Training/Workshop on

Tsunami Evacuation Maps, Plans, and Procedures and the UNESCO-IOC Tsunami Ready Recognition Programme for the Indian Ocean Member States

Hyderabad - India, 15-23 April 2025

Tsunami Inundation Modelling and MAP

TIMM #: Probabilistic Tsunami Hazard Assessment of the Indian Ocean

Result of PTHA for NWIO (UNESCAP Project)

TEMPP 2025

What and Why PTHA ?

*__PTHA__ stays for **P**robabilistic **T**sunami **H**azard **A**ssessment

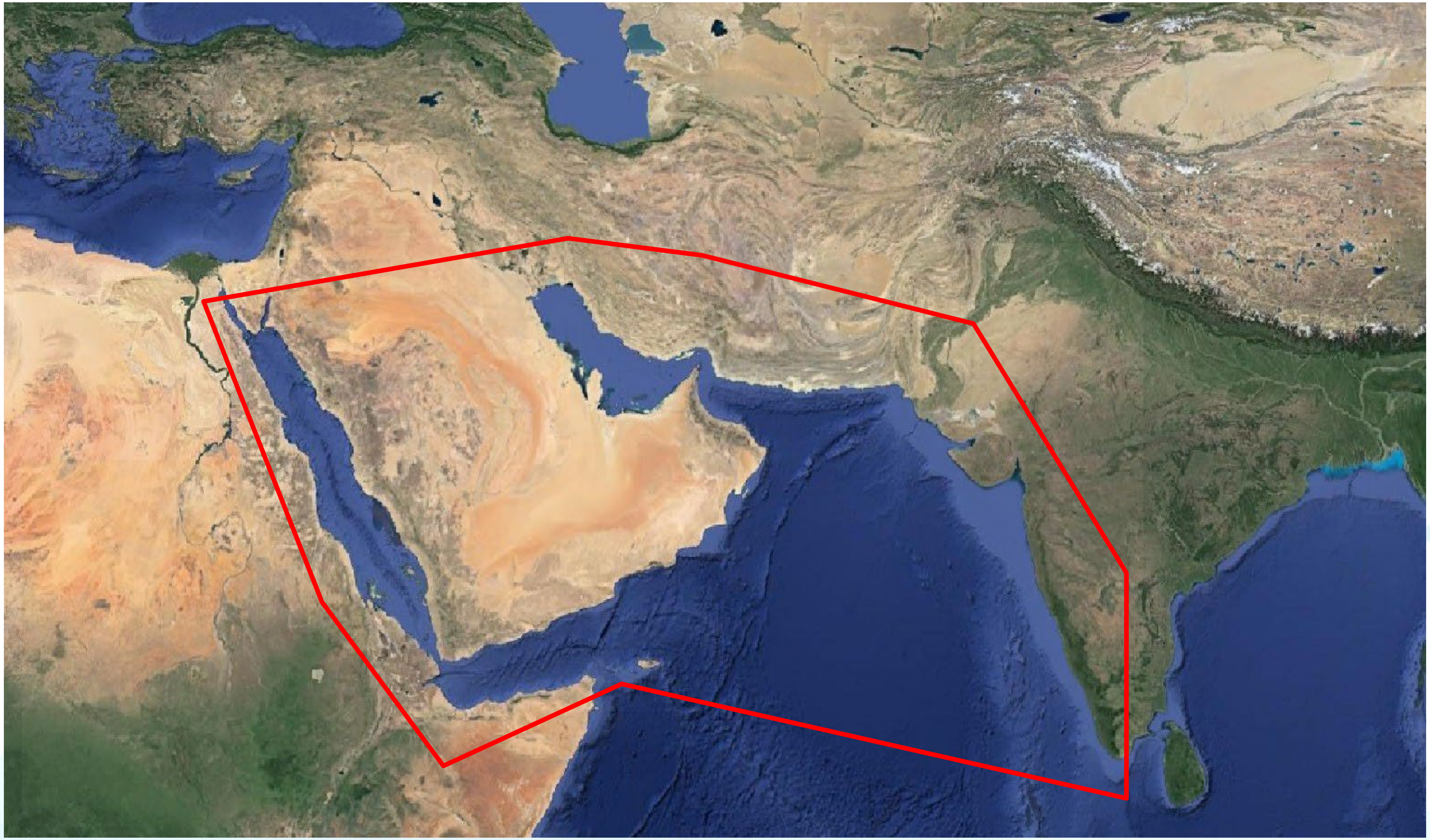
- Requires treatment of ALL possible seismic tsunamigenic sources, not only those with the large magnitudes

- 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 occurance

- That allows to answer questions like: what is the probability of a tsunami wave height above 1 m within the next 50 years?

NWIO – Makran Region



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NWIO – Makran Region

Makran PTHA v.1.0 development team

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University of Naples, Italy Sultan Qaboos University, Oman
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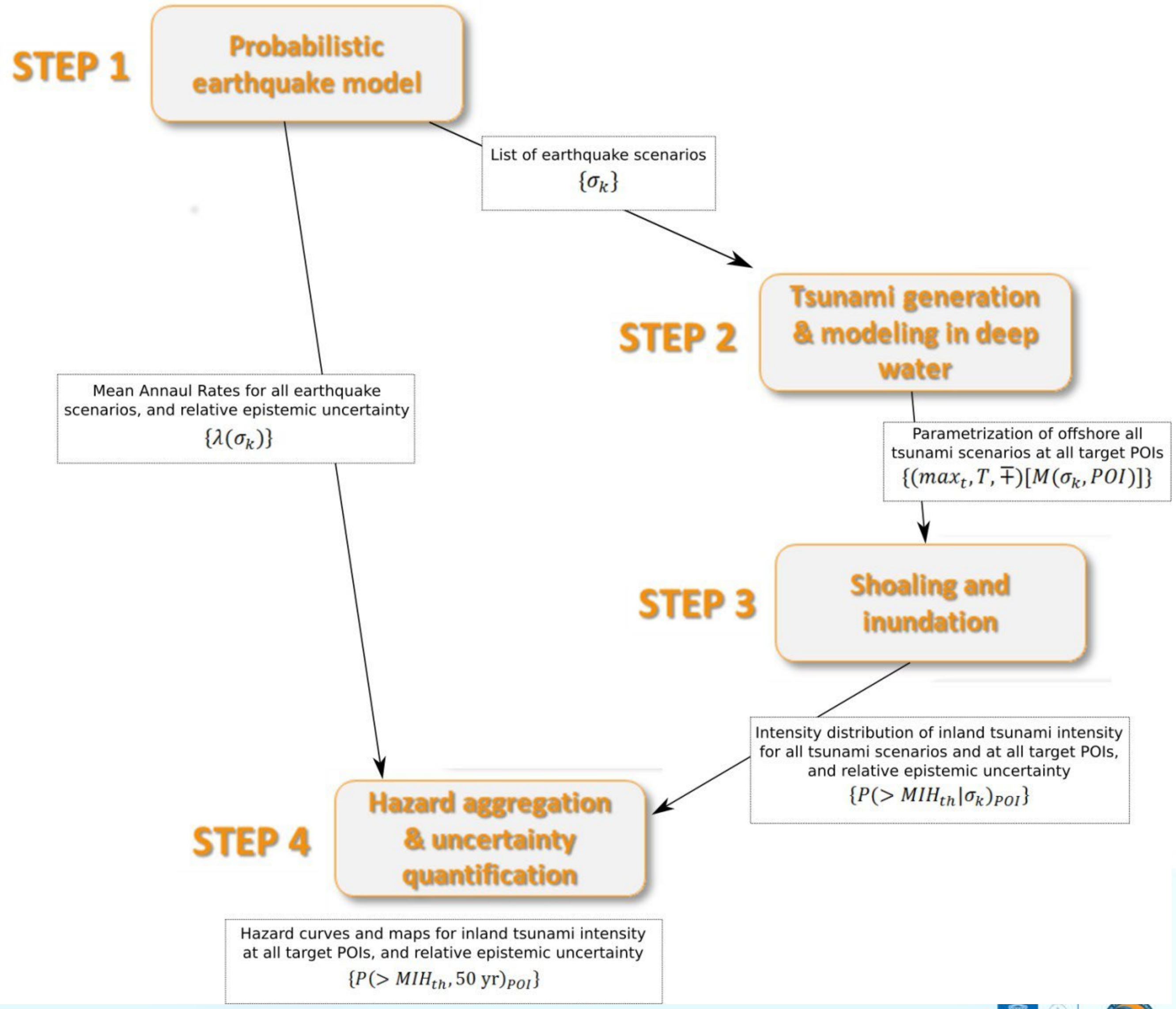
PTHA – Workflow adopted for NWIO



