

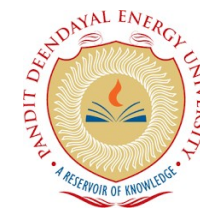
From PTHA 1.0 to a regional consensus model: a Roadmap

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S. Lorito (INGV, Italy) and F. Lovholt (NGI, Norway)

Makran PTHA v.1.0 development team

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F. Romano, M. Volpe, A. Scala, J. Selva, M. Taroni, S. Chopra, A. Deif

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National Institute for Geophysics and Volcanology INGV, Italy
University of Naples, Italy
Sultan Qaboos University, Oman
Pandit Deendayal Petroleum University, India*



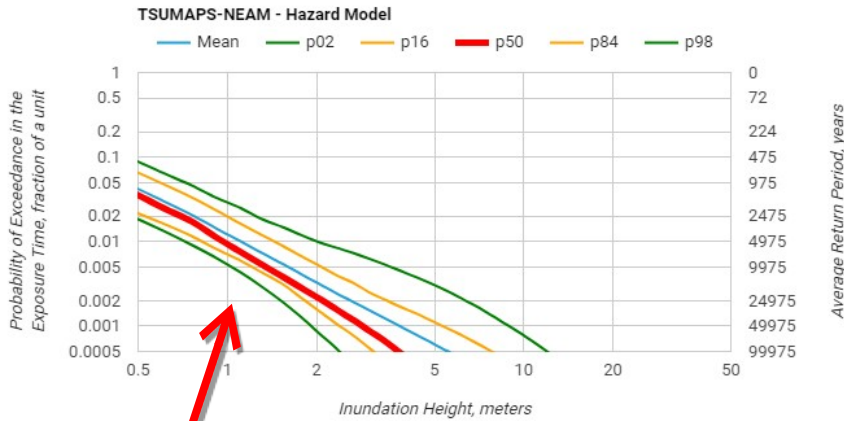
Why PTHA*?

***PTHA** stands for **P**robabilistic **T**sunami **H**azard **A**ssessment

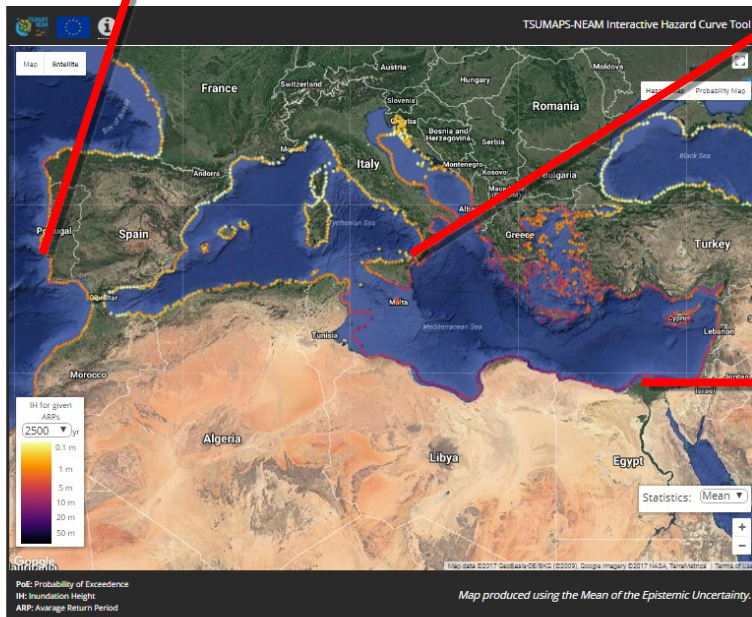
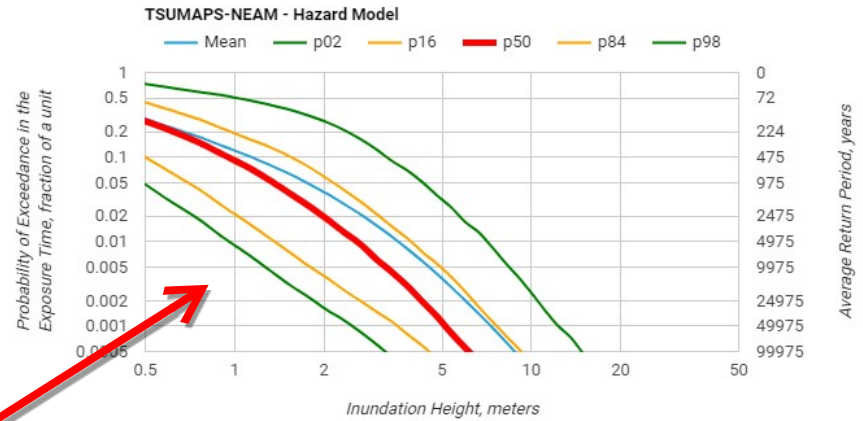
- Requires treatment of ALL possible seismic tsunamigenic sources, not only those with the large magnitudes
- Byproduct: Tsunami database which could be used for any kind of further studies and applications, e.g., for early warning, inundation mapping, evacuation planning
- Sources and, hence, their tsunami impacts, come with probabilities of occurrence
- That allows to answer questions like: what is the probability of a tsunami wave height above 1 m within the next 50 years?

Approach: make PTHA following the methodology of <http://tsumaps-neam.eu>

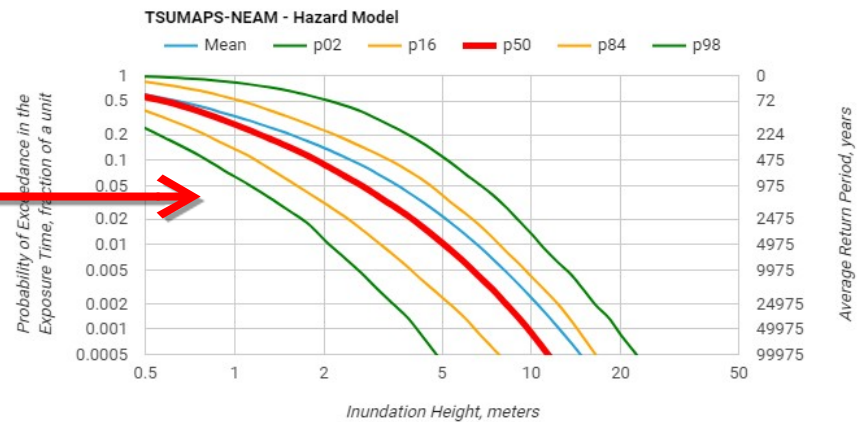
Lisbon, Portugal



Messina, Italy



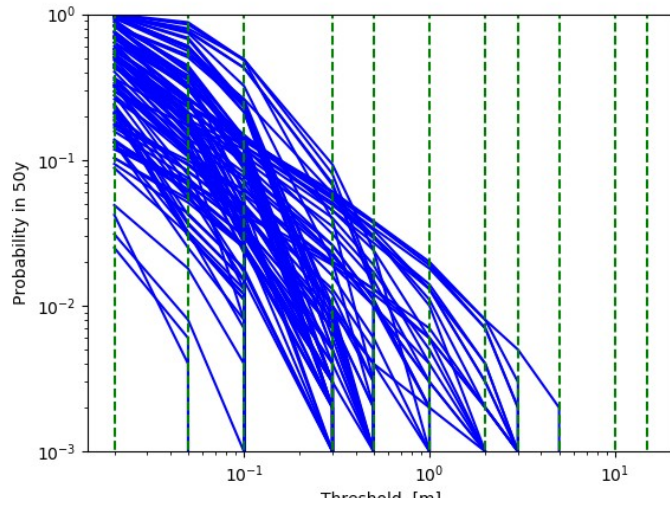
Alexandria, Egypt



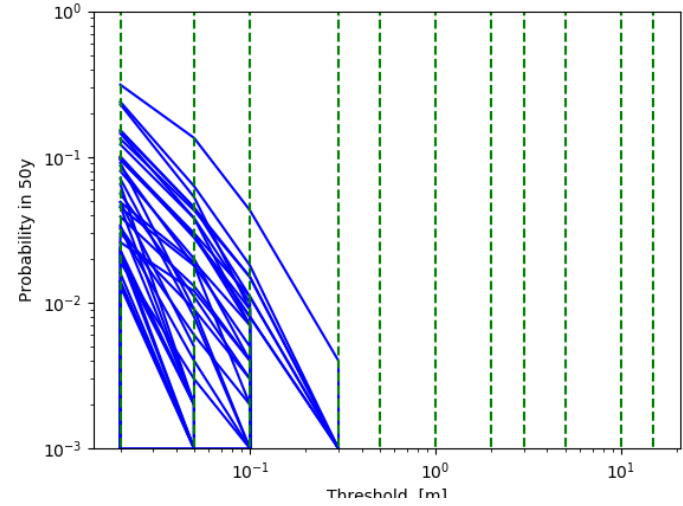
PTHA Makran Region v.1.0 Hazard Curves

M1

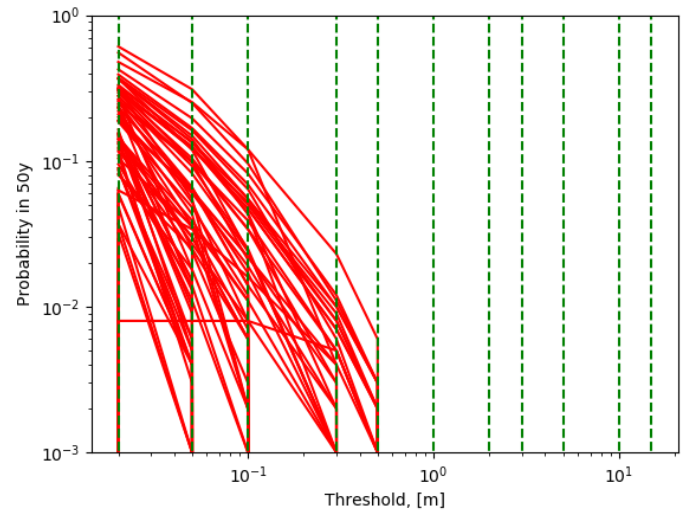
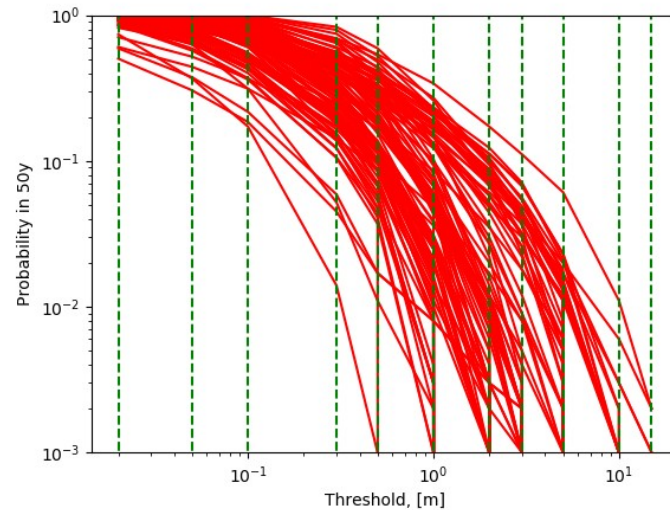
Arabian Sea
(all 111 POIs)



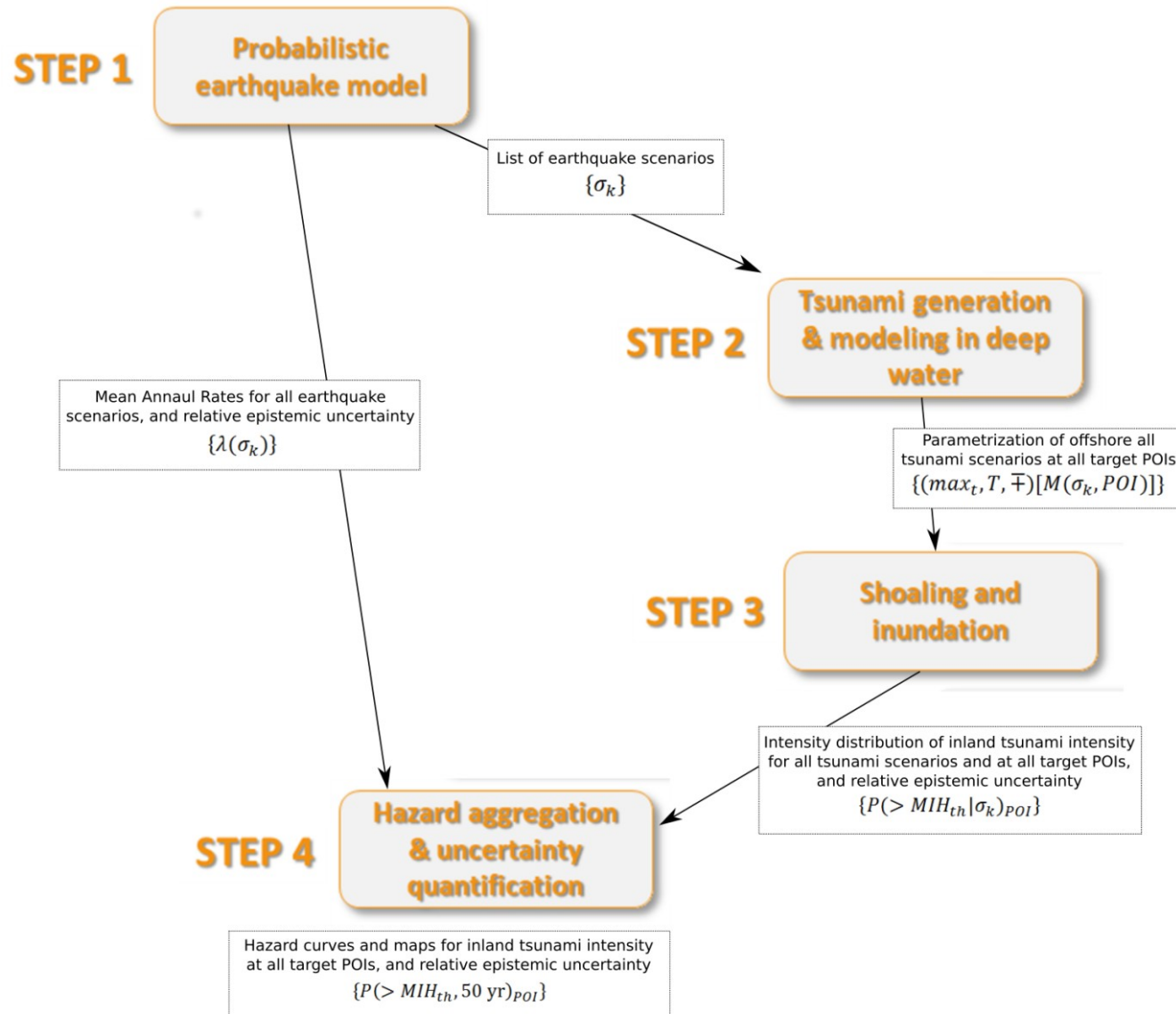
Persian Gulf
(all 197 POIs)



M2



PTHA method as implemented in TSUMAPS-NEAM



PTHA method as implemented in TSUMAPS-NEAM

- Hazard assessment: STEPS & LEVELS workflow -

STEP 1 **Probabilistic earthquake model** **Goals:**

- definition of all the possible representative seismic sources that may generate tsunamis in the future;
- quantification of their long-term mean annual rate.

