The southern Peru and northern Chile seismic gap: regional and global implications on tsunami hazard assessment

J. González, M. Carvajal, A. Gubler, D. Stewart, M. Cisternas, D. Melnick, G. González, R. Aránguiz, J. Moris, M. Shrivastava & G. Bravo

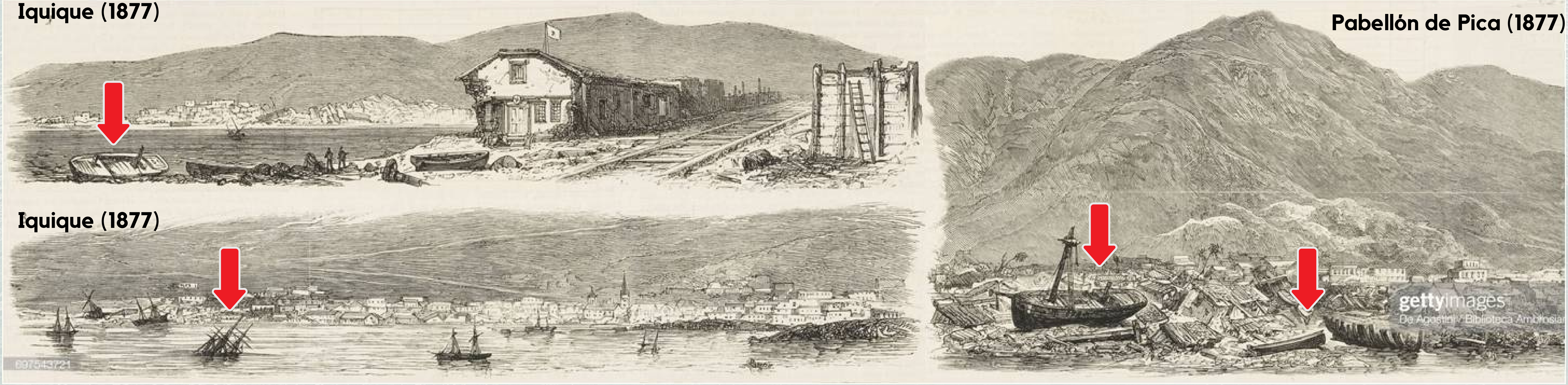
Centro de Investigación para la Gestión Integrada del Riesgo de Desastres (CIGIDEN)

Geología, Facultad de Ingeniería,
Universidad Andrés Bello (UNAB), Viña del Mar

UNESCO-IOC Meeting of Experts on tsunami sources and hazard in southern Peru and northern Chile