PTHA following the methodology of http://tsumaps-neam.eu

PTHA – Methodology for NWIO

- 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

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

Arabian Journal of Geosciences (2018) 11: 435
https://doi.org/10.1007/s12517-018-3797-7

ORIGINAL PAPER

CrossMark

Developing a seismic source model for the Arabian Plate

I. El-Hussain[1] · Y. Al-Shijbi[1] · A. Deif[1,2] · A. M. E. Mohamed[1,2] · M. Ezzelarab[1,2]

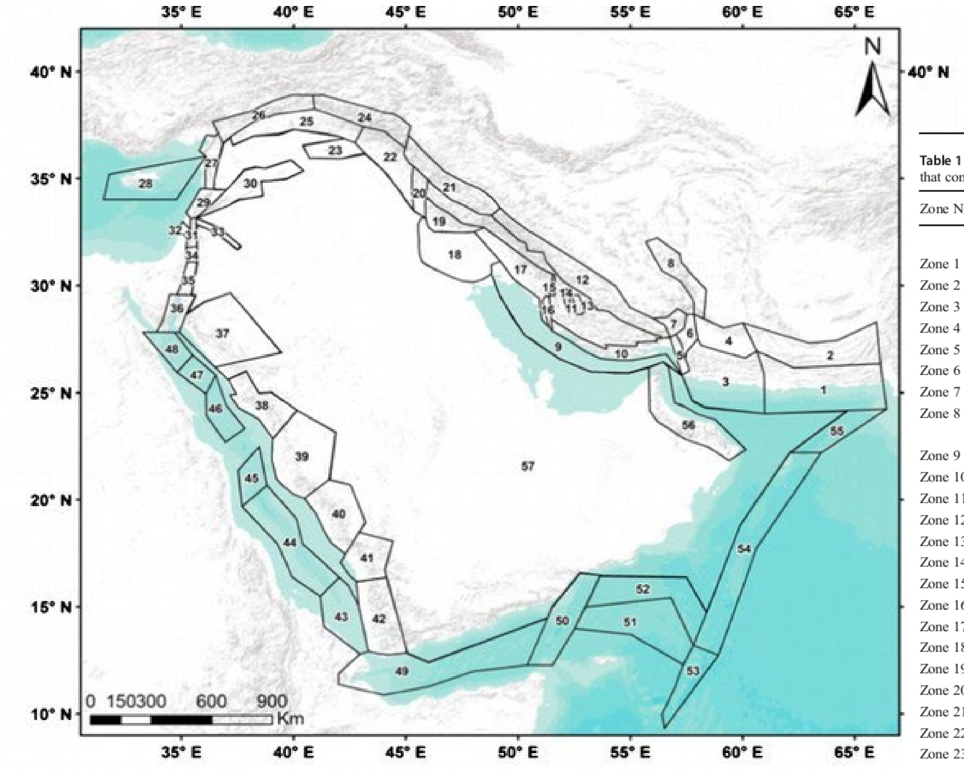
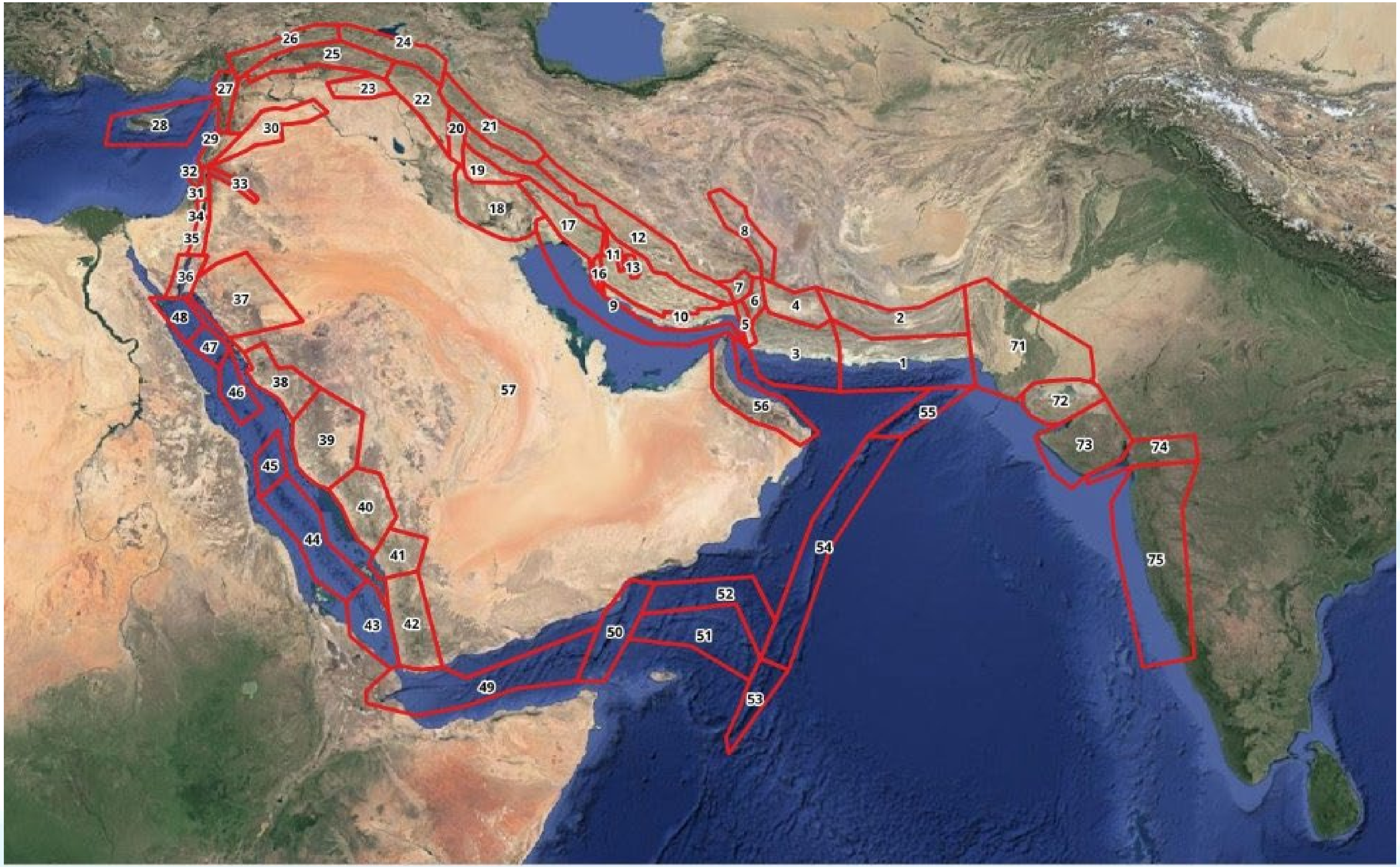


Table 1 Earthquake recurrence parameters for the delineated seismic sources. Italic font are the recurrence parameters for t[…] that contains the delineated seismic sources (All Makran, All Zagros, All Gulf of Aqaba-Dead Sea Fault, All Red Sea, All A[…]

