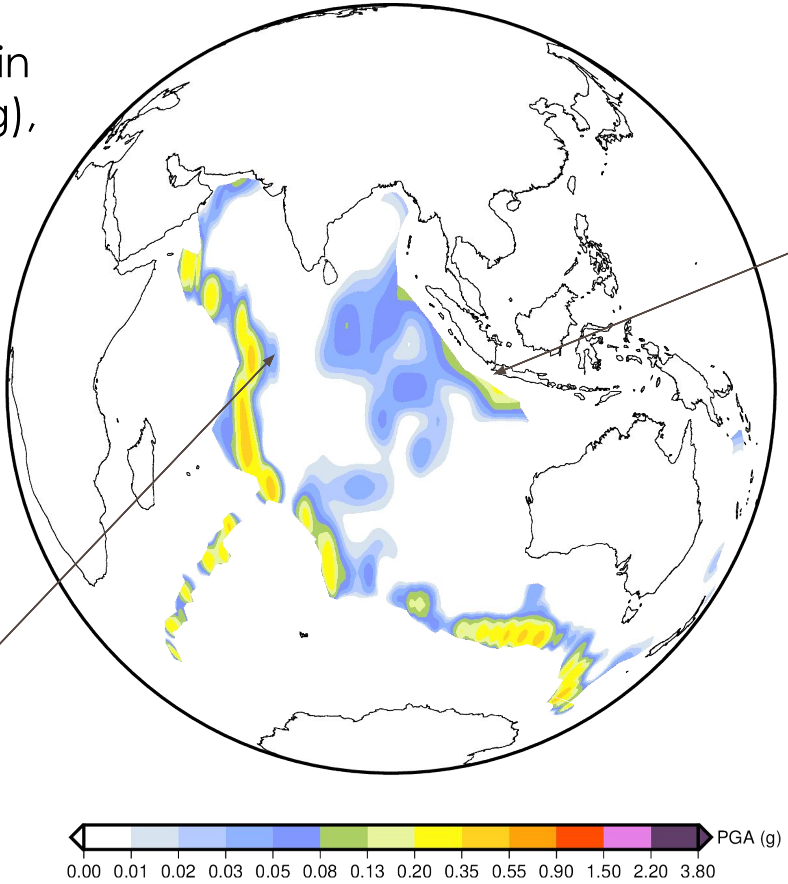
Hazard results - Indian Ocean

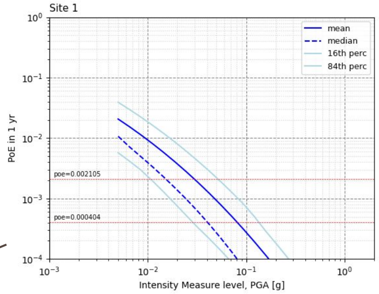
Very low hazard in Maldives (< 0.01g), higher in Cocos and Christmas island, Diego Garcia (Chagos Islands)

Diego Garcia

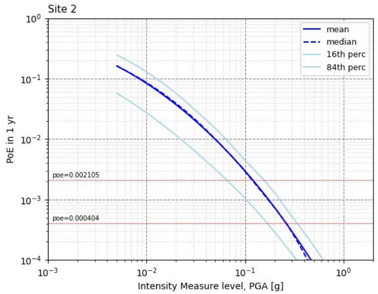




Pulu Selma, Cocos



Flying fish cove, Christmas island



PGA on reference rock for 10% in 50 years for the Indian Ocean model, with the scale consistent with the 2023 seismic hazard model.

Completeness calculations

- For each zone, jointly estimate the completeness and FMD

- Given a list of possible years and magnitude, calculate FMD params for each possible set of windows and compare with some norm

- For oceans, we use the criterion of a Poisson rate in the declustered catalogue - this is (generally) less influenced by declustering choices than an alternative that looks for GR FMD and is less strongly influenced by large numbers of small events