This analysis is performed with an Event Tree that decomposes the problem into a chain of discrete conditional probabilities for aleatory variables describing the earthquakes.

Levels:

Regionalization & Seismic DBs

Magnitude-Frequency Distribution (MFD)

Variability of earthquakes for each source (rupture position, mechanism, size, slip) and for each magnitude of the MFD

STEP 2 **Tsunami generation & modeling in deep water** **Goals:**

- simulation of the sea-floor displacement;
- simulation of the tsunami generation and propagation from source to target area, at a given bathymetric depth.

The output of this step are tsunami waveforms, modeled on a chosen isobath along the coasts of interest at chosen points of interest in front of them.

Levels:

Crustal model (elastic parameters, friction), topo-bathymetric datasets, and digital elevation models

Coseismic displacement

Tsunami generation model

Tsunami propagation model in deep water

STEP 3 **Shoaling and inundation** **Goals:**

- simulation of the last phases of the tsunami impact;
- stochastic simulation of the associated uncertainty (including both source and tsunami modeling).

The output of this step is the maximum inundation distance (the chosen hazard metrics) and its distribution at the chosen points of interest along the coast.

Levels:

Topo-bathymetric datasets and digital elevation models

Amplification and inundation model

Uncertainty modeling for hazard metrics (including stochastic modeling of non-modeled effects from STEPS 1-3)

STEP 4 **Hazard aggregation & uncertainty quantification** **Goals:**

- calculation of the hazard curves at the target sites for different percentiles of the epistemic uncertainty;
- sensitivity and disaggregation analyses.

Each considered alternative produces a hazard curve. Weights assigned to alternatives are critical. The ensemble of the hazard curves is analyzed for uncertainty estimation. Statistics (quantiles) of the ensemble characterize results and their uncertainty. Hazard curves are used to produce hazard and probability maps.

Levels:

Elicitation of experts

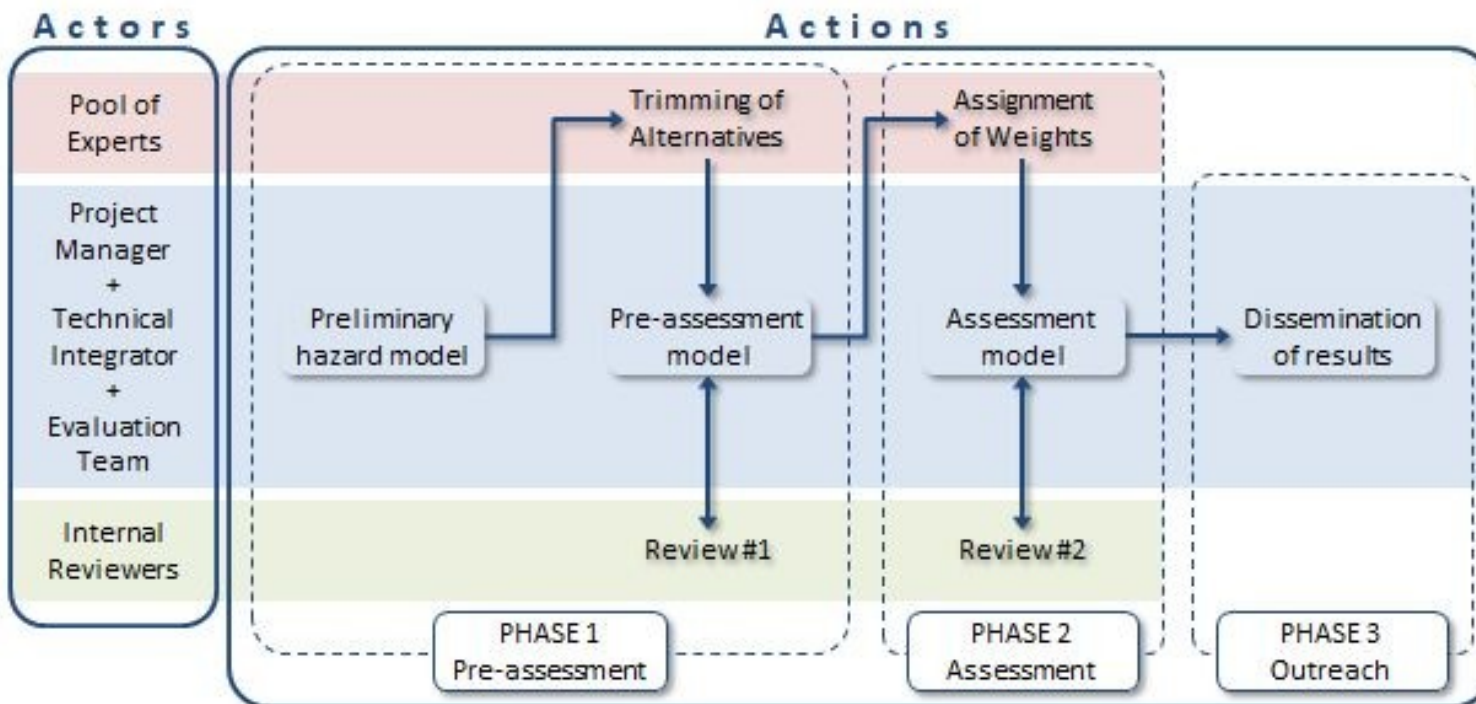
Combination of STEPS from 1-3

Quantification of uncertainty

PTHA method as implemented in TSUMAPS-NEAM

Problem: Too many alternatives at each step but especially by constructing earthquake source model – which of them are “better”? What means “better”? Who should decide which alternatives are better than others? And on which criteria?

Solution attempt: Let’s ask experts. Ask them about their preferences. And then we will use expert’s recommendations to “weight” the alternatives.





Developing a seismic source model for the Arabian Plate

I. El-Hussain¹ · Y. Al-Shijbi¹ · A. Deif^{1,2} · A. M. E. Mohamed^{1,2} · M. Ezzelarab^{1,2}

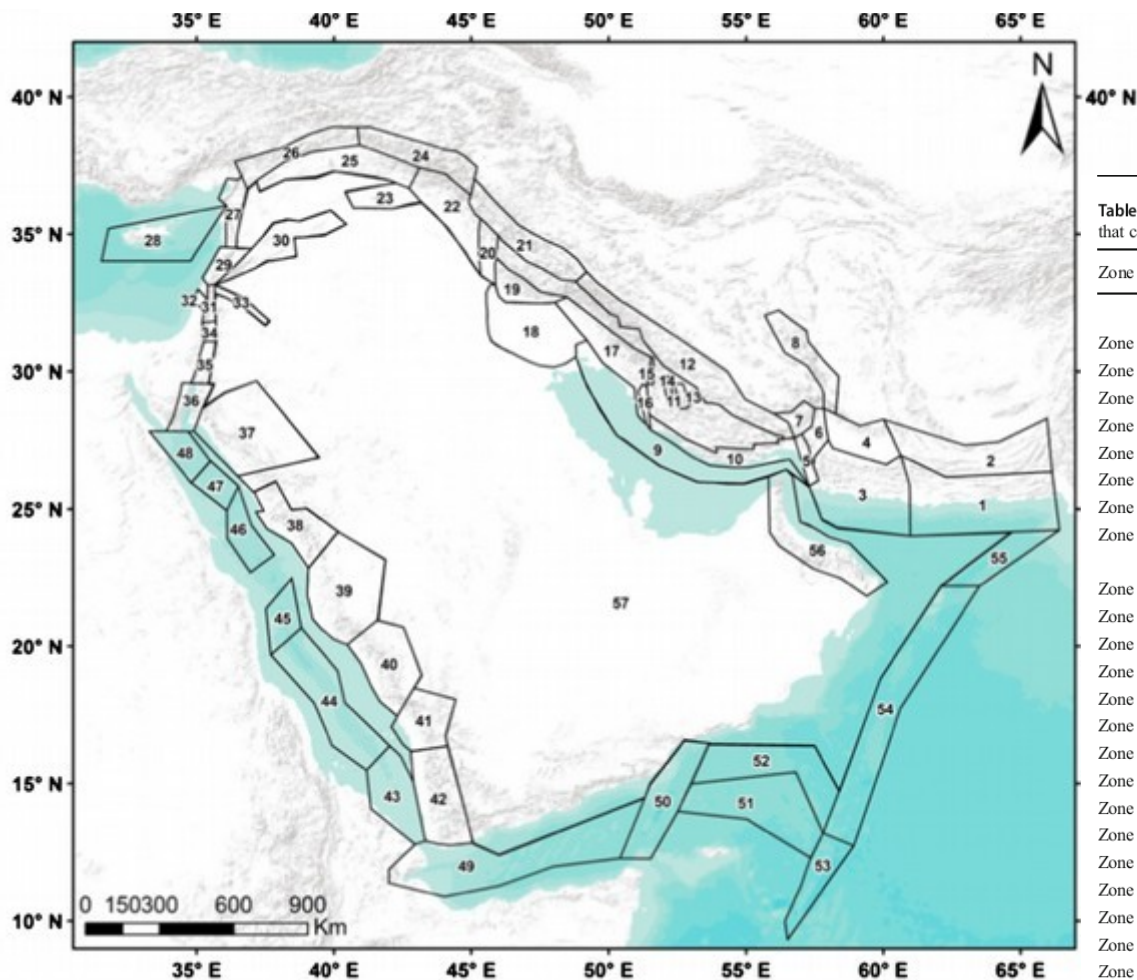
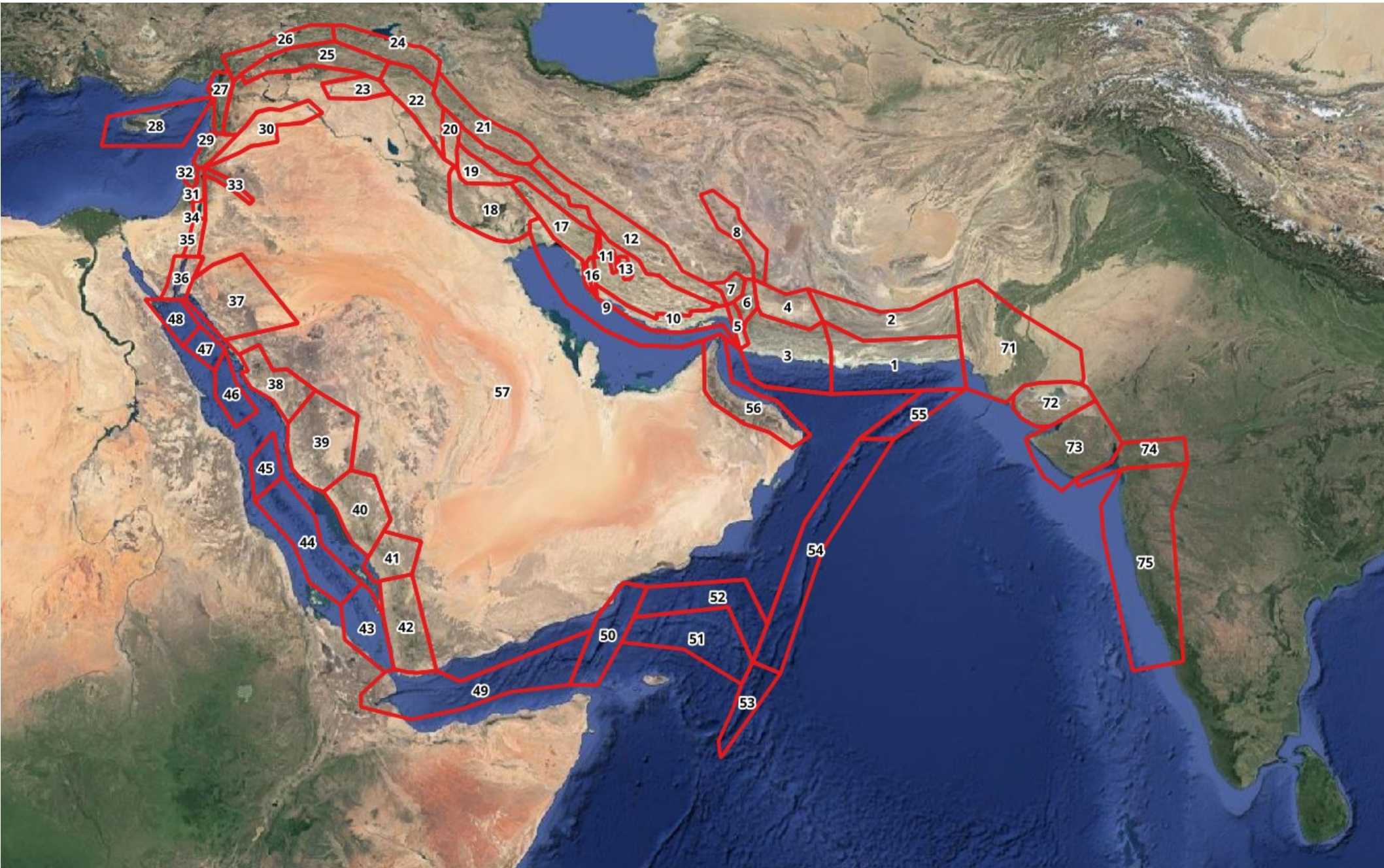


Table 1 Earthquake recurrence parameters for the delineated seismic sources. *Italic font* are the recurrence parameters for the zone that contains the delineated seismic sources (All Makran, All Zagros, All Gulf of Aqaba-Dead Sea Fault, All Red Sea, All Arabian Gulf)