Zone No.	Zone Name	M_{max}	σ M_{max}	M_{min}	M_{max}obs	β	σβ	b	σb
	All Makran	*8.4*	*0.27*	*4*	*8.1*	*1.67*	*0.07*	*0.73*	*0.03*
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
	All Zagros	*7.5*	*0.12*	*4*	*7.4*	*1.84*	*0.04*	*0.8*	*0.02*
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

A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

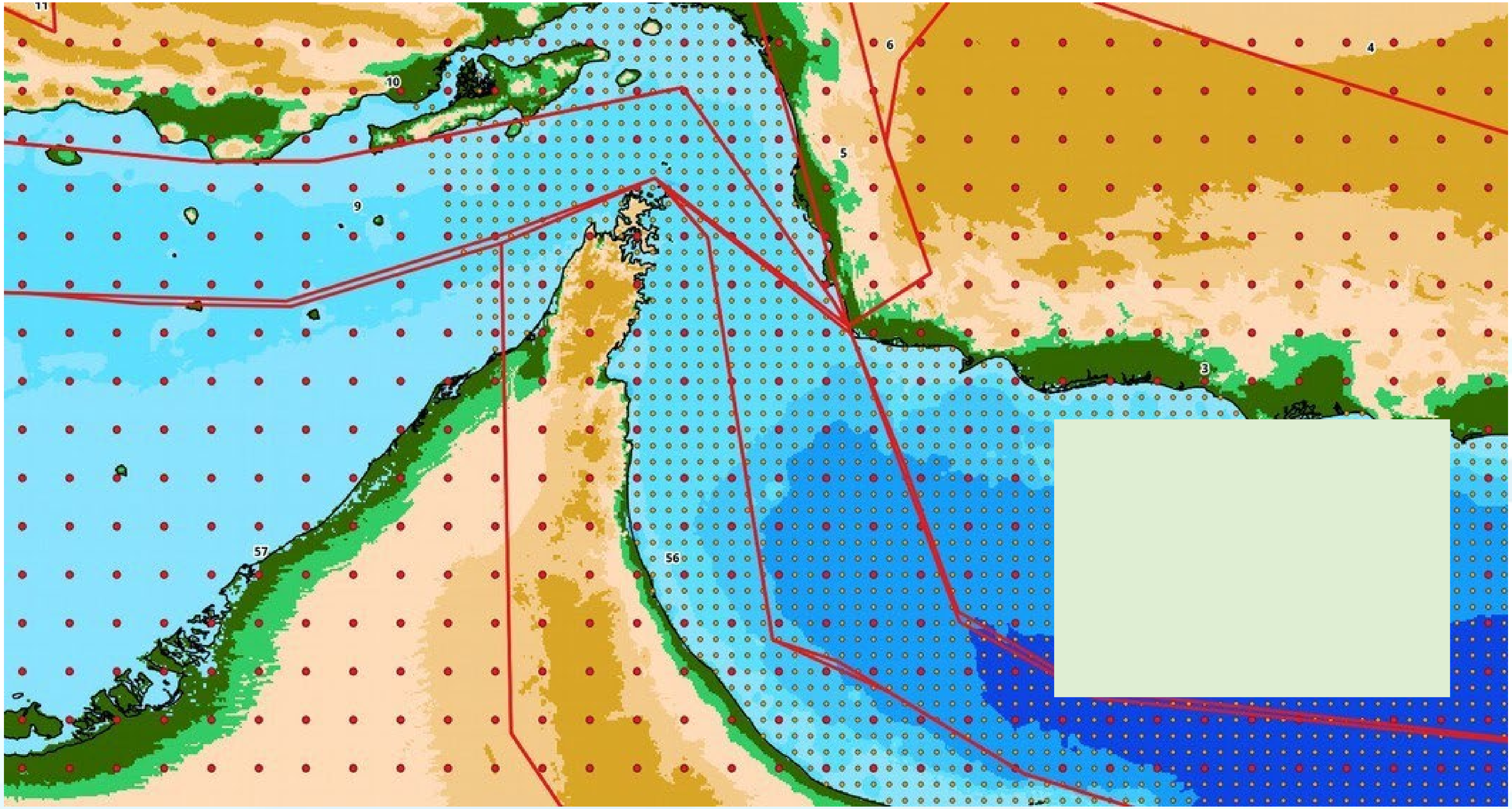
Makran PTHA :: STEP 1 “Earthquake Model”



A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

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

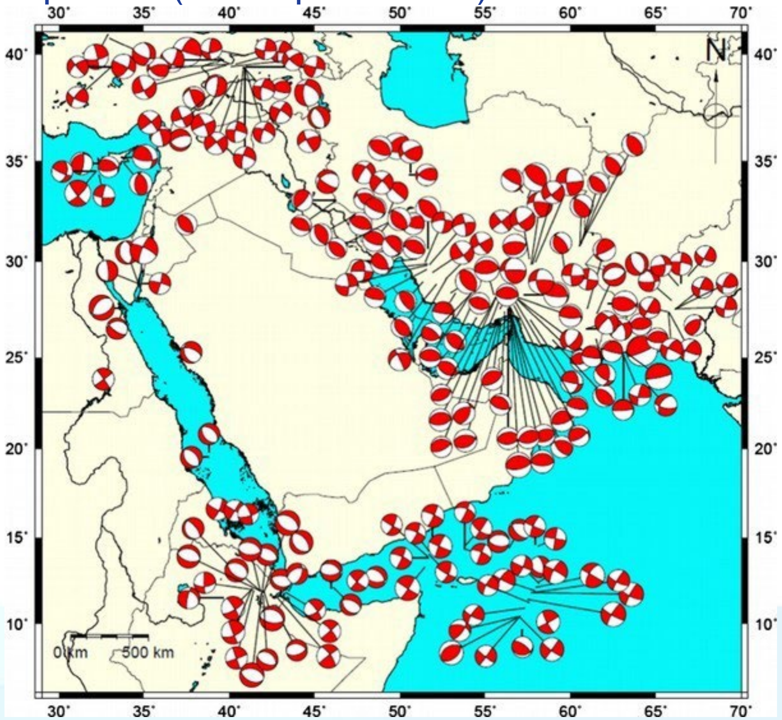
Arabian plate zones:

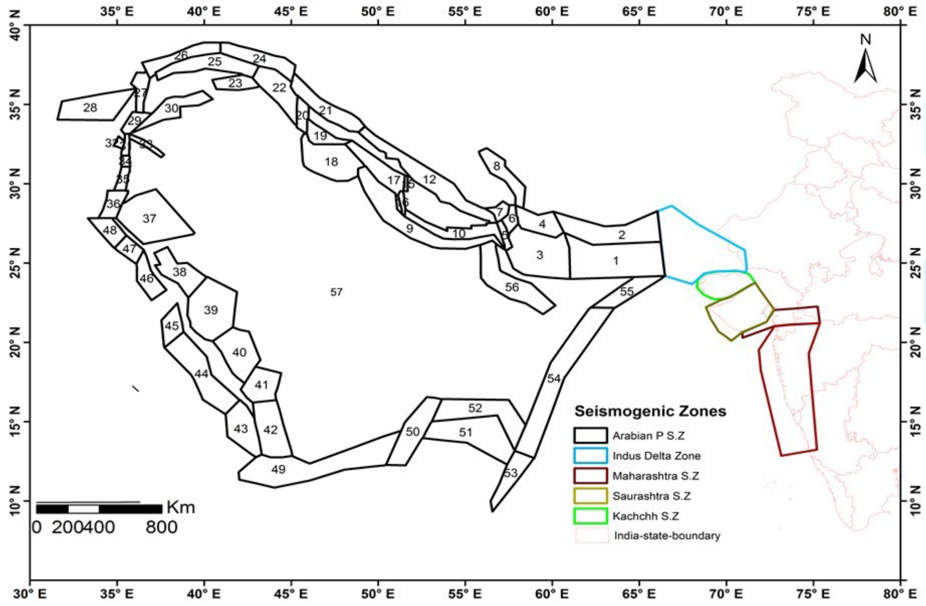
- Mmax and G-R based on PSHA (El-Hussain et al.’2018)

