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Abstract

Depth-dependent stochastic slip models governed by stress drop and rigidity variations in subduction zones: Advancements in probabilistic tsunami hazard analysis

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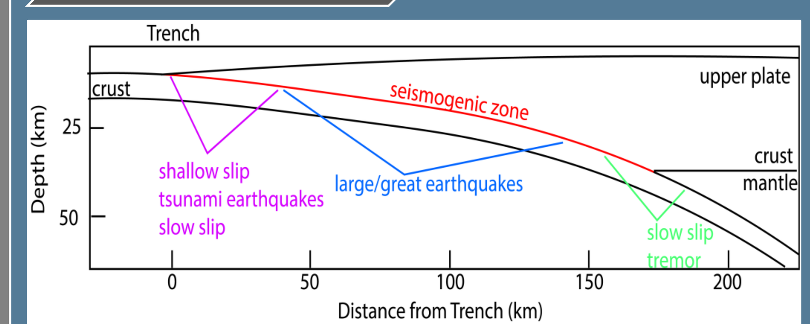
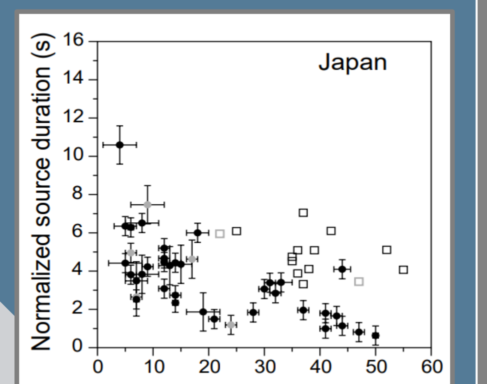
MOTIVATION

- Since tsunamis are rare, most mitigation actions rely on numerical modelling. These requires a highly complex modelling approach with several simplifications and assumptions on different components of tsunami process.
- Developing advanced seismic source models enhances the accuracy of tsunami modelling, leading to a more reliable assessment of tsunami hazard and its potential impact at specific locations.
- Hence, this study seeks to answer the following question: To what extent does more advanced source modelling impact hazard assessment?

INTRODUCTION



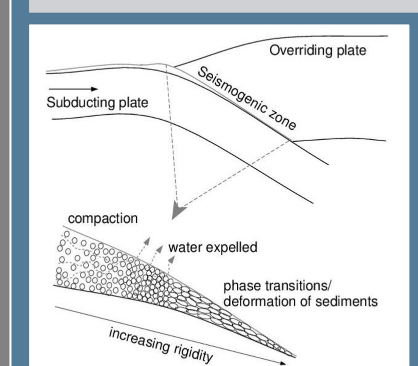


Earthquakes @ Shallow regions

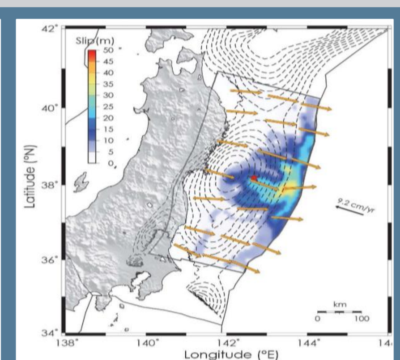
Shallow slip Amplification

Large rupture duration & Slower rupture

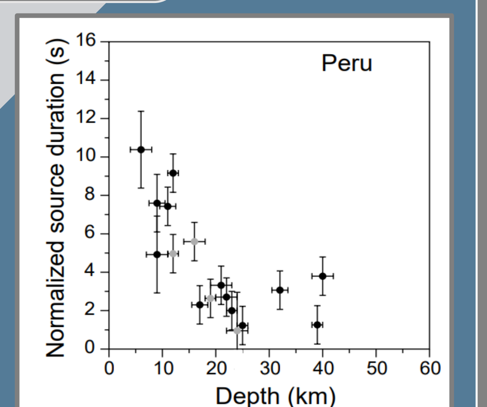
Bilek&Lay (1999)



Bilek&Lay (1999)



Romano et. al. (2014)



SEISMIC SOURCE MODELLING

- $M_0 = \mu \bar{D} S = \mu \bar{D} L W$
- $M_0 = C \Delta\sigma L \frac{W^2}{2}$
- $M_0 = C \Delta\sigma \beta^3 f_c^{-3}$