22 to 25 August 2023
Arica, Chile

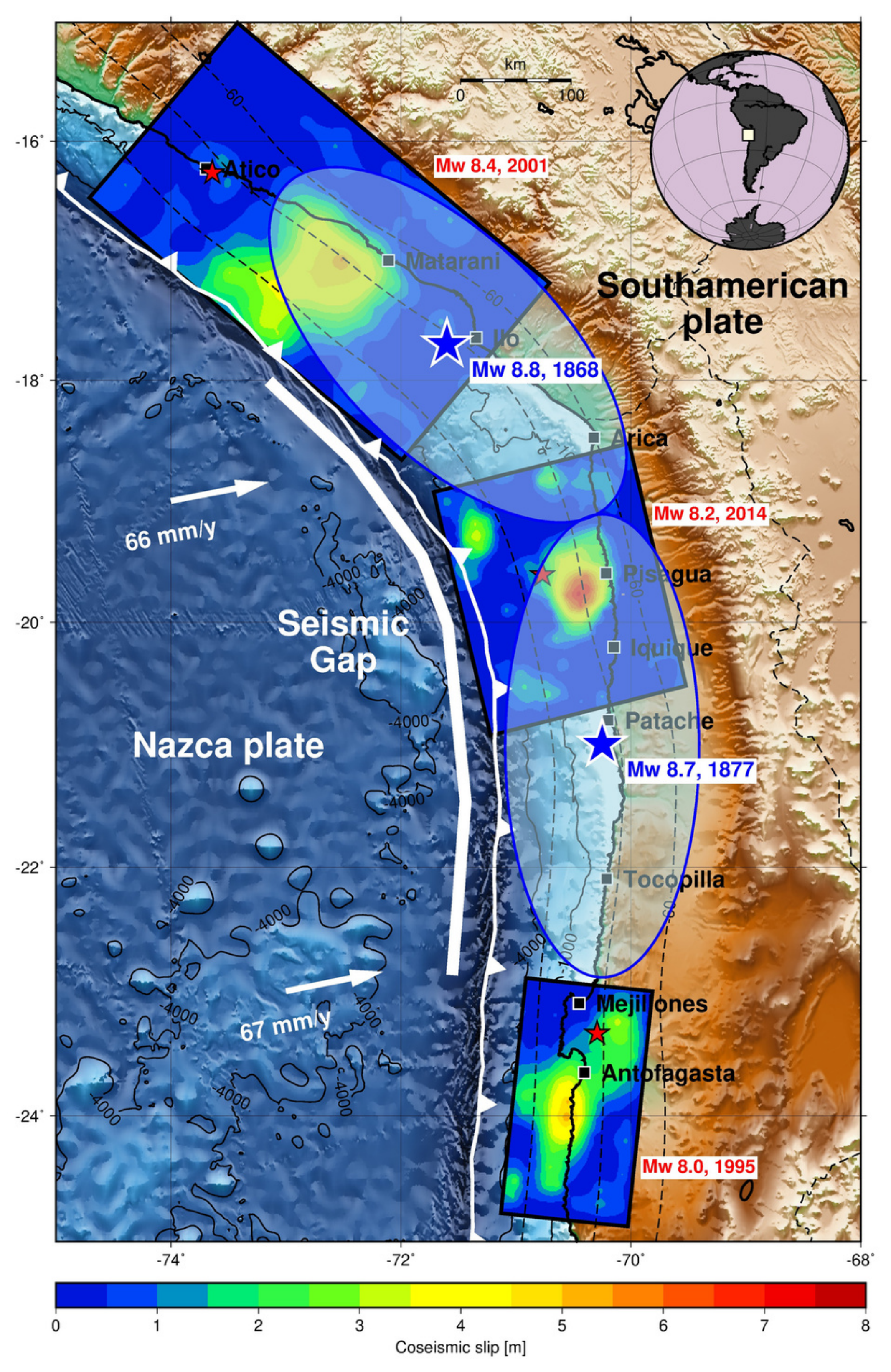
Motivation: Mw 8.1 Iquique earthquake



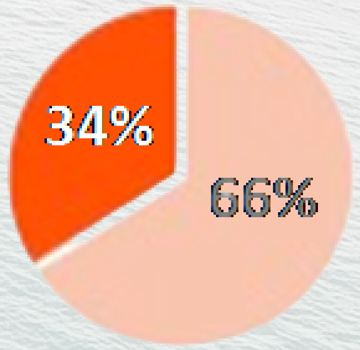
Local tectonic situation

- The subduction zone of southern Peru and northern Chile is a highly active system (65 to 70 mm/y) (**Angermann *et al.*, 1999**), being recognized as a mature seismic gap in the southwestern Pacific basin.
- Historically it has been affected by major earthquakes and tsunamis (**Métois *et al.*, 2012**), such as the last two tsunamigenic events: Mw 9.0, 1868 and Mw 8.8, 1877 (**Comte & Pardo, 1991; Lay *et al.*, 2014**).
- The Iquique earthquake Mw 8.1, 2014 has generated a partial rupture of the seismic rift (**Hayes *et al.*, 2014; Schurr *et al.*, 2014**).

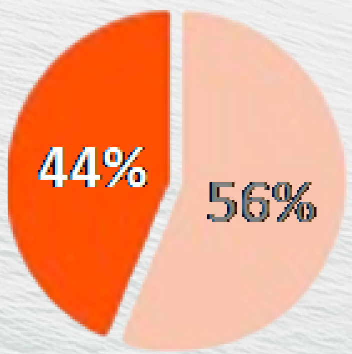
González *et al*, 2020



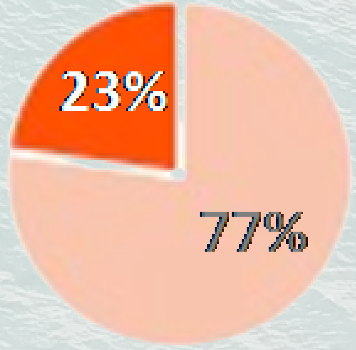
Arica
202.131 inhab.



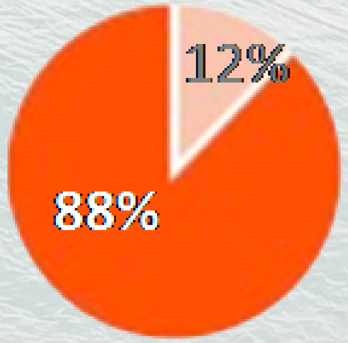
Iquique
188.003 inhab.