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

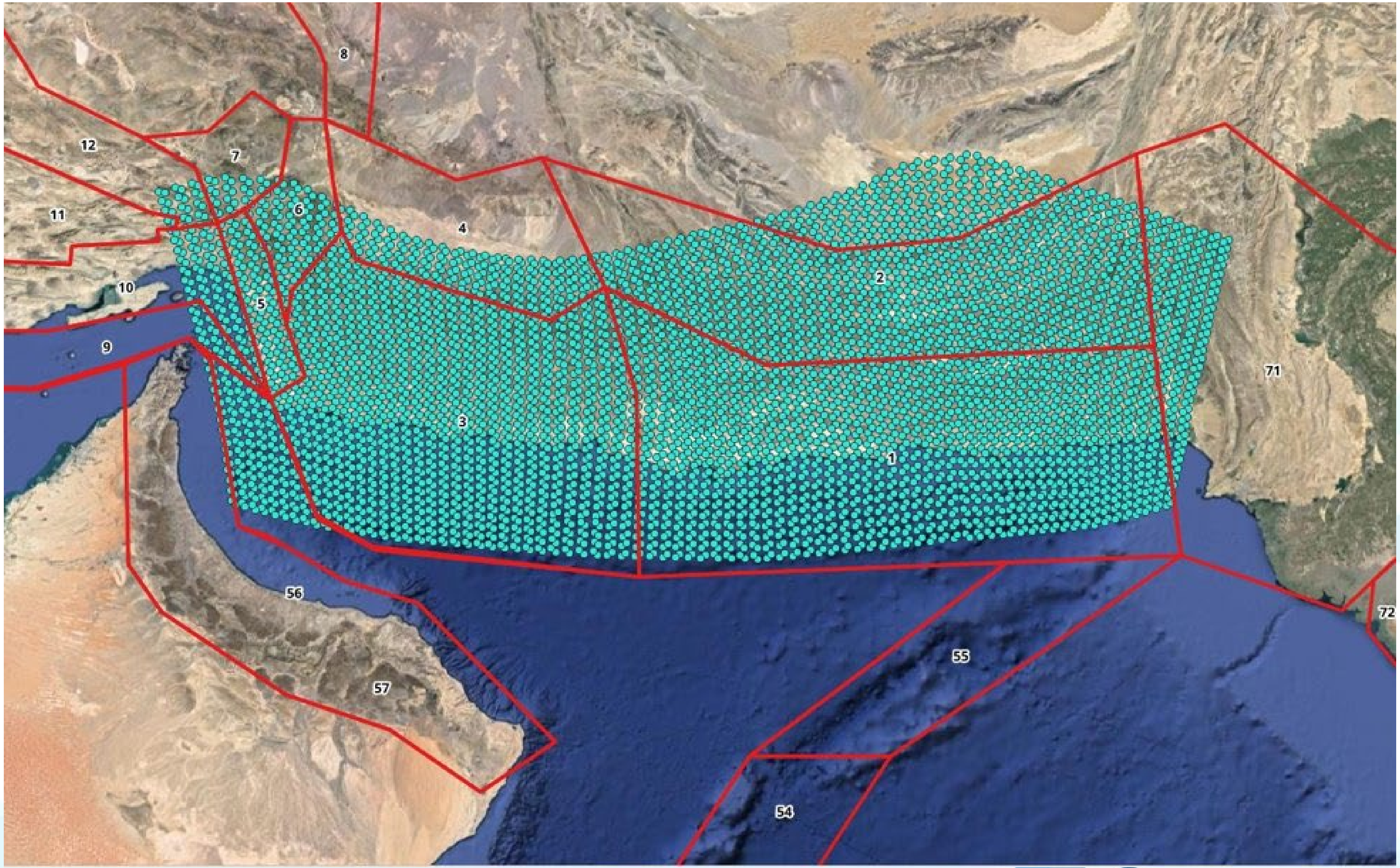
West Indian zones (71-75):

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





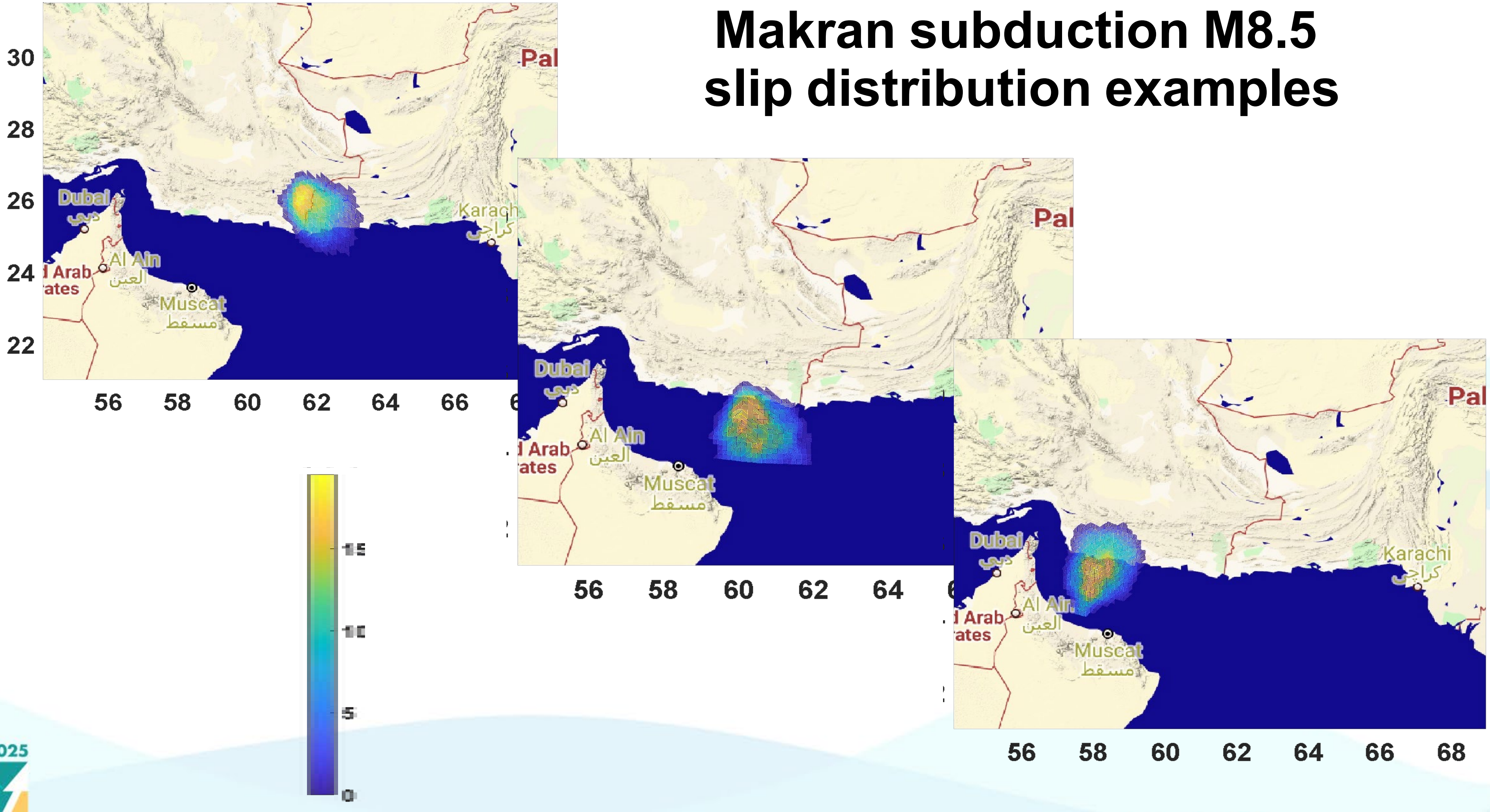
Makran PTHA :: STEP 1 “Earthquake Model” :: PS