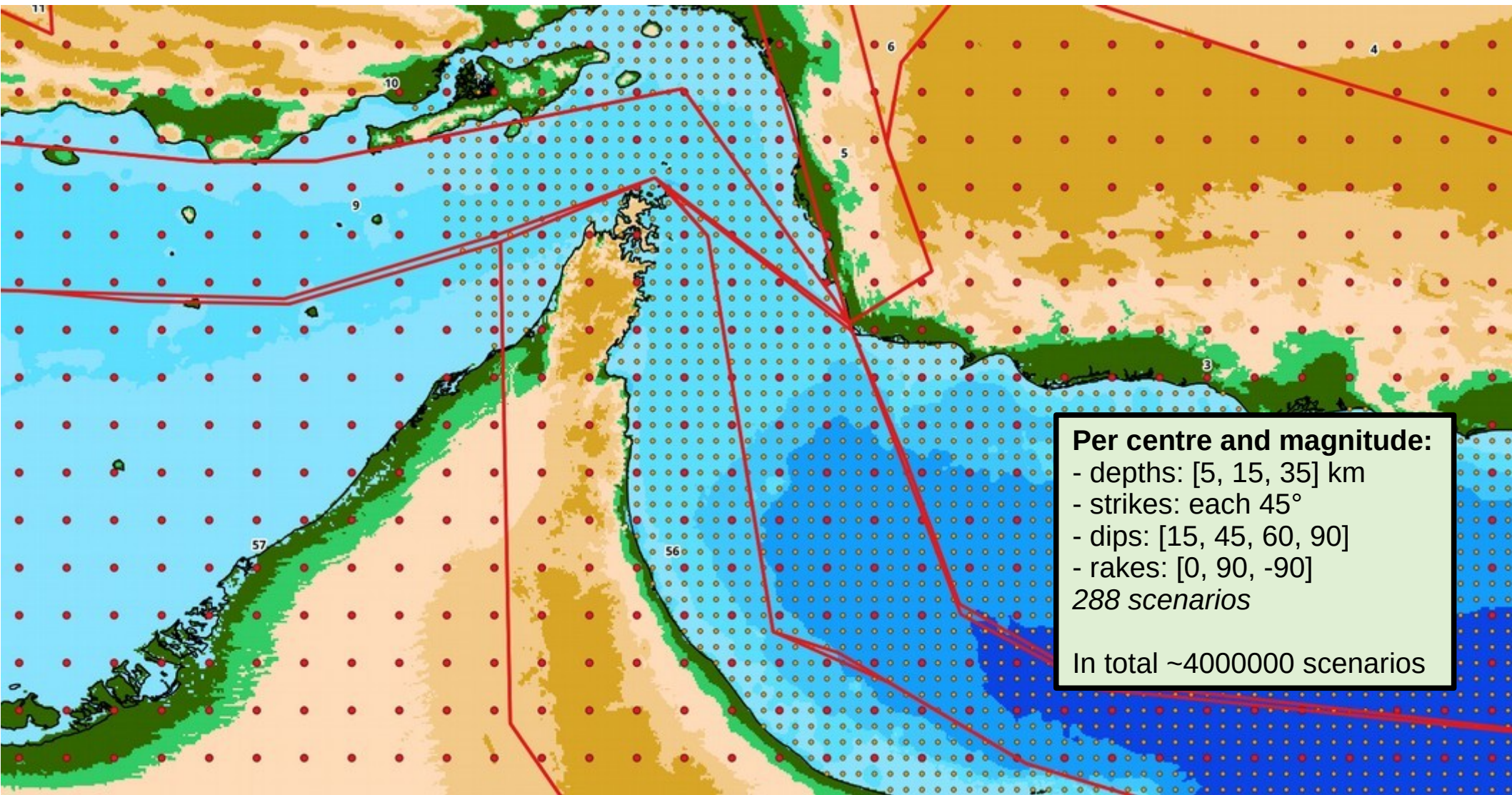
Zone No.	Zone Name	M_{max}	σM_{max}	M_{min}	M_{maxobs}	β	$\sigma\beta$	b	σb
	<i>All Makran</i>	<i>8.4</i>	<i>0.27</i>	<i>4</i>	<i>8.1</i>	<i>1.67</i>	<i>0.07</i>	<i>0.73</i>	<i>0.03</i>
Zone 1	Makran East	8.4	0.1	4	8.1	1.57	0.14	0.68	0.06
Zone 2	Makran Intraplate	7.8	0.3	4	7.3	1.49	0.16	0.65	0.06
Zone 3	Makran West	6.2	0.23	4	5.9	1.65	0.19	0.72	0.08
Zone 4	Jaz Murian	6.8	0.82	4	6.1	1.56	0.2	0.68	0.09
Zone 5	Zendan Fault	6.3	0.22	4	6.1	1.30	0.2	0.57	0.09
Zone 6	Jiroft Fault	6.0	0.14	4	5.8	1.70	0.17	0.74	0.07
Zone 7	Ali Abad	6.8	0.18	4	6.6	1.52	0.14	0.66	0.06
Zone 8	Gowk Fault	7.5	0.34	4	7.2	1.68	0.13	0.73	0.06
	<i>All Zagros</i>	<i>7.5</i>	<i>0.12</i>	<i>4</i>	<i>7.4</i>	<i>1.84</i>	<i>0.04</i>	<i>0.8</i>	<i>0.02</i>
Zone 9	Arabian Gulf	6.2	0.26	4	6.1	1.74	0.16	0.76	0.07
Zone 10	Zagros Foredeep	6.8	0.21	4	6.7	1.83	0.11	0.79	0.05
Zone 11	Zagros Simple Fold	6.9	0.21	4	6.8	1.82	0.07	0.79	0.03
Zone 12	High Zagros	7.6	0.24	4	7.4	1.75	0.1	0.76	0.04
Zone 13	Sabz Pushan Fault	6.3	0.34	4	6.1	1.69	0.19	0.73	0.08
Zone 14	Karebas Fault	5.8	0.46	4	5.4	1.81	0.22	0.78	0.09
Zone 15	Kazerun Fault	6.0	0.21	4	5.9	1.60	0.19	0.69	0.08
Zone 16	Borazgan Fault	5.8	0.22	4	5.7	1.61	0.19	0.7	0.08
Zone 17	Dezful Embayment	6.8	0.12	4	6.7	1.86	0.1	0.81	0.04
Zone 18	Mesopotamia	6.5	0.3	4	6.4	2.15	0.18	0.93	0.08
Zone 19	MFF	6.4	0.22	4	6.3	1.59	0.15	0.69	0.06
Zone 20	Khanagin Fault	7.3	0.32	4	7.2	1.76	0.16	0.76	0.07
Zone 21	Posht-E Kuh Arc	7.0	0.31	4	6.9	1.86	0.14	0.81	0.06
Zone 22	Kirkuk Embayment	6.6	0.3	4	6.5	1.68	0.17	0.73	0.07
Zone 23	Abdelaziz-Sinjar	5.4	0.36	4	5.2	1.91	0.22	0.83	0.1
Zone 24	Bitilis	6.9	0.32	4	6.8	1.91	0.2	0.83	0.09
Zone 25	Karacadag Extension	6.9	0.31	4	6.8	1.72	0.23	0.75	0.1

Makran PTHA :: STEP 1 “Earthquake Model”



Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Modeling of volume-distributed (background) seismicity



● - centres of back-ground seismicity (distance ~25 km)

Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Modeling of Mmax, G-R parameters, focal mechanisms

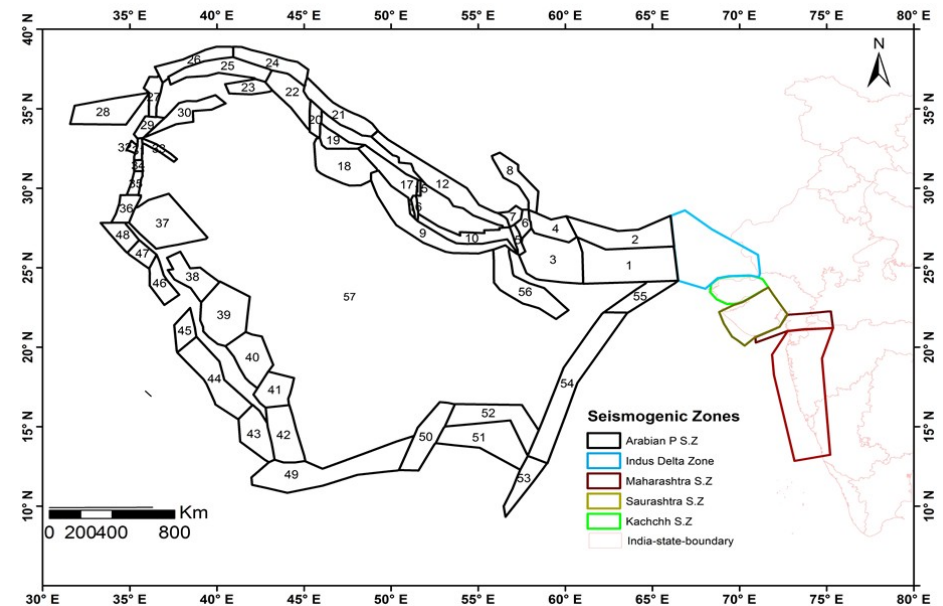
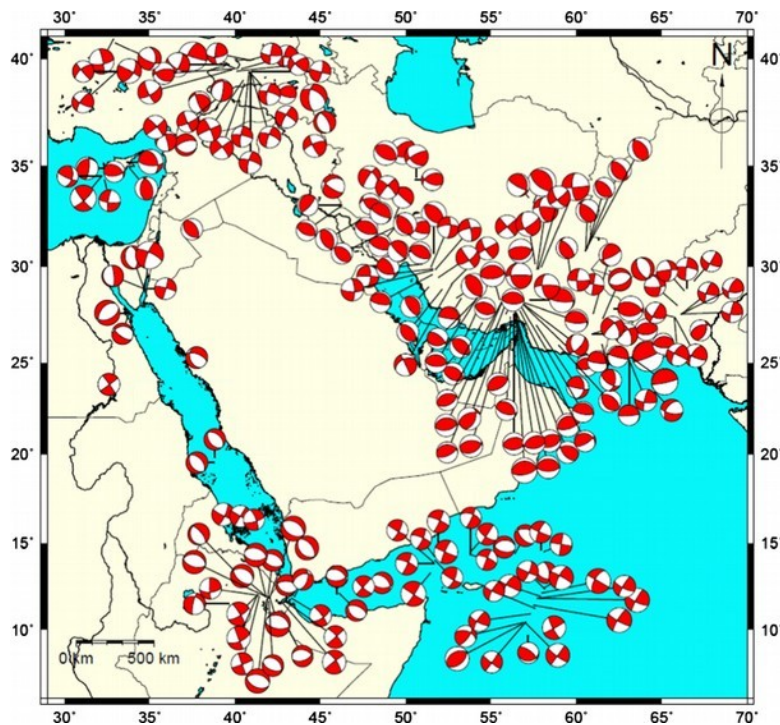
Arabian plate zones:

- Mmax and G-R based on PSHA (El-Hussain et al.'2018)

- Focal mechanisms: PDF derived from CMT compilation (A.Deif pers.comm)

West Indian zones (71-75):

- All parameters based on pers. comm. S. Chopra

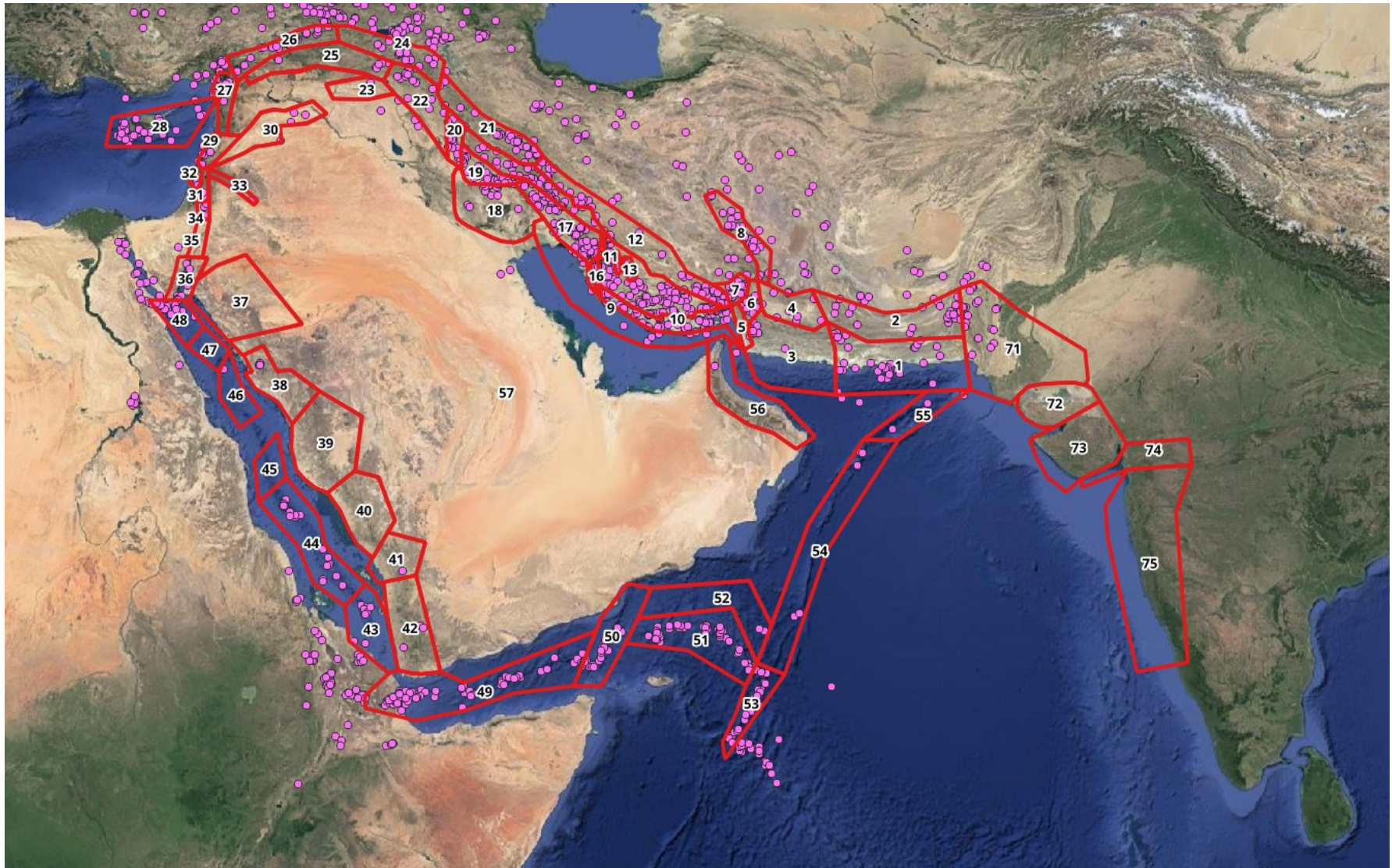


Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Modeling of seismicity: Mmax, G-R parameters, focal mechanisms