Longer Duration at shallower depth can be due to;

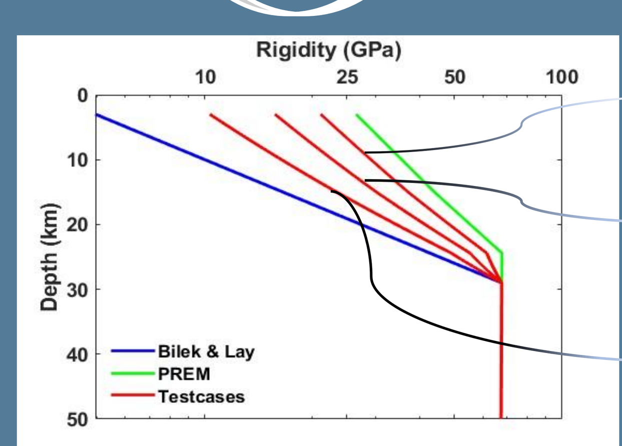
Larger Rupture — Smaller Stress Drop — Slower Rupture — Smaller Rigidity

$$\tau(z) = \frac{1}{f_c(z)} = \frac{\left(\frac{L}{2}\right)^{1/3} W^{2/3}}{\beta} = \frac{{M_0}^{1/3} (C\Delta\sigma(z))^{-1/3}}{\mu(z)^{1/2} \rho^{-1/2}}$$

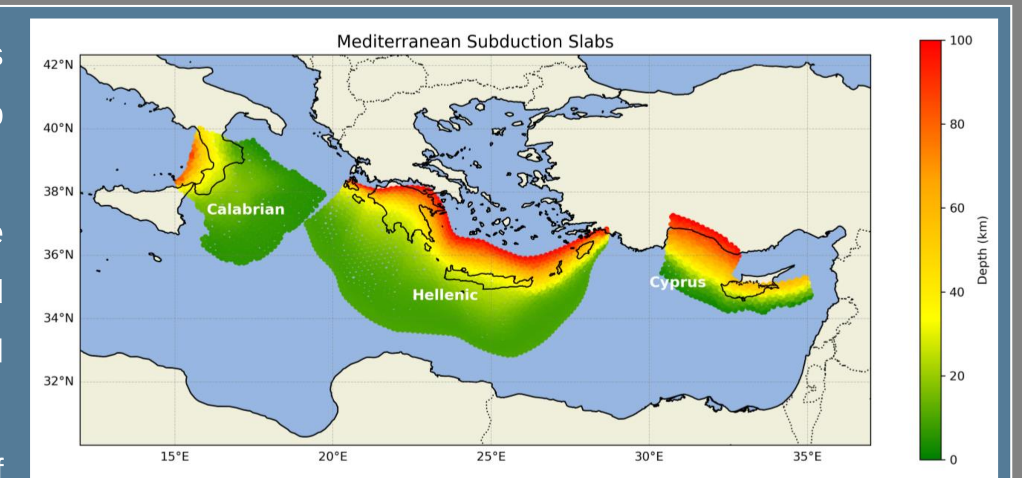
Depth-independent rigidity: Highly unrealistic Models.

Scala et al.(2020): Depth-dependent Rigidity and depth-independent Stress drop.

This Research: Depth-dependent Rigidity & Stress drop.



- Classical models identify rigidity and stress drop as the two main parameters driving slowness and slip amplification.
- Given the seismic moment (Mo), the rupture duration (τ) depends on stress drop (Δσ) and rigidity (μ) (and density (ρ)), allowing us to model depth-dependent changes.
- We defined three cases of smoother gradients of rigidity but consistent with the observed duration through a depth-dependent variation of stress drop.



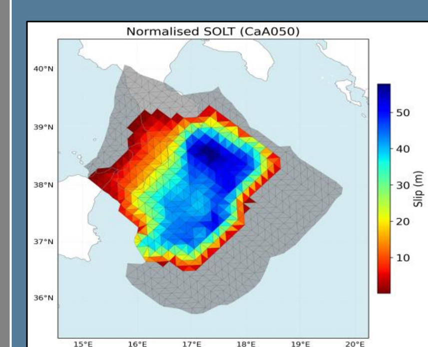
This study focuses on three main subduction slabs in the Mediterranean: Calabrian, Hellenic and Cyprus arc, each containing several seismogenic zones with varying seismicity rates.