A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

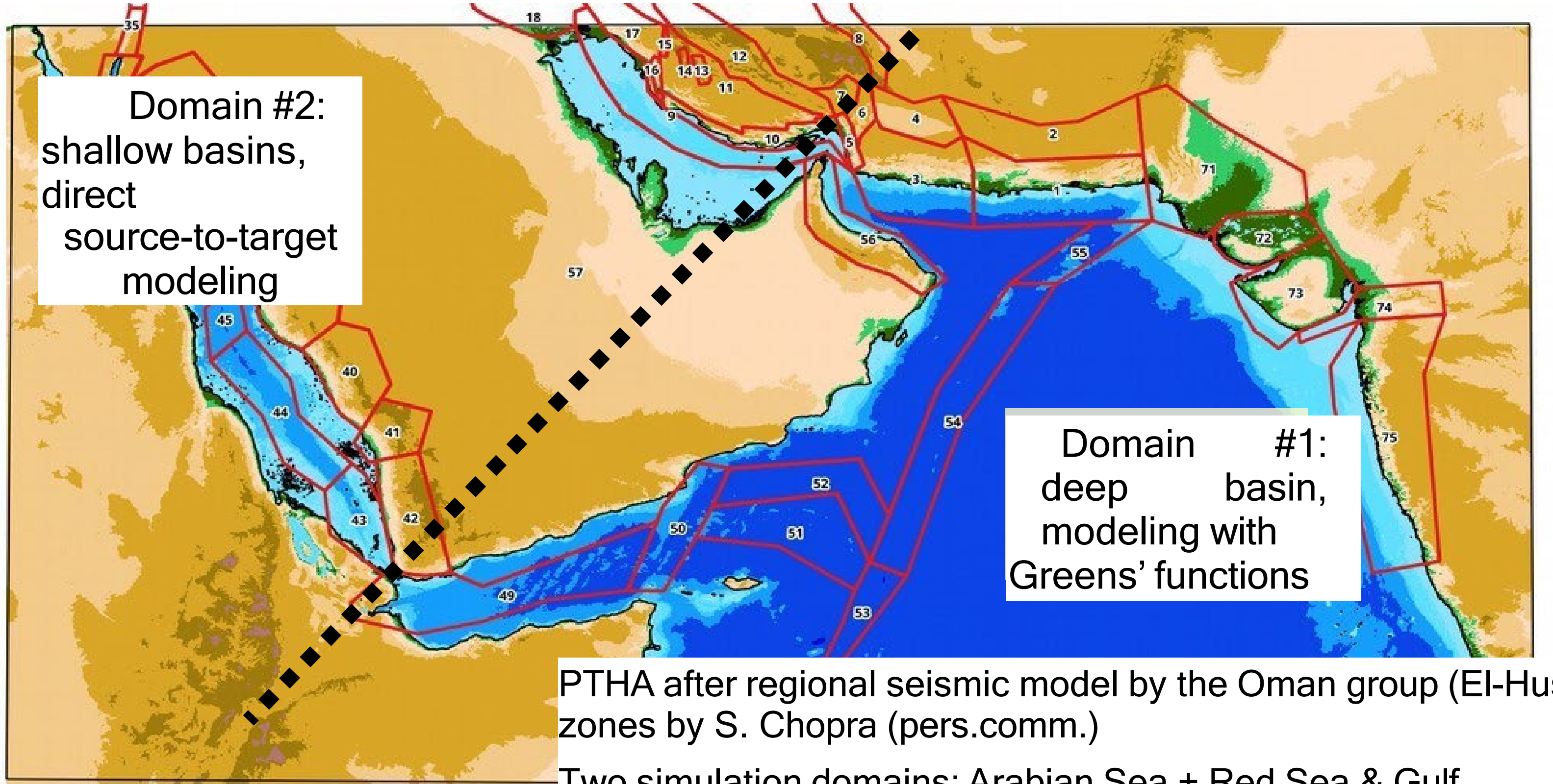
Makran PTHA :: STEP 1 “Earthquake Model” :: BS

Makran subduction M8.5 slip distribution examples



A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

Makran PTHA :: STEP 2 “Tsunami Modelling”