Arabian plate zones

Problem with focal mechanism statistics: Few observations for many zones

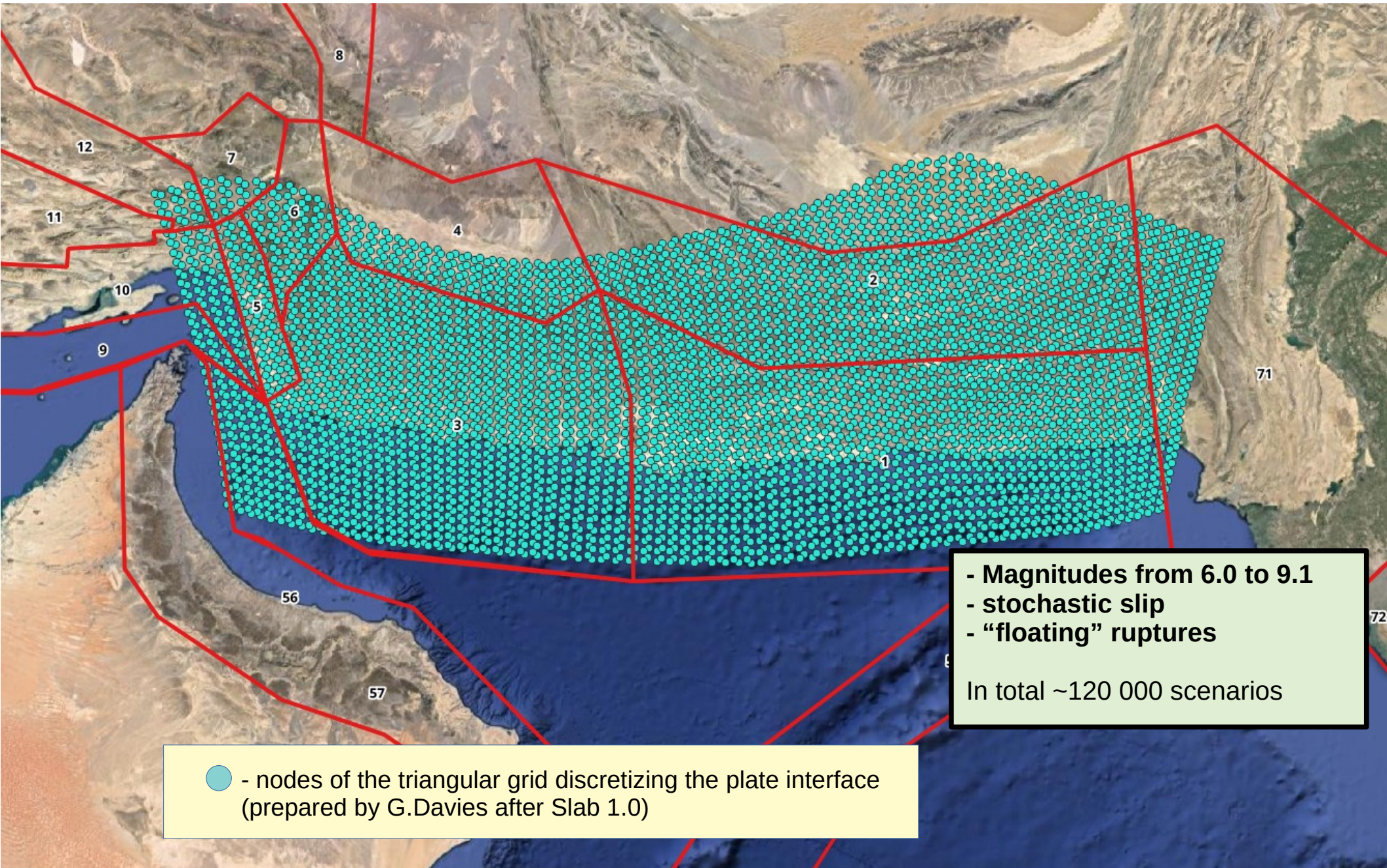


Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Alternatives to consider?

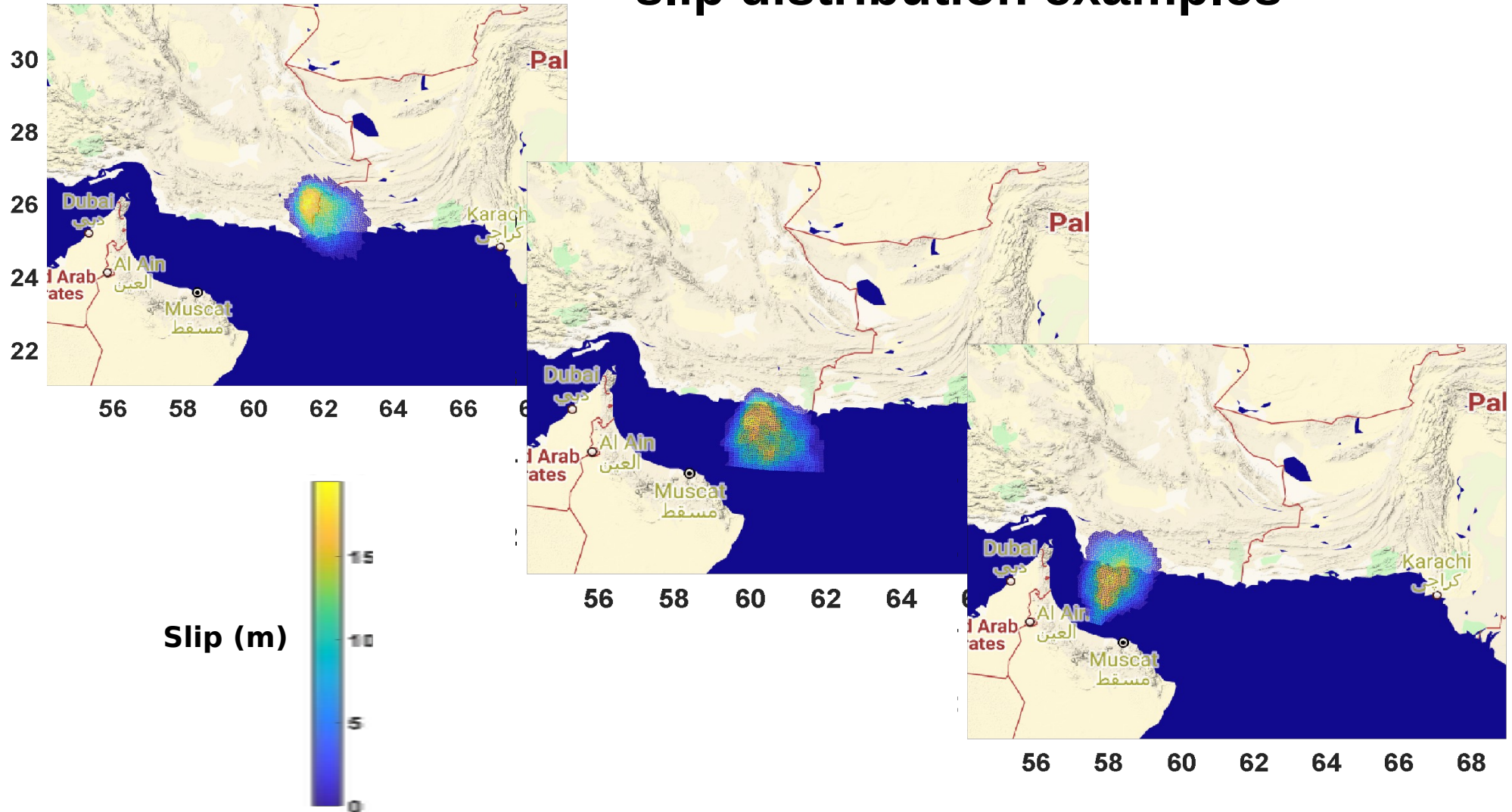
- 1) Alternative zone **rates** based on re-analysis of the last earthquake catalogs version :: **done by INGV+UniNapoli**
- 2) Add a new zone with normal faults (shallow, close to the Makran coast) :: **done(?) by INGV+UniNapoli**
- 3) Derive predominant focal parameters (strike, dip, rake) from geology. E.g., for Zagros :: **to do by Iranian colleagues(?)**

Makran PTHA :: STEP 1 “Earthquake Model” :: PS Modeling of seismicity along the plate interface



Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Makran subduction M8.5 slip distribution examples

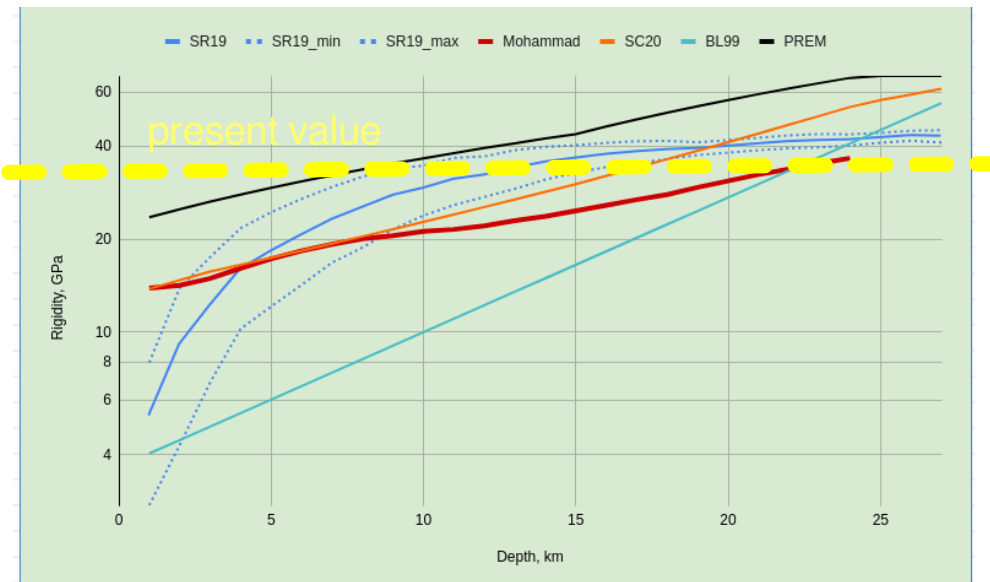


Makran PTHA :: STEP 1 “Earthquake Model” :: PS

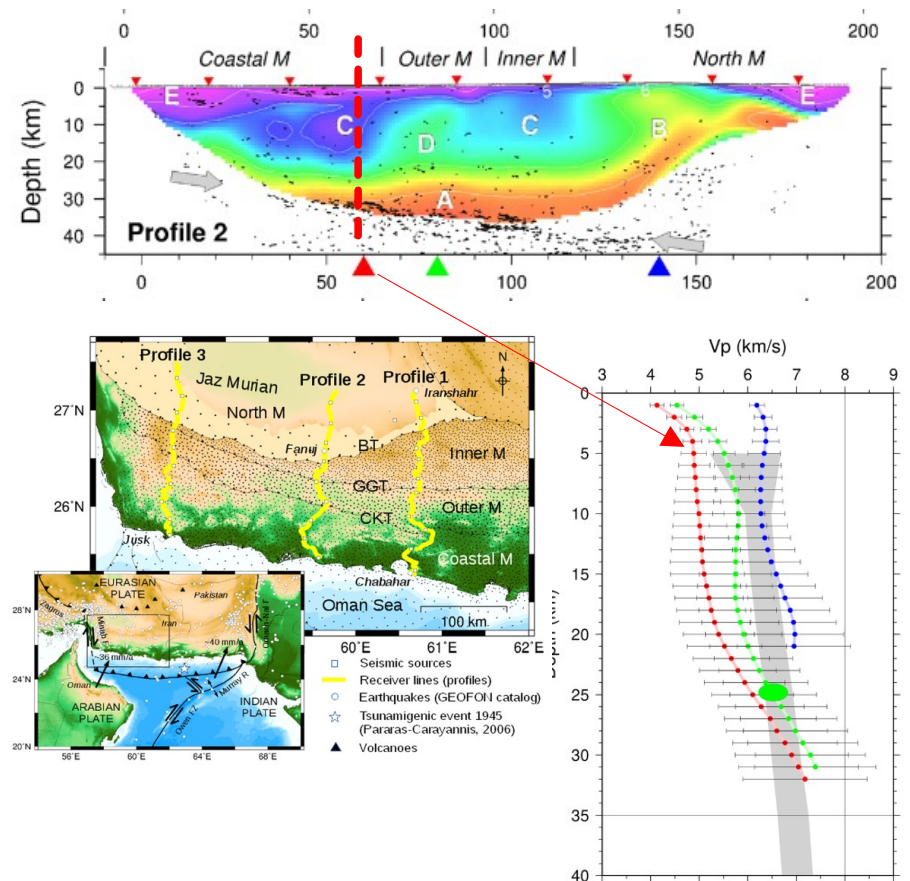
Alternatives to consider?

Rigidity of the upper crustal layer

The **lower** is rigidity, the **higher** will be slip (and uplift!) for the same magnitude



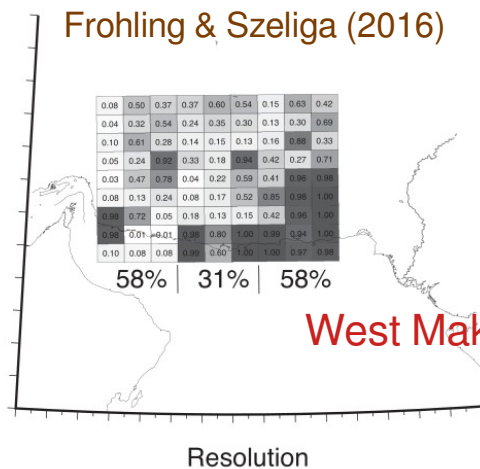
Haberland et al. (2020)



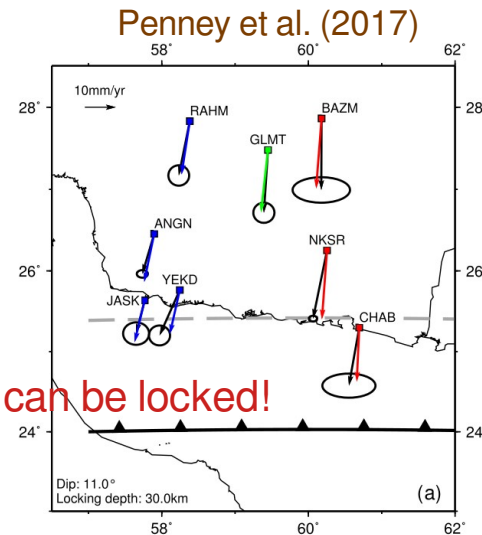
Makran PTHA :: STEP 1 “Earthquake Model” :: PS

Alternatives to consider?

- 1) Segmented/unsegmented (West/East Makran problem)
- 2) Tectonic and seismic rates
- 3) Various coupling along the plate interface



West Makran can be locked!