METHODOLOGY

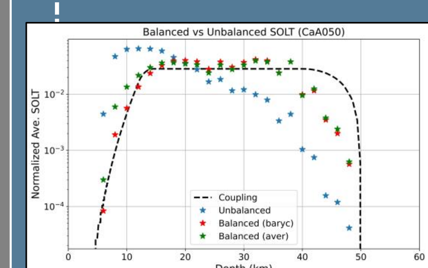
$\delta_n = \sum_{M_{wmin}}^{M_{wmax}} \sum_{i=1}^{N_{Mw}} \delta_{ni} . P(M_w). P(Sl_i|M_w)$

pyANTI-FASc

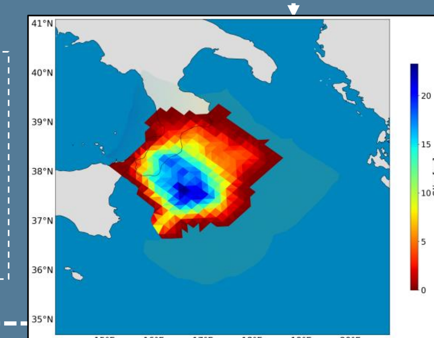
Software allowing the fast computation of large ensembles of slip distributions (δ_{ni}).



Normalised slip over long term (SOLT)

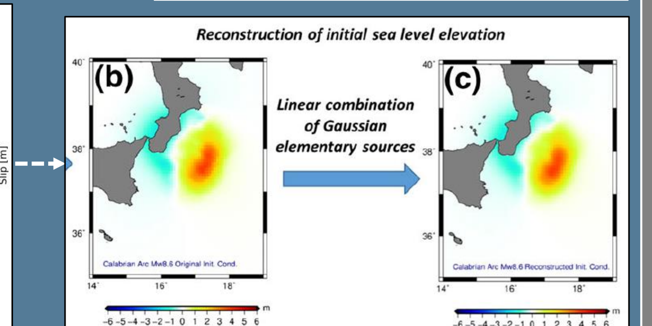


Balancing SOLT



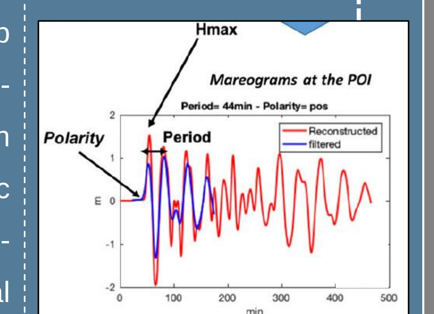
An earthquake slip distribution

Tsunami Linear Combinations

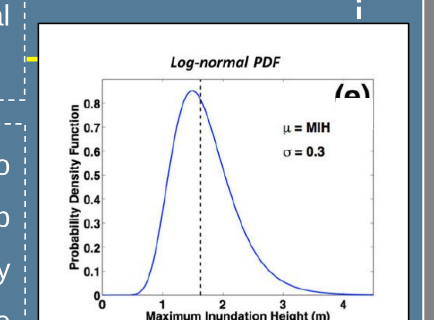


Scala et.al (2020)

Tsunami Linear Combination: The process starts with earthquake slip distributions to compute initial sea surface deformation using triangular sub-fault dislocations and a low-pass filter. This deformation is then reconstructed through a linear combination of Gaussian sources. A synthetic mareogram is generated at the Point of Interest (POI), from which a log-normal tsunami Probability Distribution Function (PDF) is derived from local amplification factors as a function of dominant wave period & polarity. Finally, the CCDF is calculated for each slip scenario, that is the conditional probability of exceeding a tsunami intensity threshold $\mathbf{H_0}$ at the POI.



Scala et.al (2020)



Balanced slip distribution conditional probability: $P(Sl_i|M_w)$

Balancing: A depth-dependent probability of occurrence must be defined to ensure single-event slip distributions are consistent with the long-term slip expected from plate convergence rates and coupling. As this probability increases with the average rigidity of the rupture area, the largest magnitude events, rupturing nearly the entire fault surface, can be considered spatially equiprobable for a given magnitude. To balance the systematic slip amplification from these large events, the occurrence probability of smaller events must be adjusted, making deeper events more probable than shallower ones. This maintains consistency with the long-term slip budget.