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

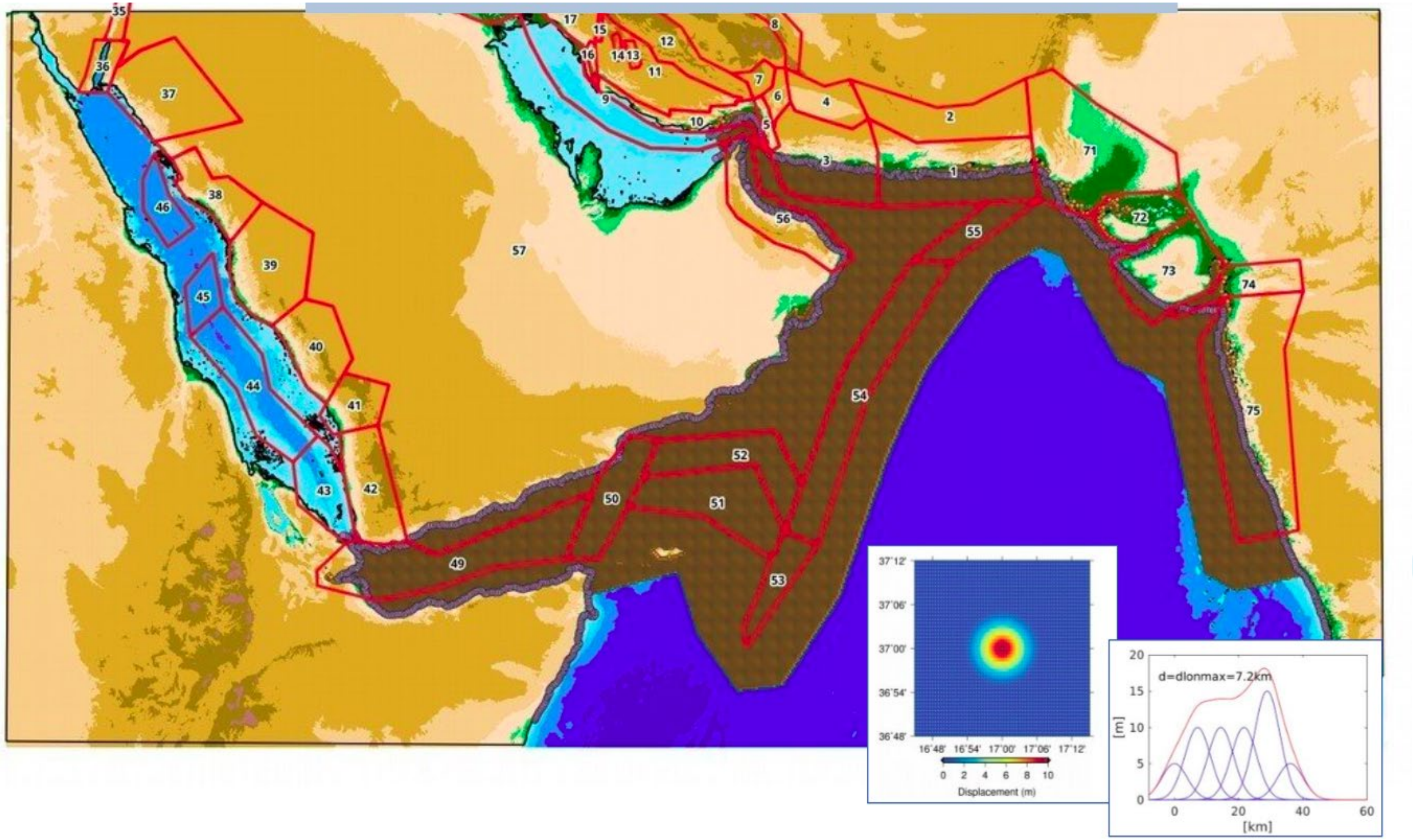
~ 2000 coastal Points-of-Interest

~ 40 000 pre-computed Green’s functions

to simulate ~5 000 000 propagation scenarios

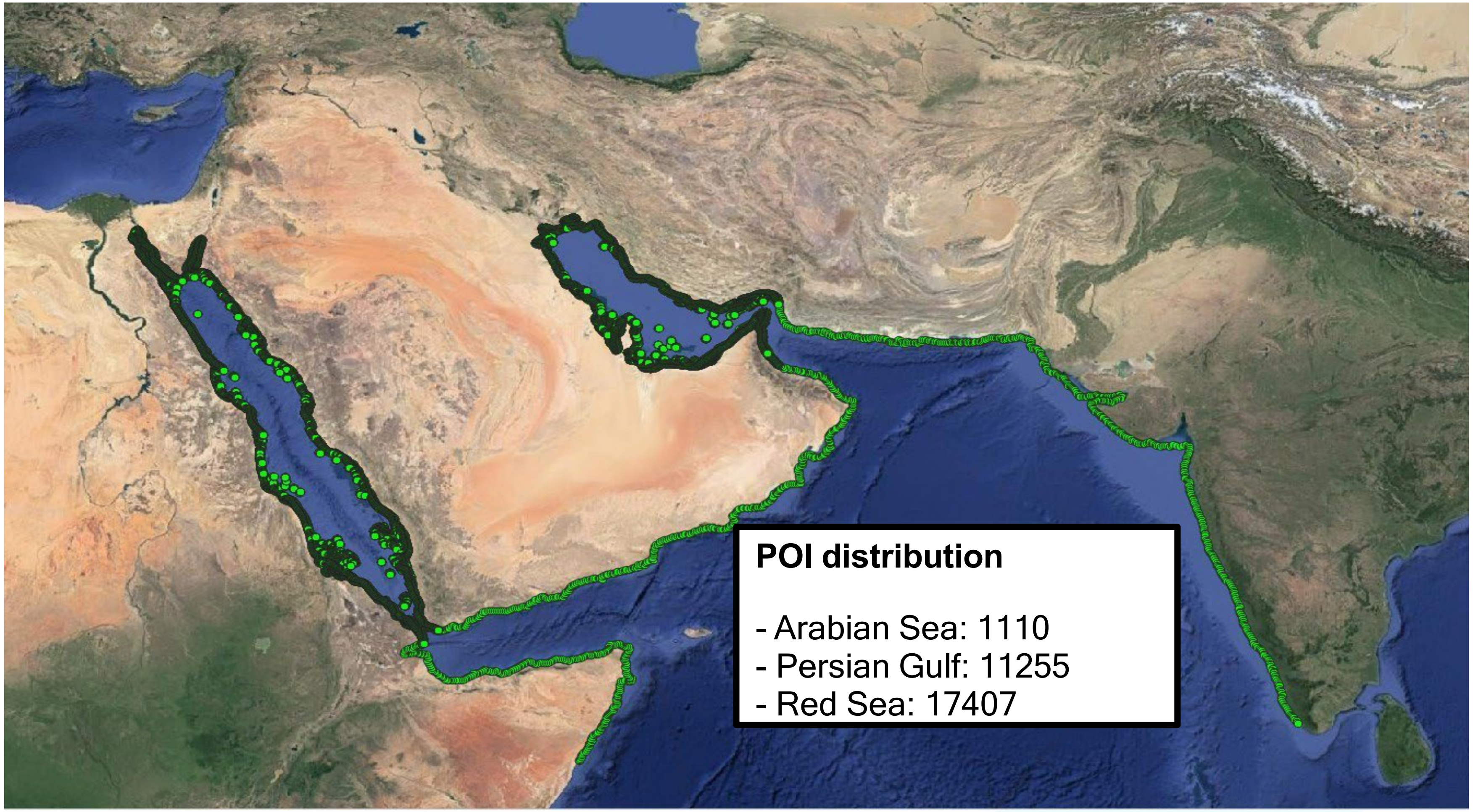
Makran PTHA :: STEP 2 “Tsunami Modelling”

Greens’ functions for the Arabian Sea



Molinari et al (2016)

Makran PTHA :: STEP 2 “Tsunami Modelling”



A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

Makran PTHA :: Ver 01

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	

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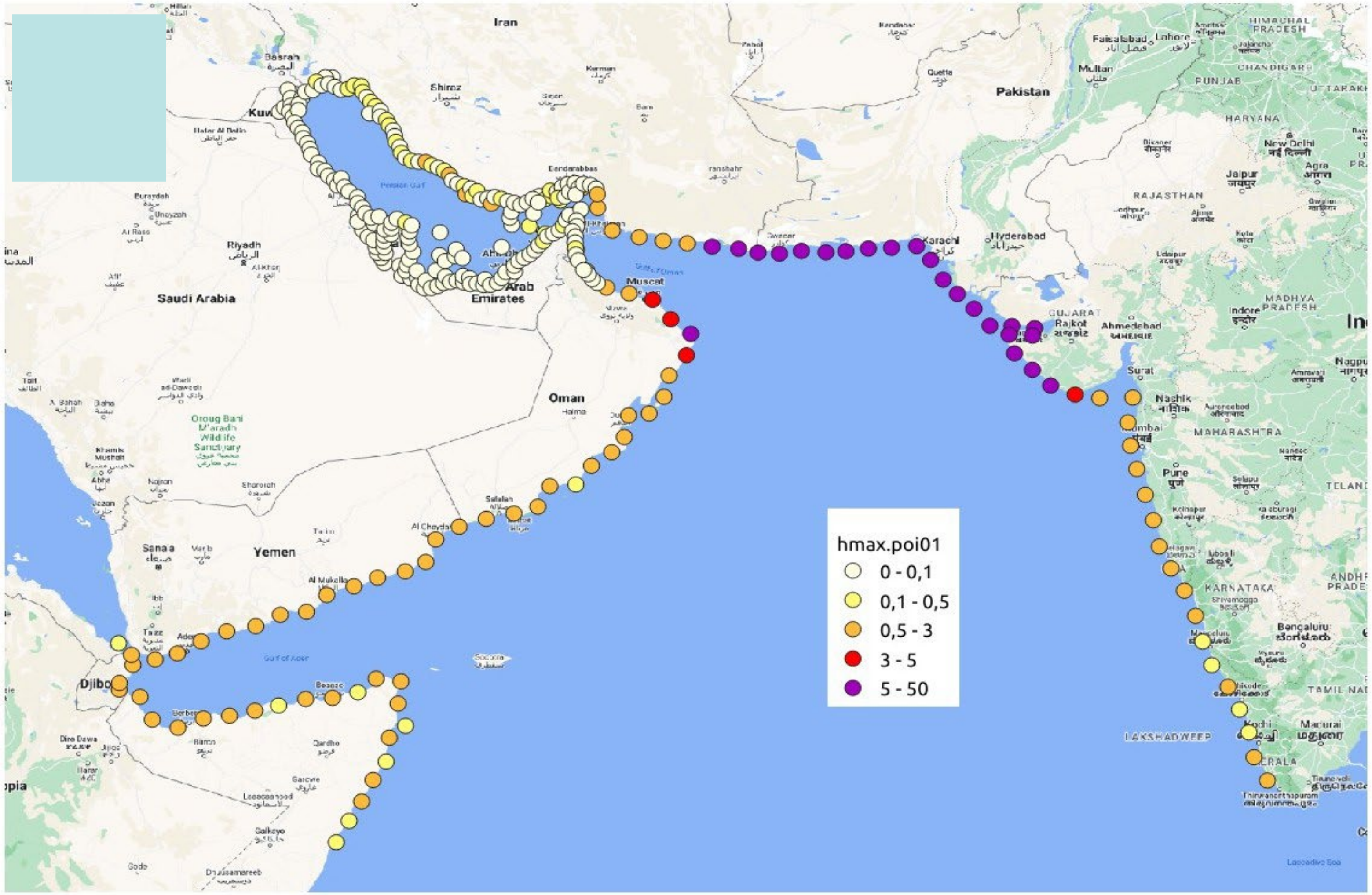
Maximum modeled wave heights (deterministic)