Mokhtari (2014)

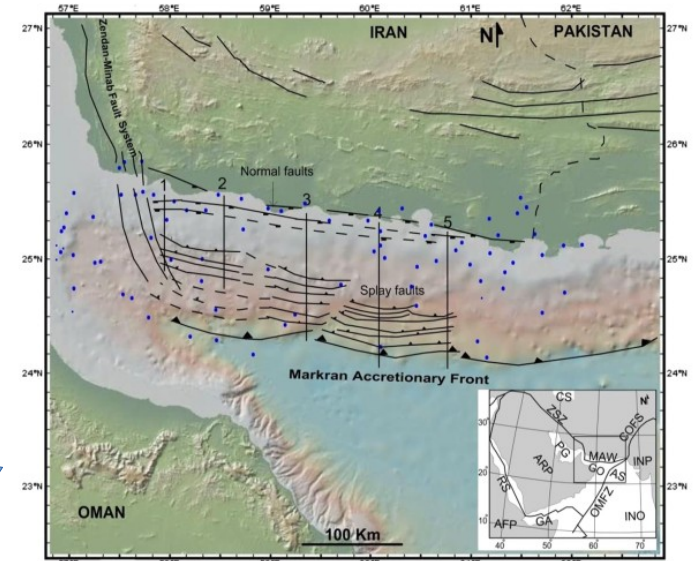
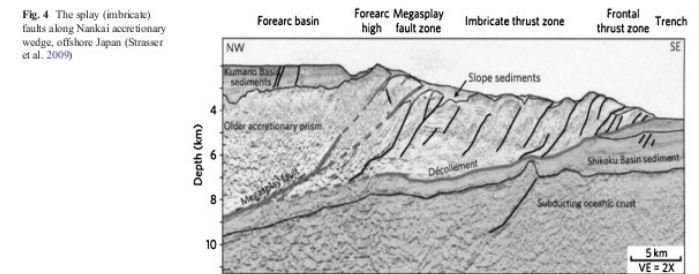
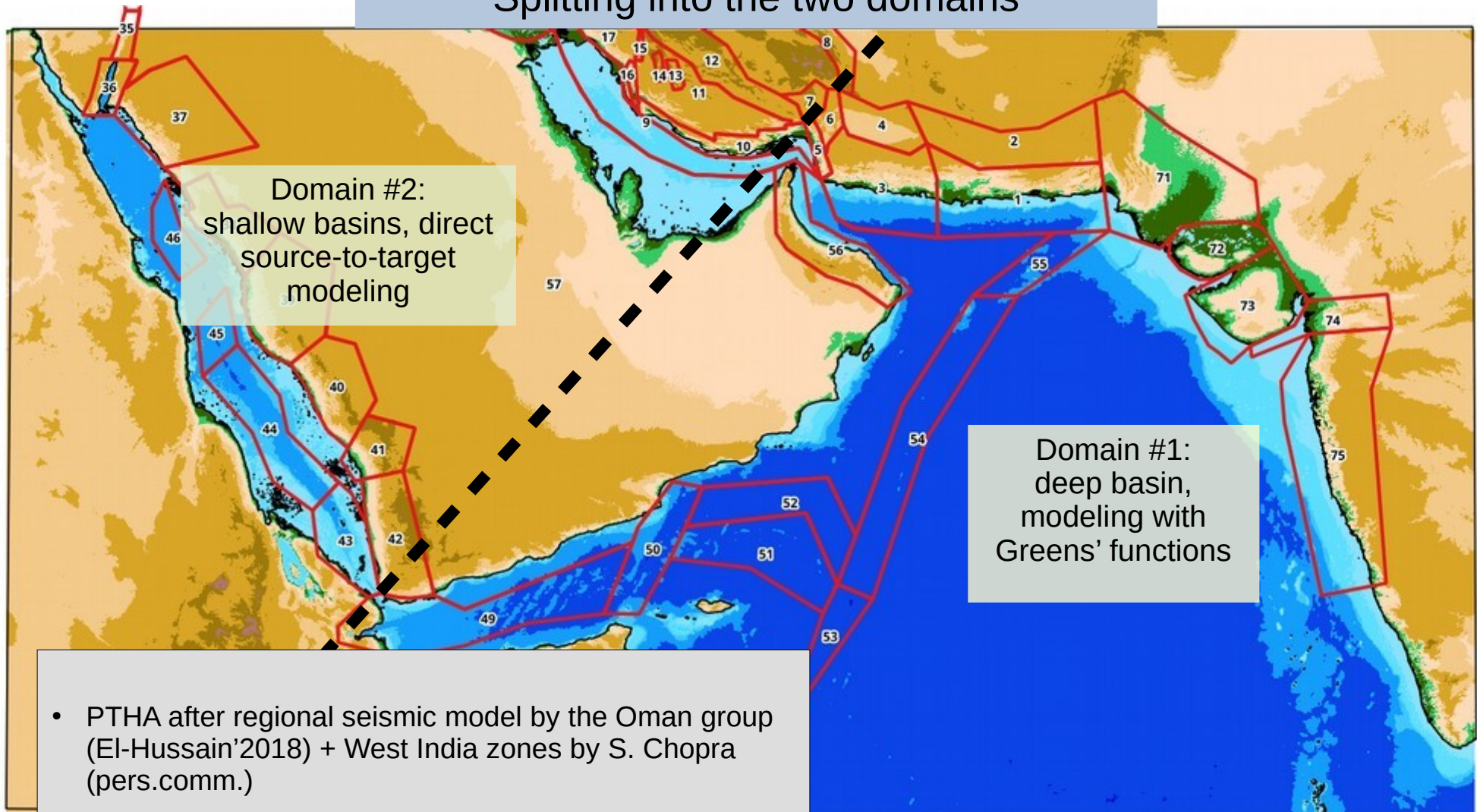


Fig. 5 The location of seismic profiles used in this study (vertical solid black lines), the splay and normal faults (in the south and north, respectively) and earthquake events (dark blue dots). The dashed lines indicate extrapolated faults due to the lack of seismic reflection data coverage

4) Also IMPORTANT(!): co-triggered splay faults

Makran PTHA :: STEP 2 “Tsunami Modeling”

Splitting into the two domains



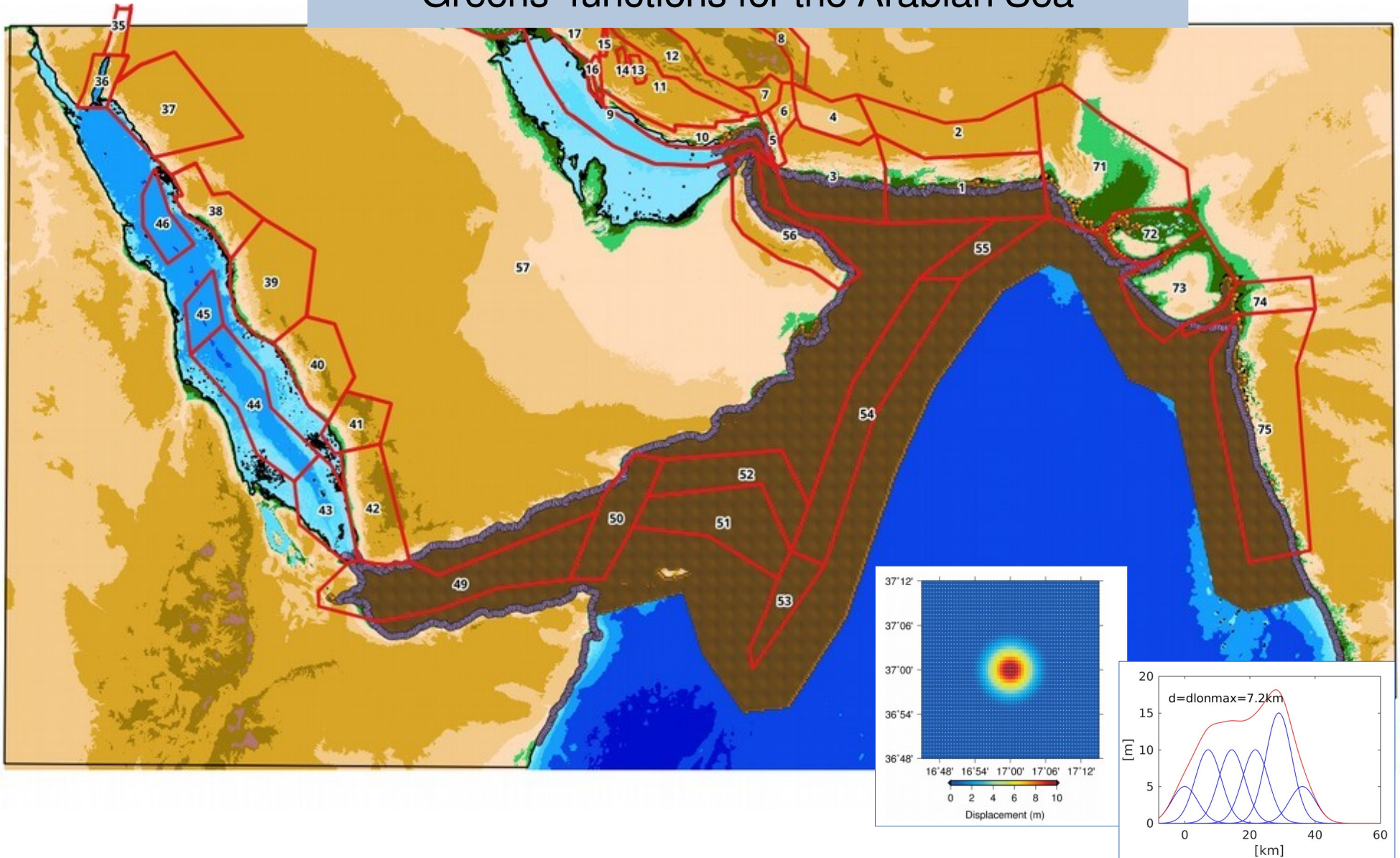
Domain #2:
shallow basins, direct
source-to-target
modeling

Domain #1:
deep basin,
modeling with
Greens' functions

- PTHA after regional seismic model by the Oman group (El-Hussain'2018) + West India zones by S. Chopra (pers.comm.)
- Two simulation domains: Arabian Sea + Red Sea & Gulf
- ~ 2000 coastal Points-of-Interest
- ~ 40 000 pre-computed Green's functions
- to simulate ~5 000 000 propagation scenarios

Makran PTHA :: STEP 2 “Tsunami Modeling”