CCDF: $P_{POI}(H > H_0|Sl_i)$

Mean Annual Rates of Tsunami Hazard Intensity Exceedance at a given POI;

$$\lambda_{POI}(H > H_0) = \sum_{j=1}^{N_z} \sum_{i=1}^{N_e} P_{POI}(H > H_0|Sl_i). \lambda_j. P(M_w). P(Sl_i|M_w)$$

$P(M_w)$ is the probability of occurrence of an earthquake (e) given a magnitude, derived from the Gutenberg–Richter law using a tapered Pareto distribution. λ_j is the mean annual rate for earthquakes with Mw > 6; for the j-th seismogenic zone (z) within each subduction slab.

$$p(H > H_0) = 1 - e^{-\lambda(H>H_0).T}$$

$p(H > H_0)$: the probability of exceedance of a threshold level of inundation height H_0 over an exposure time T. According to classical hypothesis, an earthquake occurrence is a Poissonian process.

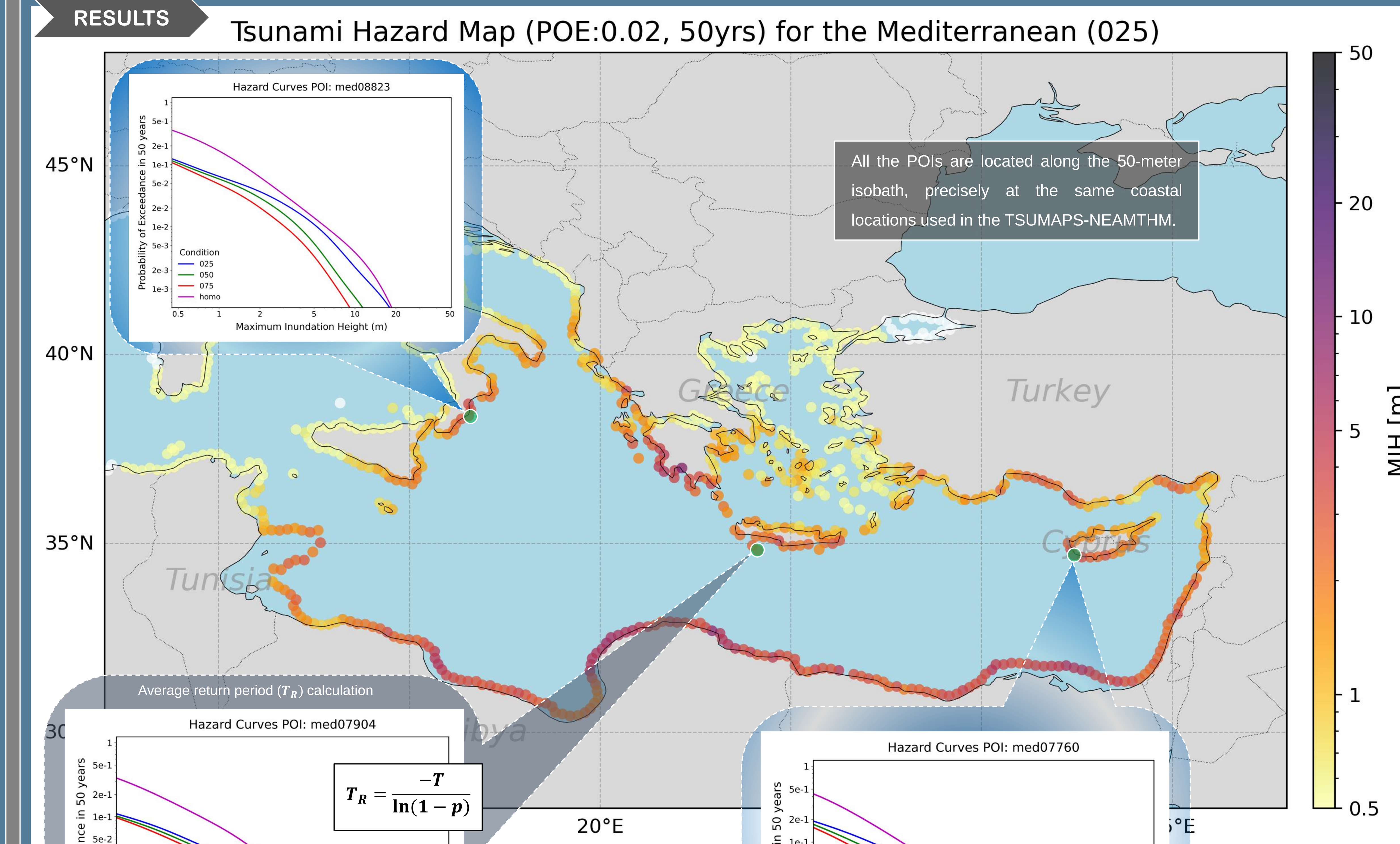
Tsunami Hazard Curves

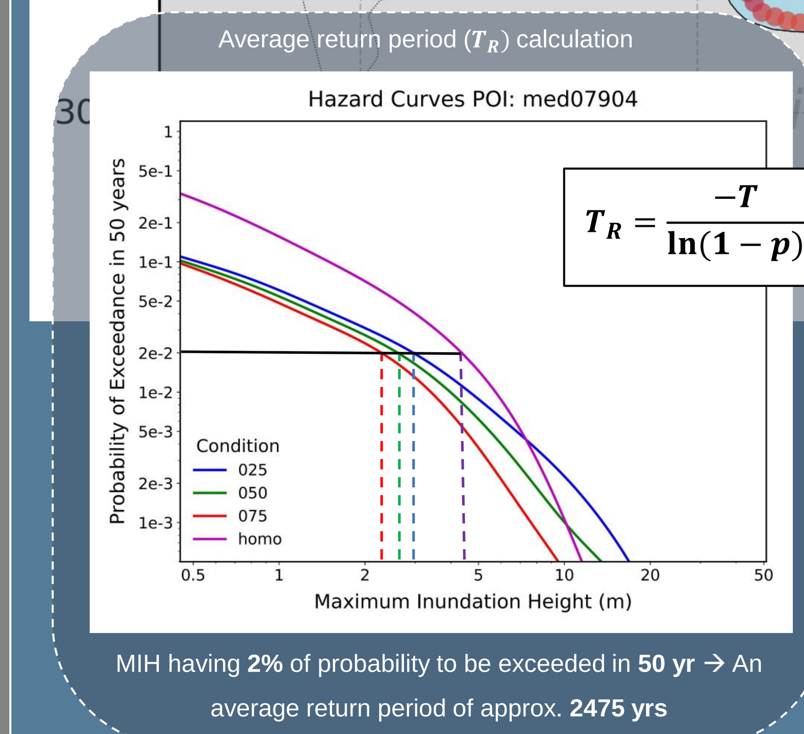
Tsunami Hazard Map

Hazard curves at several points of interest (POI) contribute to the definition of the Hazard map over a region.

RESULTS

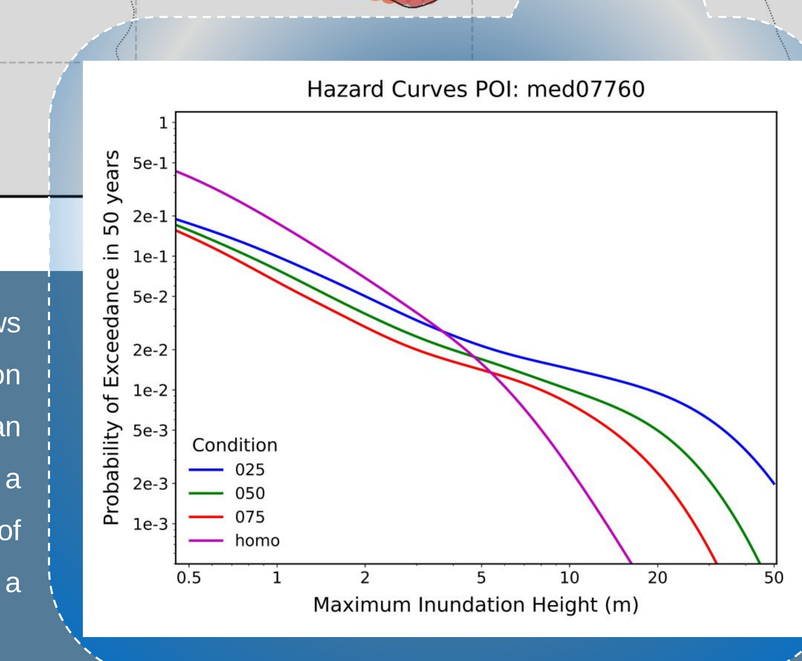
Tsunami Hazard Map (POE:0.02, 50yrs) for the Mediterranean (025)