Model1



A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

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Maximum modeled wave heights (deterministic)

Model2

A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

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Maximum expected 2500 years wave height (probabilistic

Model1

A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

Maximum expected 2500 years wave height (probabilistic

Model2

A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

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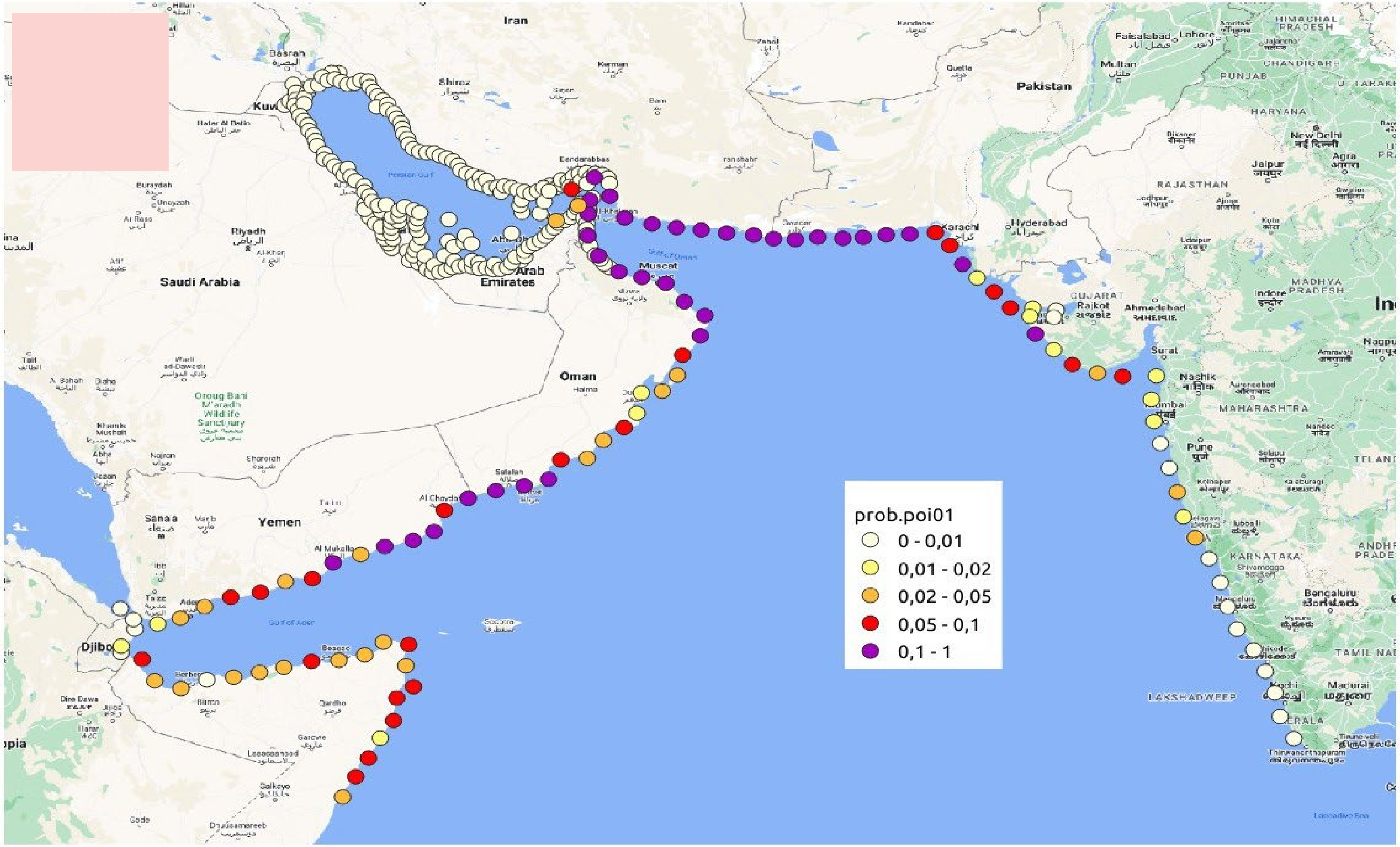
Probability of h>1 meter within next 50 years

Model1

A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

Probability of h>1 meter within next 50 years

Model2



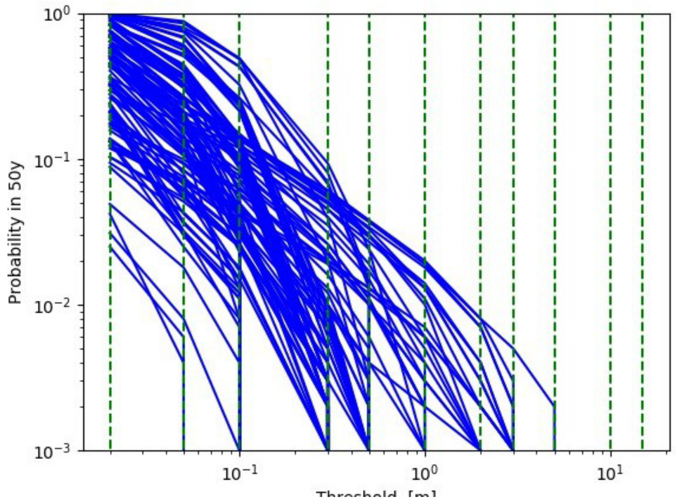
A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

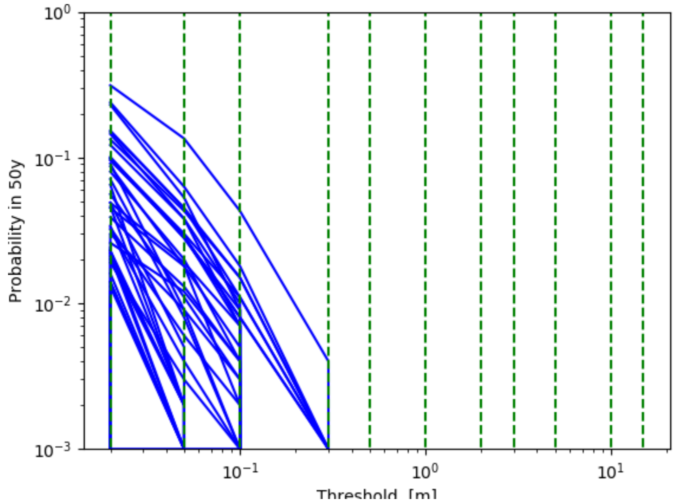
Looking at the Hazard curves

Arabian Sea
(all 111 POIs)

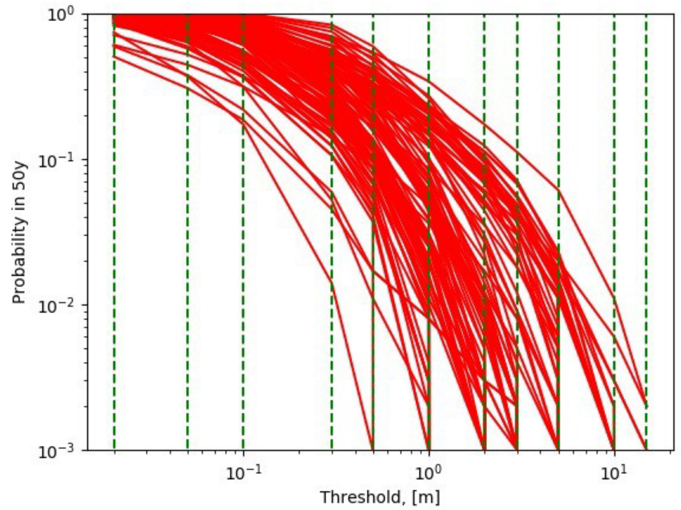
Persian Gulf
(all 197 POIs)