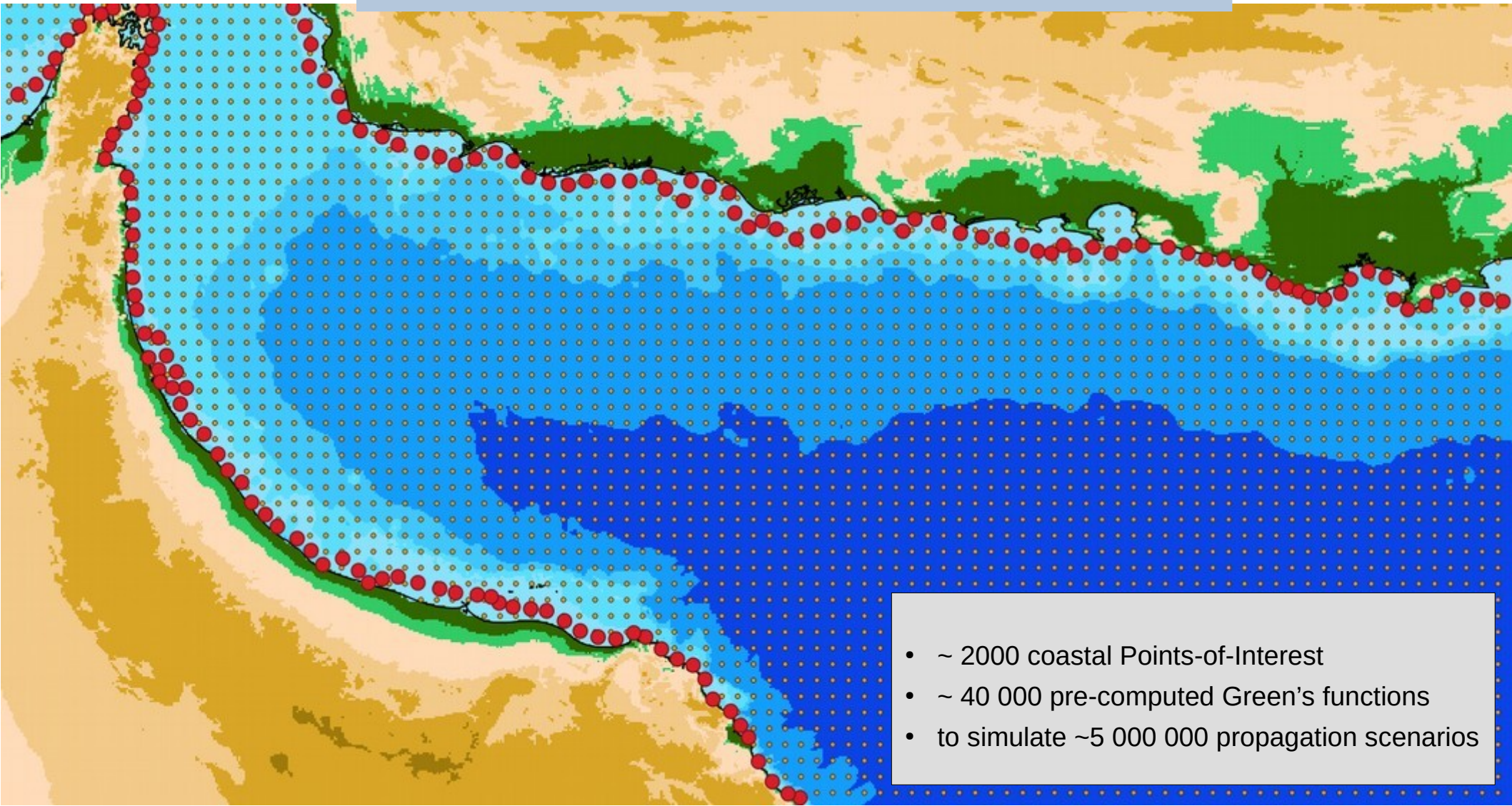
Greens' functions for the Arabian Sea



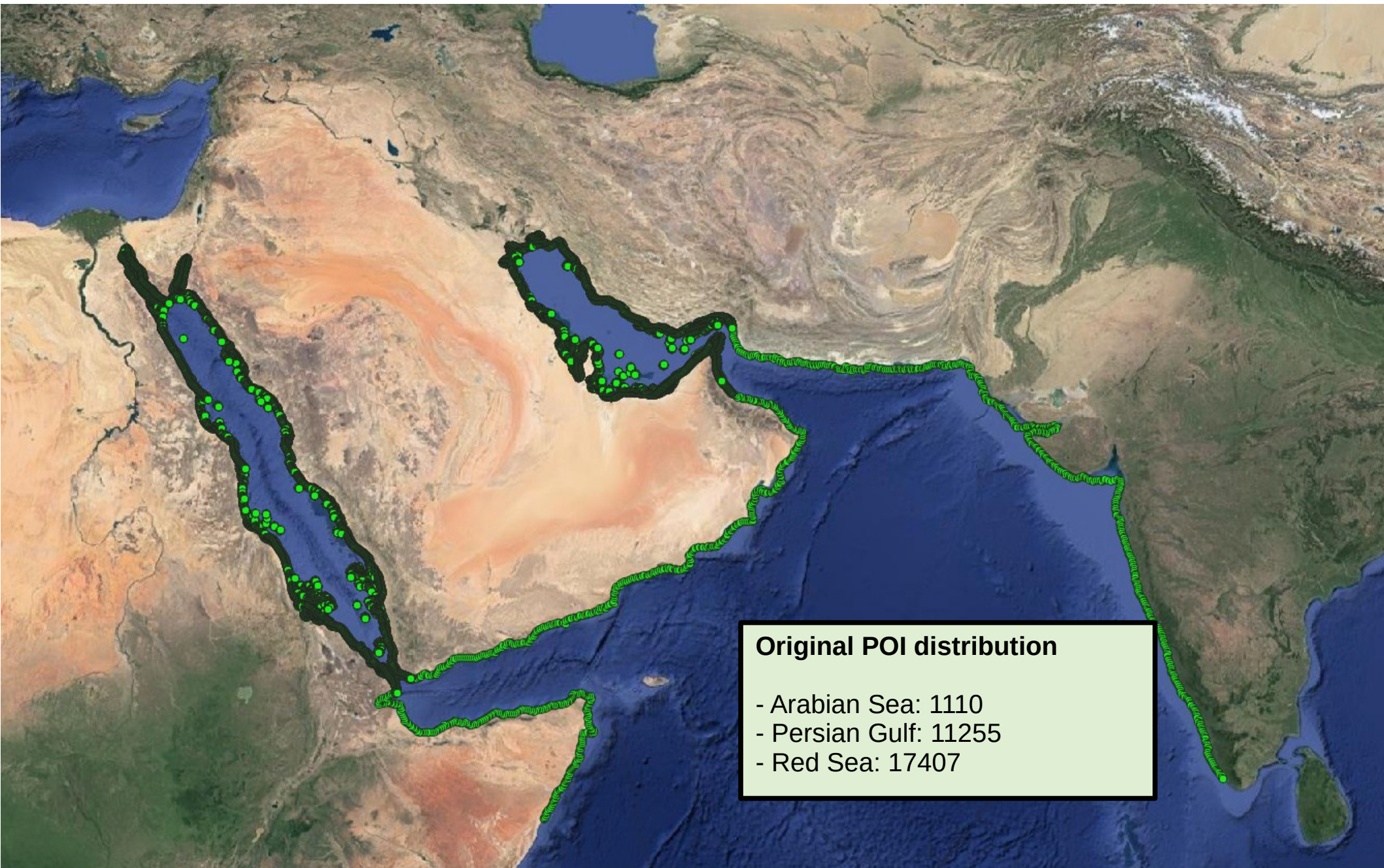
Molinari et al (2016)

Makran PTHA :: STEP 2 “Tsunami Modeling”

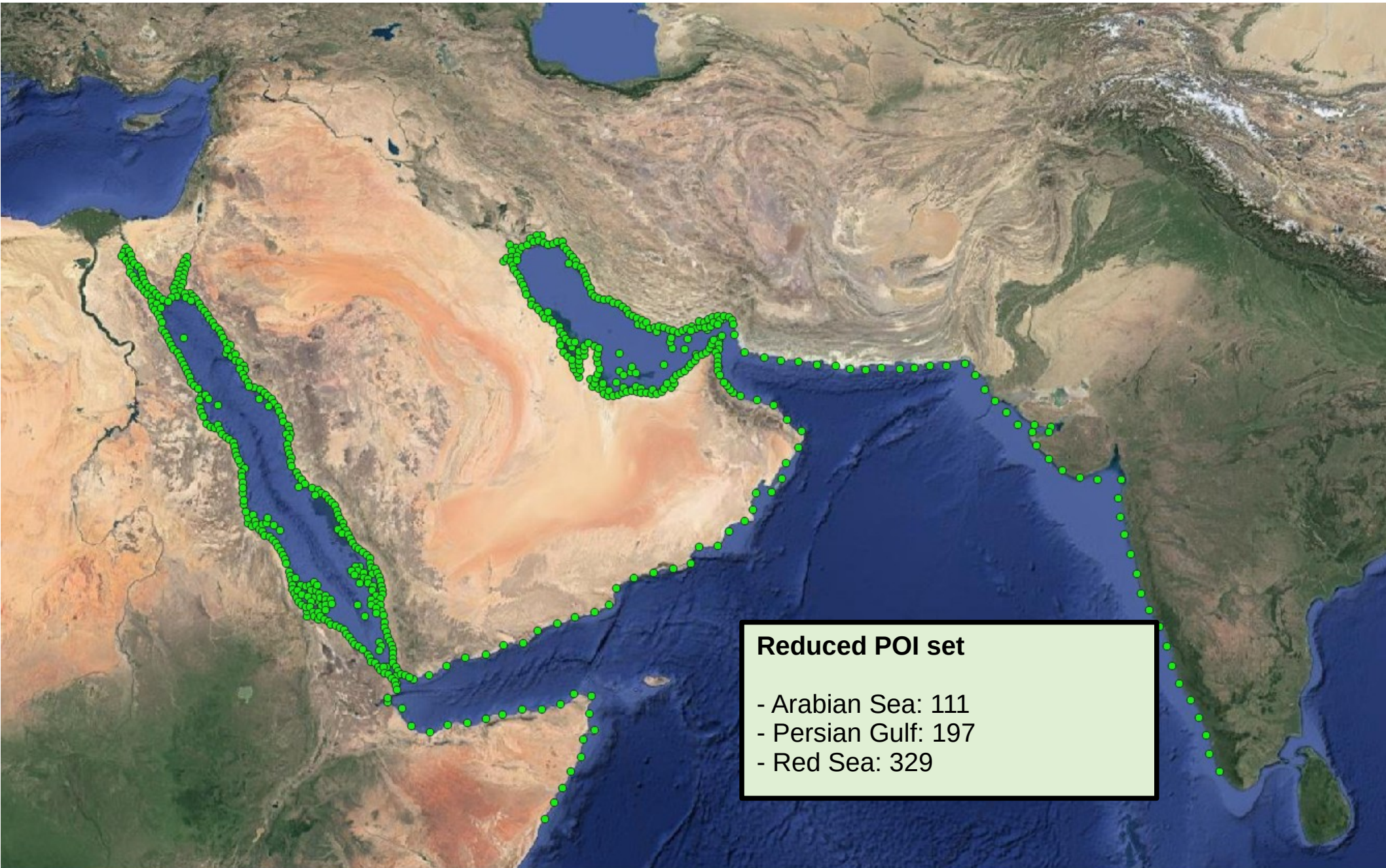
Greens’ functions for the Arabian Sea



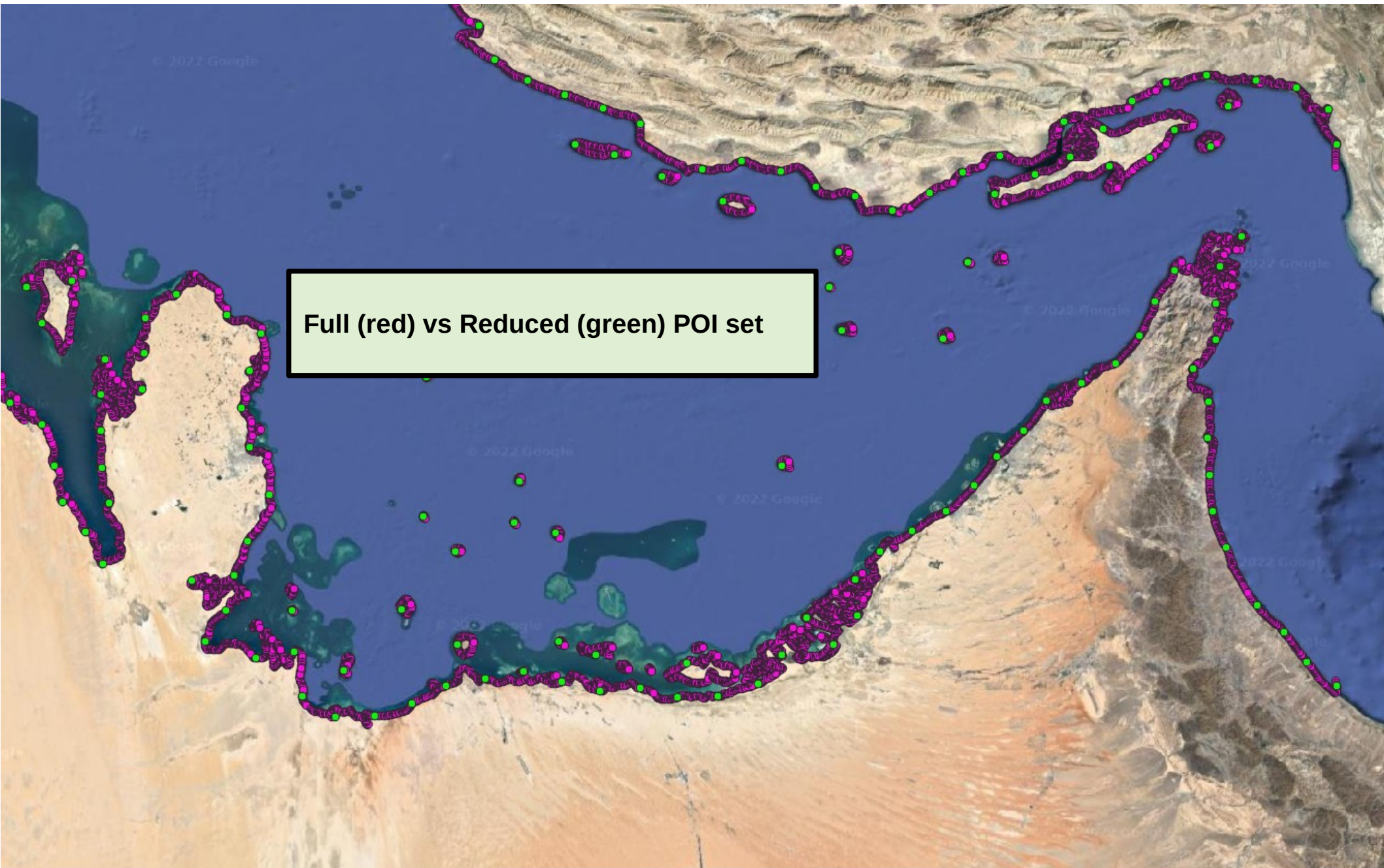
Makran PTHA :: STEP 2 “Tsunami Modeling”



Makran PTHA :: STEP 2 “Tsunami Modeling”



Makran PTHA :: STEP 2 “Tsunami Modeling”



Makran PTHA :: STEP 2 “Tsunami Modeling”

Full (red) POI set ZOOMed



Makran PTHA :: STEP 2 “Tsunami Modeling”

Alternatives to consider?

- 1) Employ Kajiura-type filter when transering sea-floor deformation into the intial conditions on the surface
- 2) Check tsunami propagation from the Arabian Sea into the Persian Gulf

Makran PTHA :: STEP 3 “Shoaling and Inundation”

Alternatives to consider?

- 1) Add tidal amplitudes (ask local oceanographers for values site by site)
- 2) Use coastal amplification factors instead of Green's law – use global set
- 3) Apply log-norm uncertainty to max wave height to account for cumulative effect of various uncertainties – use global statistical parameters

Makran PTHA ver 1.0

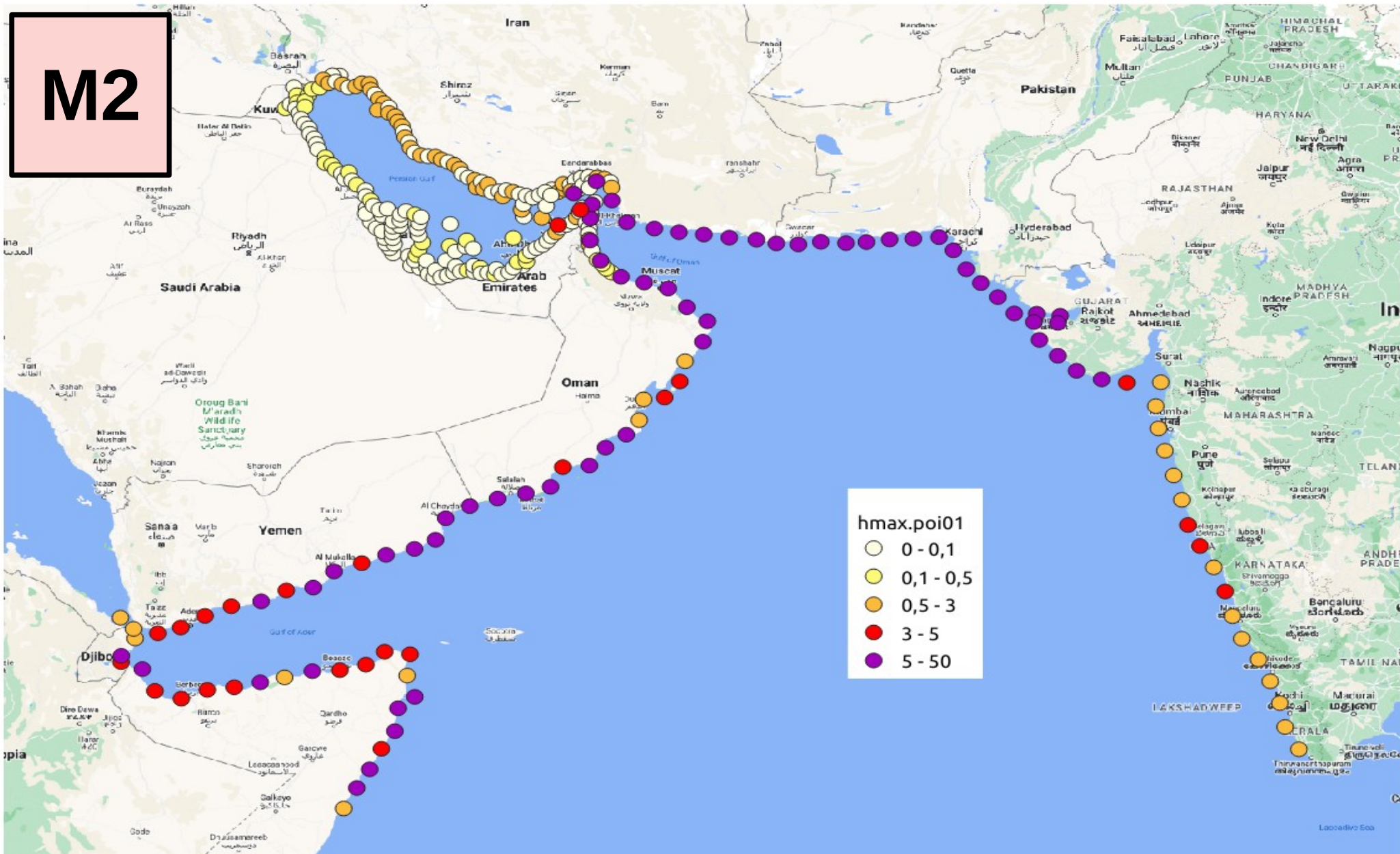
Only TWO alternative models up to now:

Model 1 “optimistic”	Model 2 “pessimistic”
BS: as in PSHA	BS: $M_{\max} + 3 \sigma$
PS: segmented as in PSHA ($M_{\max}=6.2$ for West and 8.4 for East)	PS: unsegmented, $M_{\max}=9.1$
STEP2 & 3 – no alternatives	

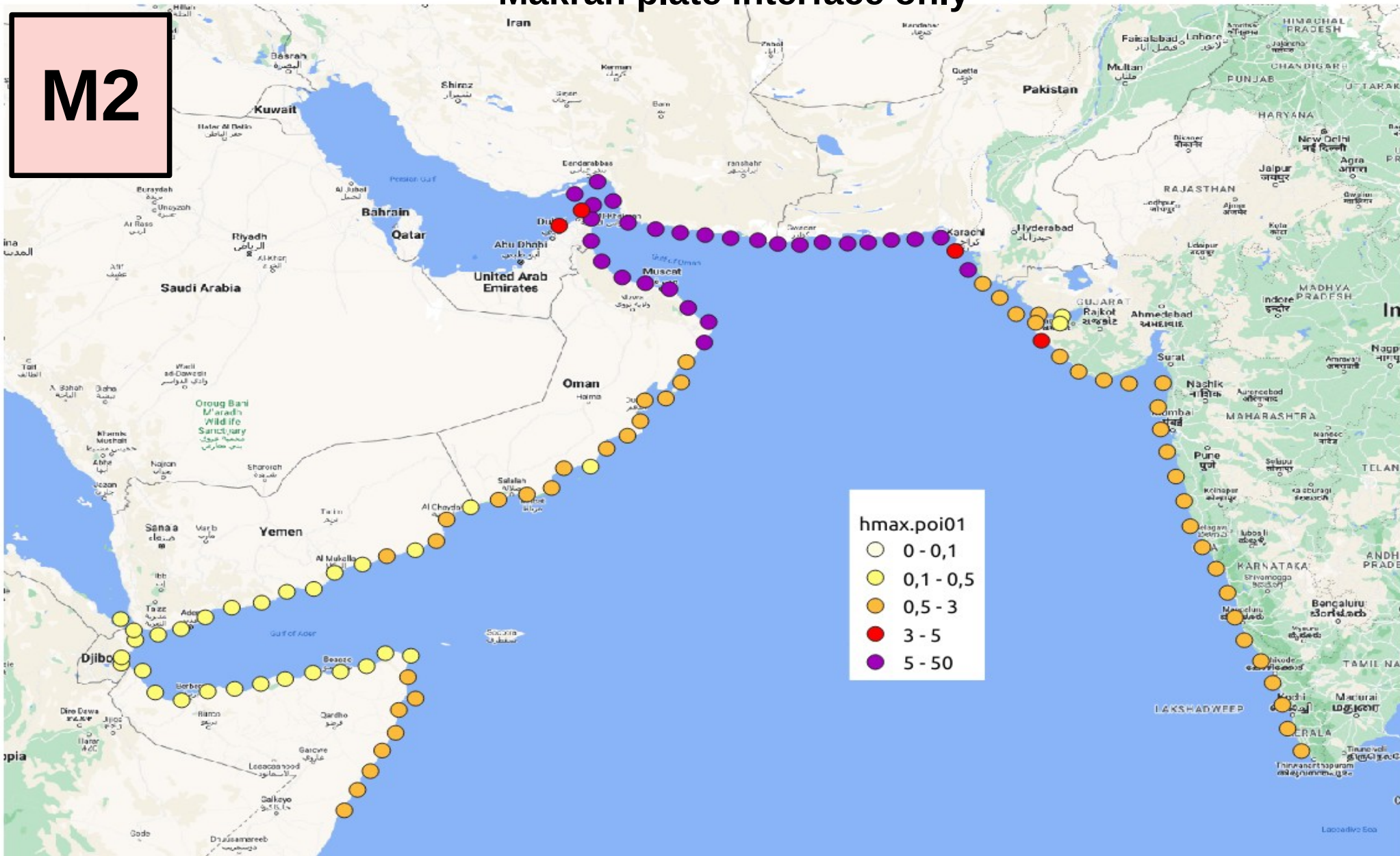
Maximum modeled wave heights (deterministic)



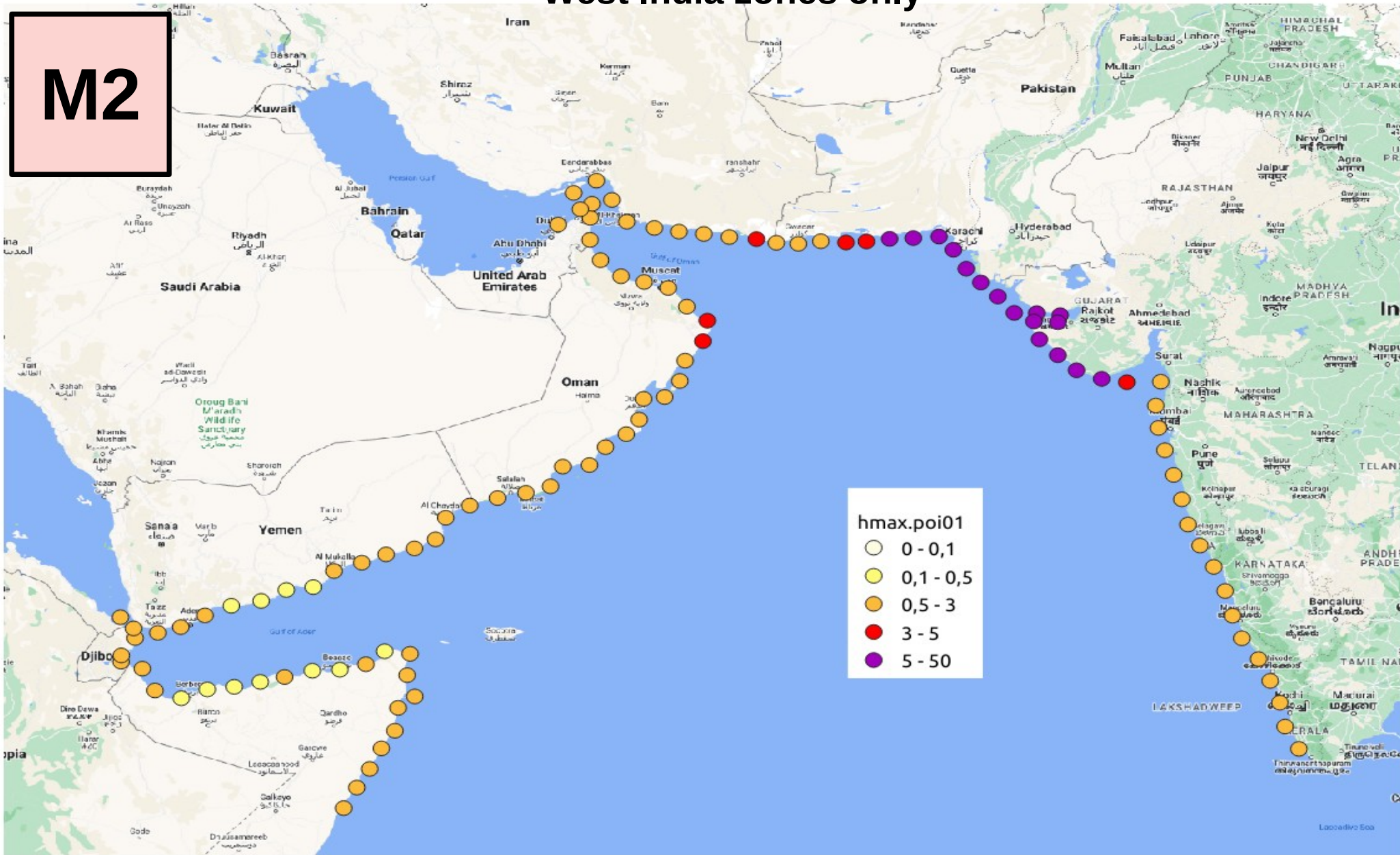
Maximum modeled wave heights (deterministic)



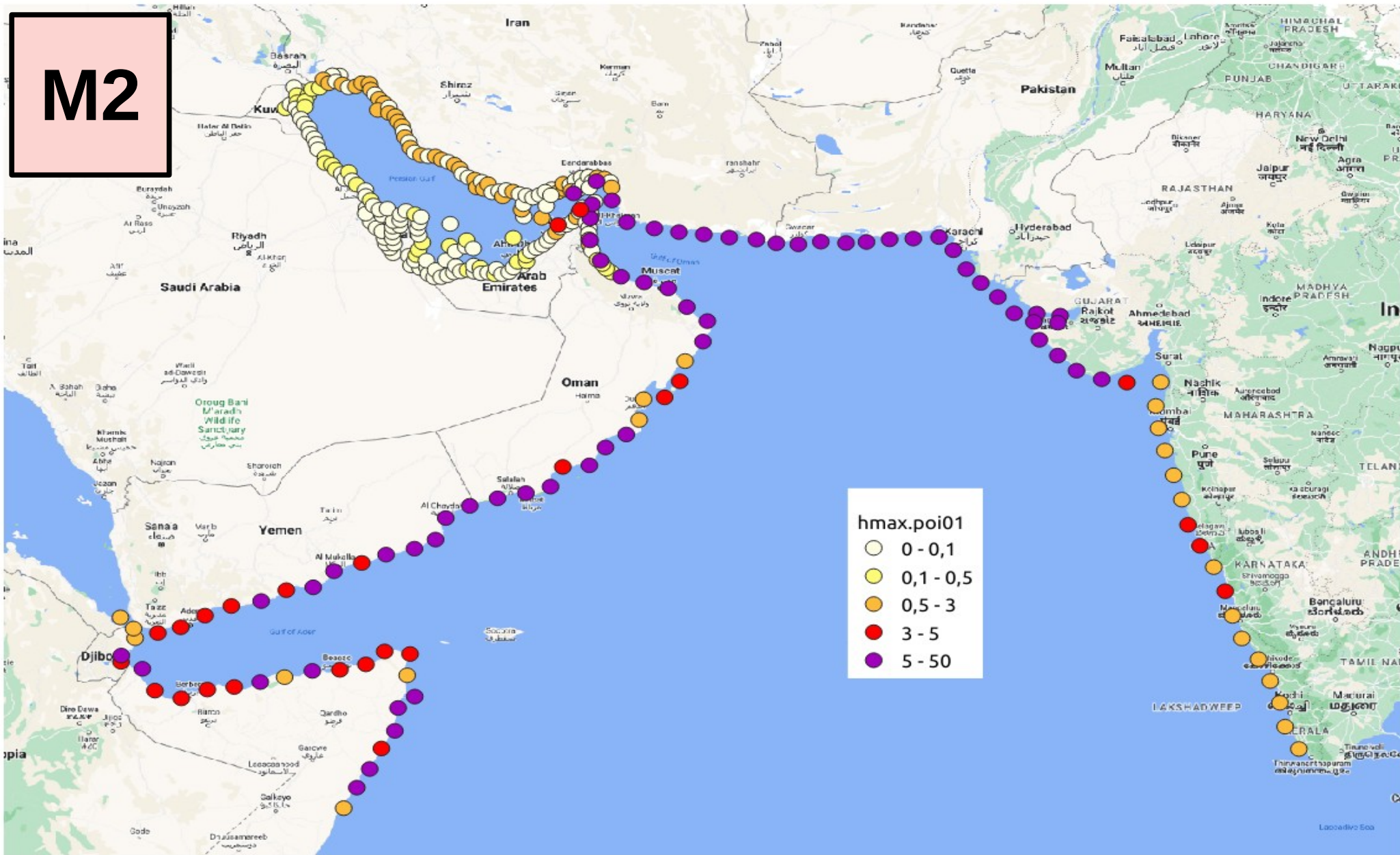
Maximum modeled wave heights (deterministic) Makran plate interface only