MIH having **2%** of probability to be exceeded in **50 yr** → An average return period of approx. **2475 yrs**

Tsunami Hazard Map: Shows the maximum inundation height (MIH) a tsunami can reach at a POI, based on a specified probability of exceedance (POE) within a given time period.



This map corresponds to one of our depth-dependent rigidity models, specifically model 025, which represents the most abrupt rigidity variation among all the models we considered.

- The hazard curves clearly show that, compared to the depth-independent case (homo), the depth-dependent models yield lower probabilities for small to moderate inundation, but higher probabilities for larger inundation levels. This crossover behavior of the depth dependent curves is least evident near the Calabrian slab, becomes more noticeable toward the Hellenic Arc, and is most pronounced at POIs near Cyprus.
- This trend may be explained by differences in slab geometry. The Cyprus slab is steeper and more elongated, which can enhance the impact of large shallow slip, leading to higher inundation probabilities at greater intensities. In contrast, the Calabrian slab is relatively flat, which might limit this effect, while the Hellenic Arc lies somewhere in between.

CONCLUSION

- We evaluated the tsunami hazard across our region of interest within the Mediterranean.
- Among the depth-dependent models, the highest hazard is observed when the most abrupt rigidity variation (025) is modelled. This occurs because a less abrupt stress drop gradient which results in larger maximum slip of seismic sources, leads to higher MIH values.
- Our study shows that the implementation of more complex seismic source modelling, accounting for more realistic depth-dependent features, leads to significant differences in hazard assessment. This implies that more accurate, physically-based seismic source modelling might be necessary to avoid misestimation.
- The forthcoming objective is to verify how well the proposed model fits real observations in terms of tsunami propagation. To achieve this, we will exploit the main tsunamigenic events that occurred in the Pacific Ocean.

Main References: [1] Scala A., Lorito S., Romano F., Murphy S., et al.; 2020: Effect of shallow slip amplification uncertainty on probabilistic tsunami hazard analysis in subduction zones: Use of long-term balanced stochastic slip models. Pure and Applied Geophysics., **[2]** Antonio Scala, Manuel Mojica, & rissclab-tester. (2024). antonioscalaunina/pyANTI-FASc: pyANTIFASc_1.0.0 (v1.0.0). Zenodo. https://doi.org/10.5281/zenodo.13614658 **[3]** Bilek S. L., Lay T.; 1999: Rigidity variations with depth along interpolate megathrust faults in subduction zones. Nature., **[4]** Geist E. L., Bilek S. L.; 2001: Effect of depth-dependent shear modulus on tsunami generation along subduction zones. Geophysical Research Letters., **[5]** Basili R., Brizuela B., Herrero A., Iqbal S., Lorito S., et al.; 2021: The making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18). Frontiers in Earth Science., **[6]** Selva J., Lorito S., Volpe M., Romano F., et al.; 2021: Probabilistic tsunami forecasting for early warning. Nature Communications., **[7]** Romano F., Trasatti E., Lorito S., et al.; 2014: Structural control on the Tohoku earthquake rupture process investigated by 3D FEM, tsunami and geodetic data. Scientific Reports., **[8]** Molinari I., Tonini R., Lorito S., et al.; 2016: Fast evaluation of tsunami scenarios: uncertainty assessment for a Mediterranean Sea database. Natural hazards and earth system sciences., [8] Davies G., & Griffin J.; 2018. The 2018 Australian Probabilistic Tsunami Hazard Assessment: Hazard from Earthquake Generated Tsunamis. [9] Davies, G., et al.; 2018. A global probabilistic tsunami hazard assessment from earthquake sources. Geological Society Special Publication.

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