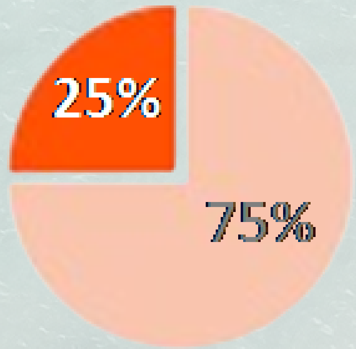
Tocopilla
25.185 inhab.



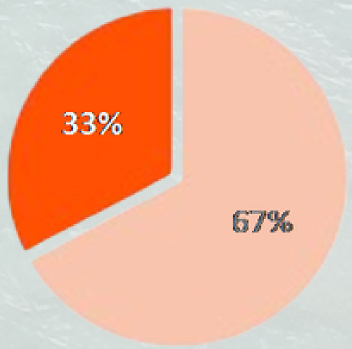
Mejillones
13.467 inhab.



Antofagasta
348.517 inhab.



Total
777.304 inhab.



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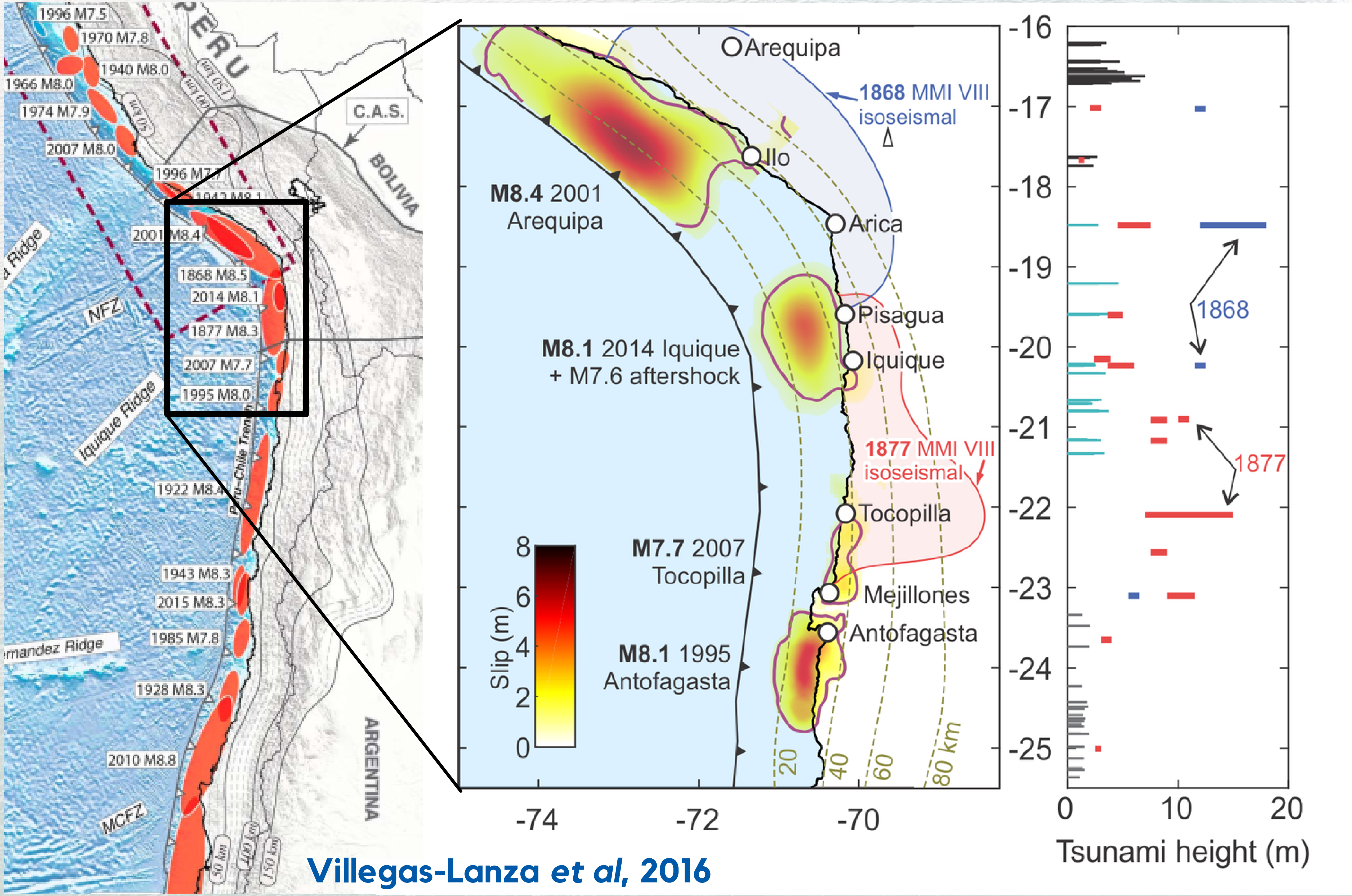
Local tectonic situation



Villegas-Lanza *et al*, 2016

The Nazca-South American convergent margin has been a geological and historical scenario for the occurrence of mega-earthquakes and destructive tsunamis, as for example the **M9.5 Valdivia**.