Maximum modeled wave heights (deterministic) West India zones only



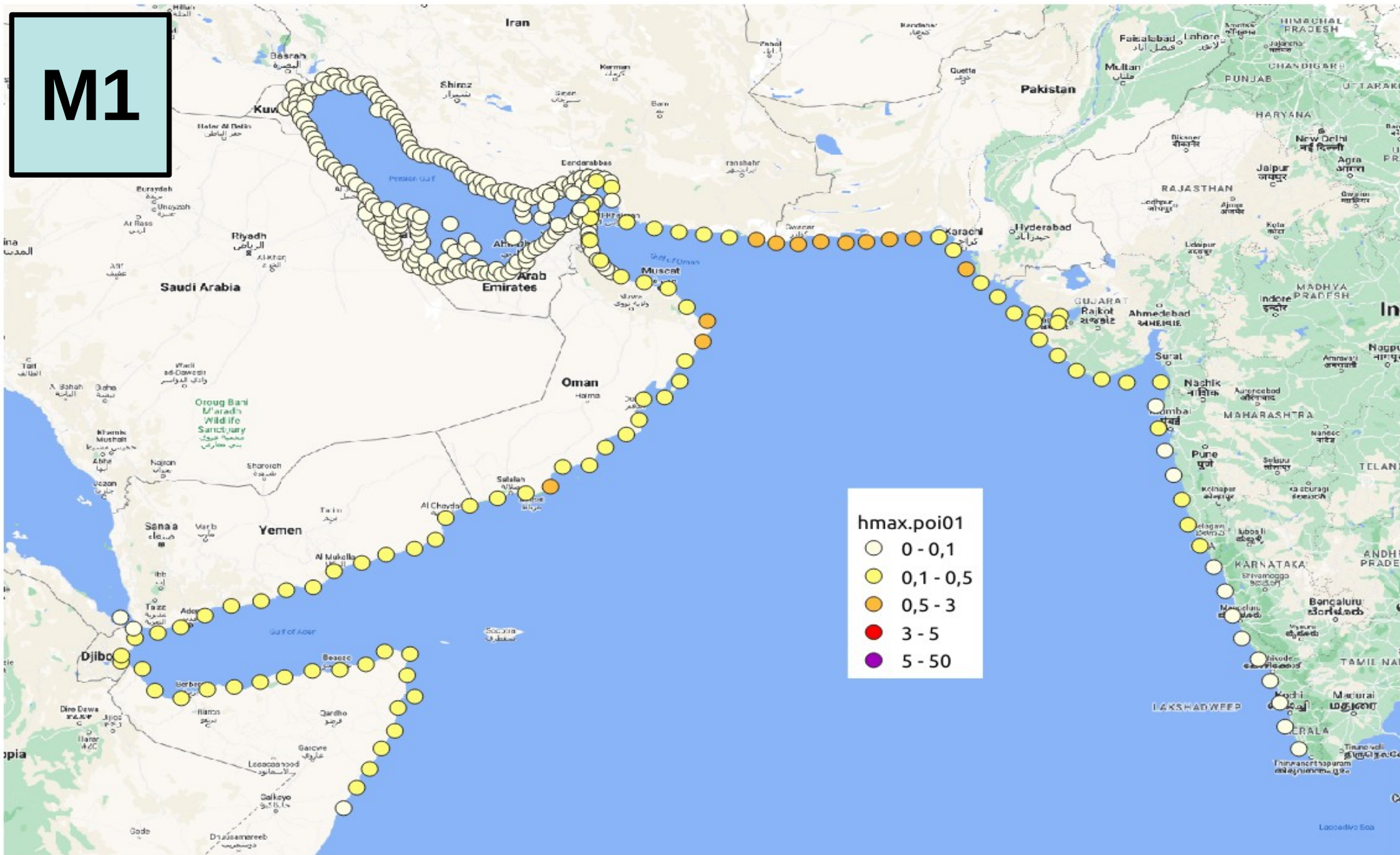
Maximum modeled wave heights (deterministic)



Maximum expected 2500 years wave height (probabilistic)



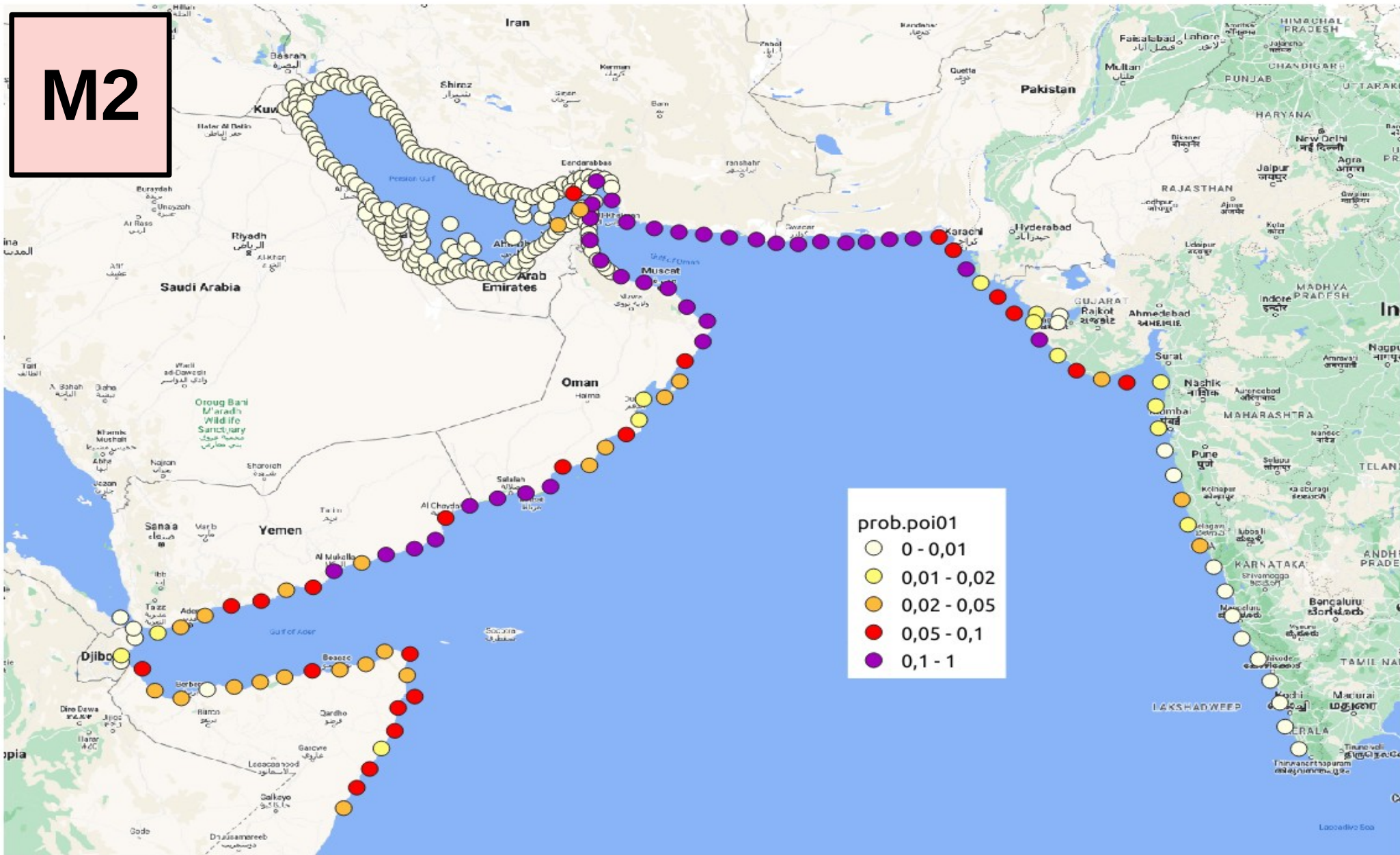
Maximum expected 2500 years wave height (probabilistic)



Probability of $h > 1$ meter within next 50 years



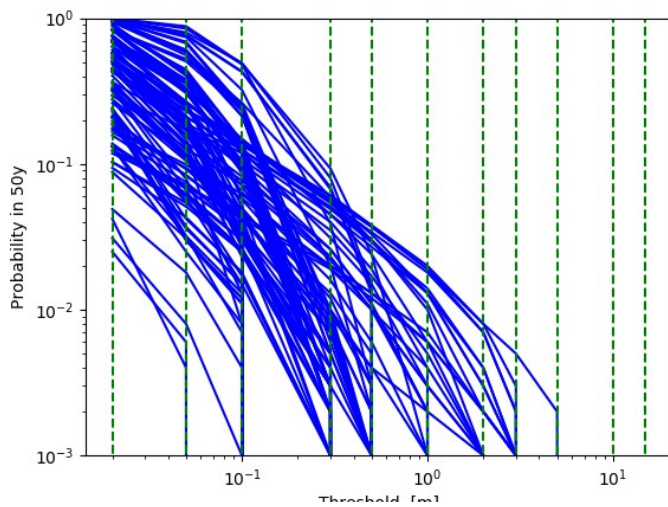
Probability of $h > 1$ meter within next 50 years



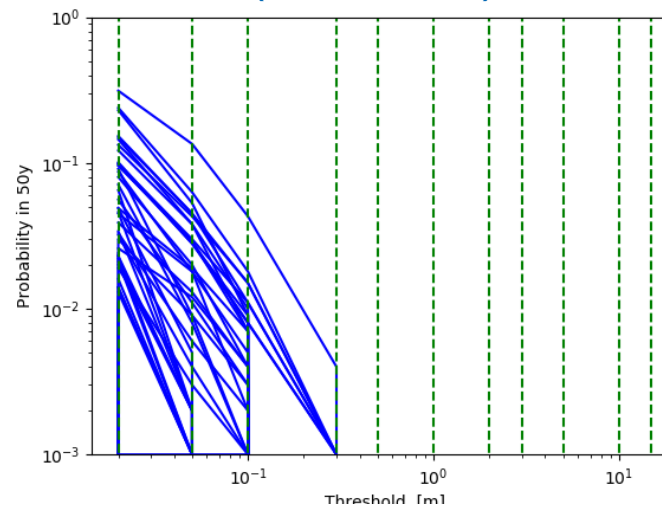
Looking at the hazard curves

M1

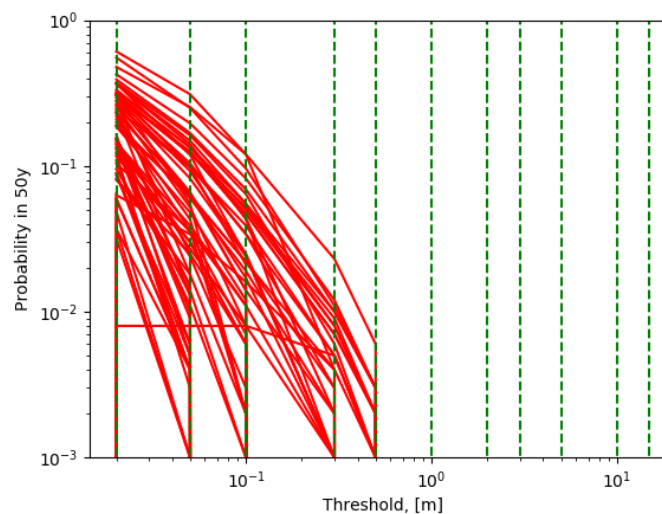
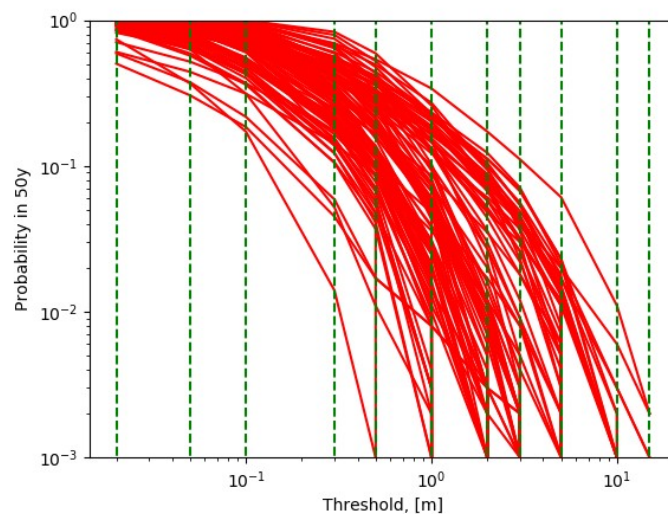
Arabian Sea
(all 111 POIs)



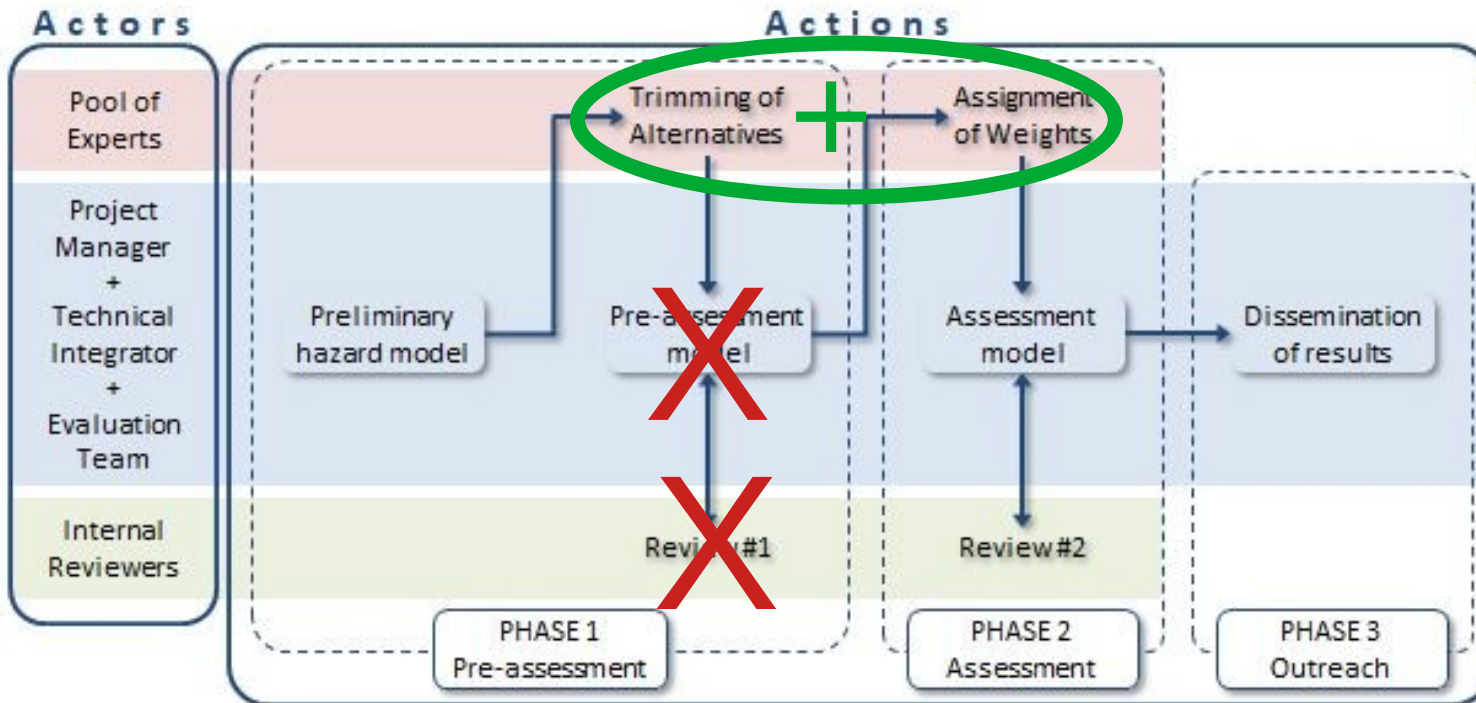
Persian Gulf
(all 197 POIs)



M2



Roadmap to consensus full PTHA



Implement alternative models	mid-Sept
Elicitation workshop (10-15 experts) on alternatives	mid-Oct
Apply weights and send PTHA to ext. Reviewers (2-3 experts)	mid-Nov
Feedback from Reviewers	Christmas
Full PTHA disseminated	Jan 2025