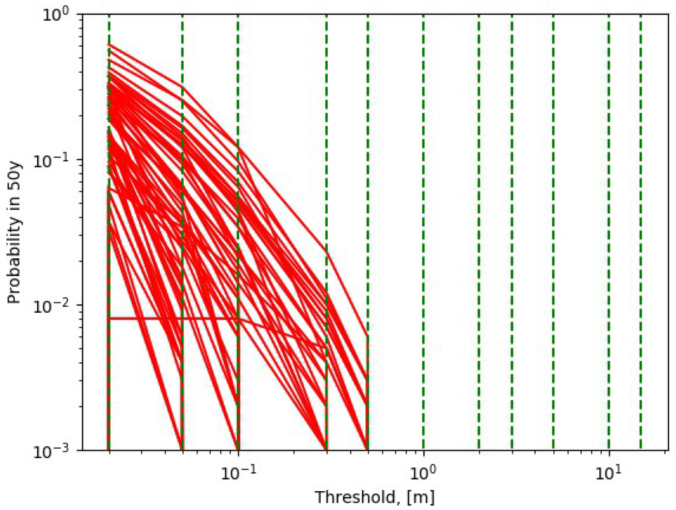
Model1





Model2

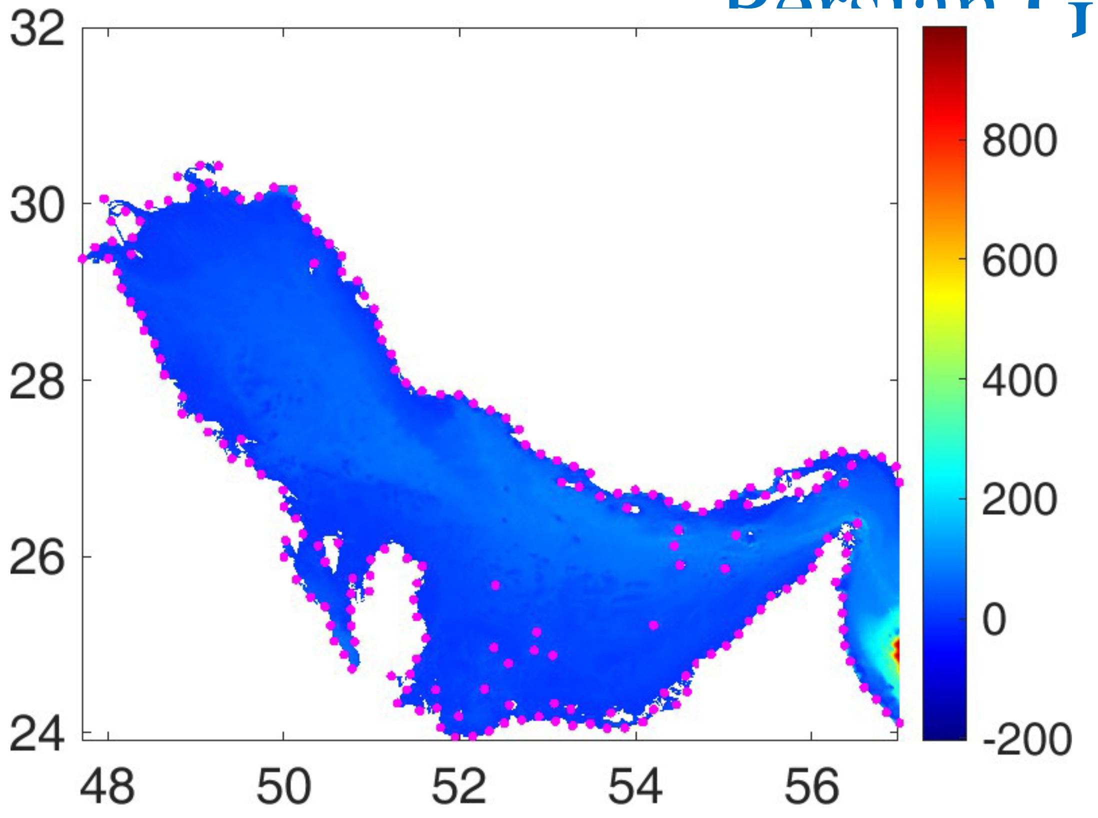




A. Babeyko: Roadmap from PTHA 1.0 to Consensus Model, NWIO

Makran PTHA :: STEP 2 “Tsunami Modelling”

PTHA simulations on the Persian Gulf

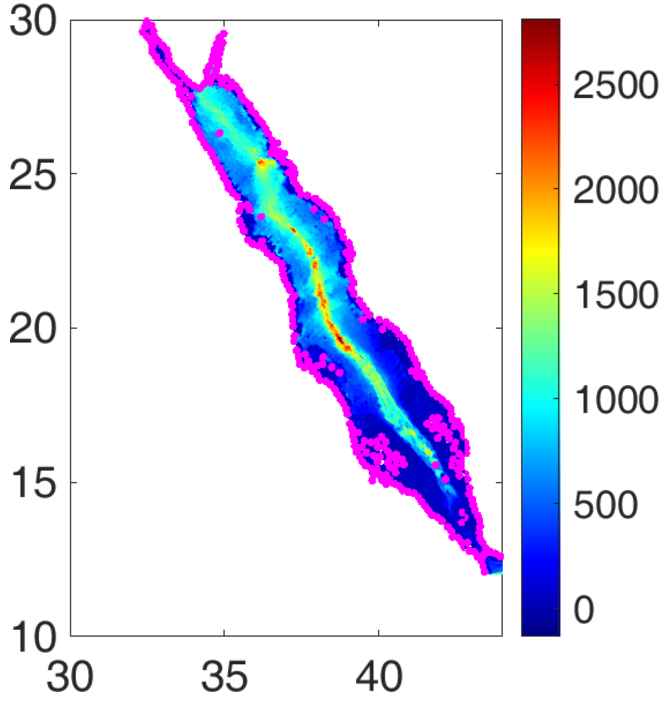


Persian Gulf region for which PTHA simulations were carried out. The magenta dots show the POIs

S. No	Zone	Original	After Cleaning	Valid
1	z09	240768	180576	148711
2	z10	128160	96120	73730
3	z11	338688	254016	47328
4	z12	475200	356400	103188
5	z13	10080	7560	14
6	z14	5760	4320	0
7	z15	2880	2160	0
8	z16	6336	4752	873
9	z17	105984	79488	13779
10	z18	184320	138240	10075
Total		**1498176**	**1123632**	**397698**

nele = 1737915
nnodes = 874620
Simulation time = 12 hrs
Computational time = 1 min
Processors = 180

PTHA simulations on the Red Sea



Red Sea region for which PTHA simulations were carried out. The magenta dots show the POIs

S. No	Zone	Original	After Cleaning	Valid
1	z36	138240	103680	94072
2	z37	784512	588384	333521
3	z38	115200	86400	21907
4	z41	45504	34128	8933
5	z42	216000	162000	45895
6	z43	156960	117720	102339
7	z44	515520	386640	361579
8	z45	29376	22032	15504
9	z46	120960	90720	82264
Total		**2122272**	**1591704**	**1066014**

nele = 2650346
nnodes = 1333616
Simulation time = 12 hrs
Computational time = 2 min
Processors = 288

Thank you