Recent central Andes earthquakes (M8+) occurred in 1995, 2001 and 2014.

The last tsunamigenic events occurred in 1868 and 1877, generating local and remote impacts.

Tsunamigenic source approaches

Tsunamigenic source

Tsunamigenic event

Deterministic approach

Probabilistic approach

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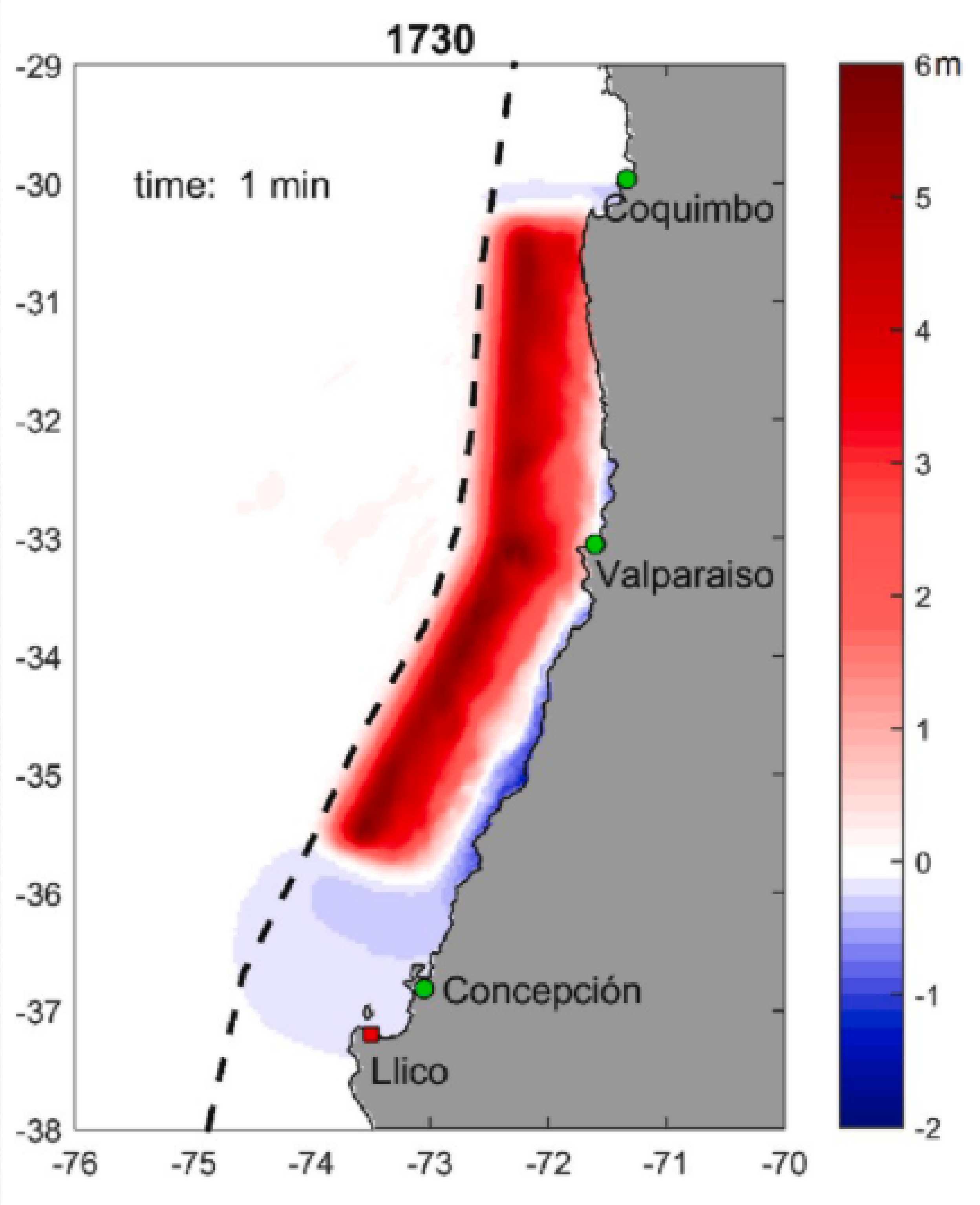
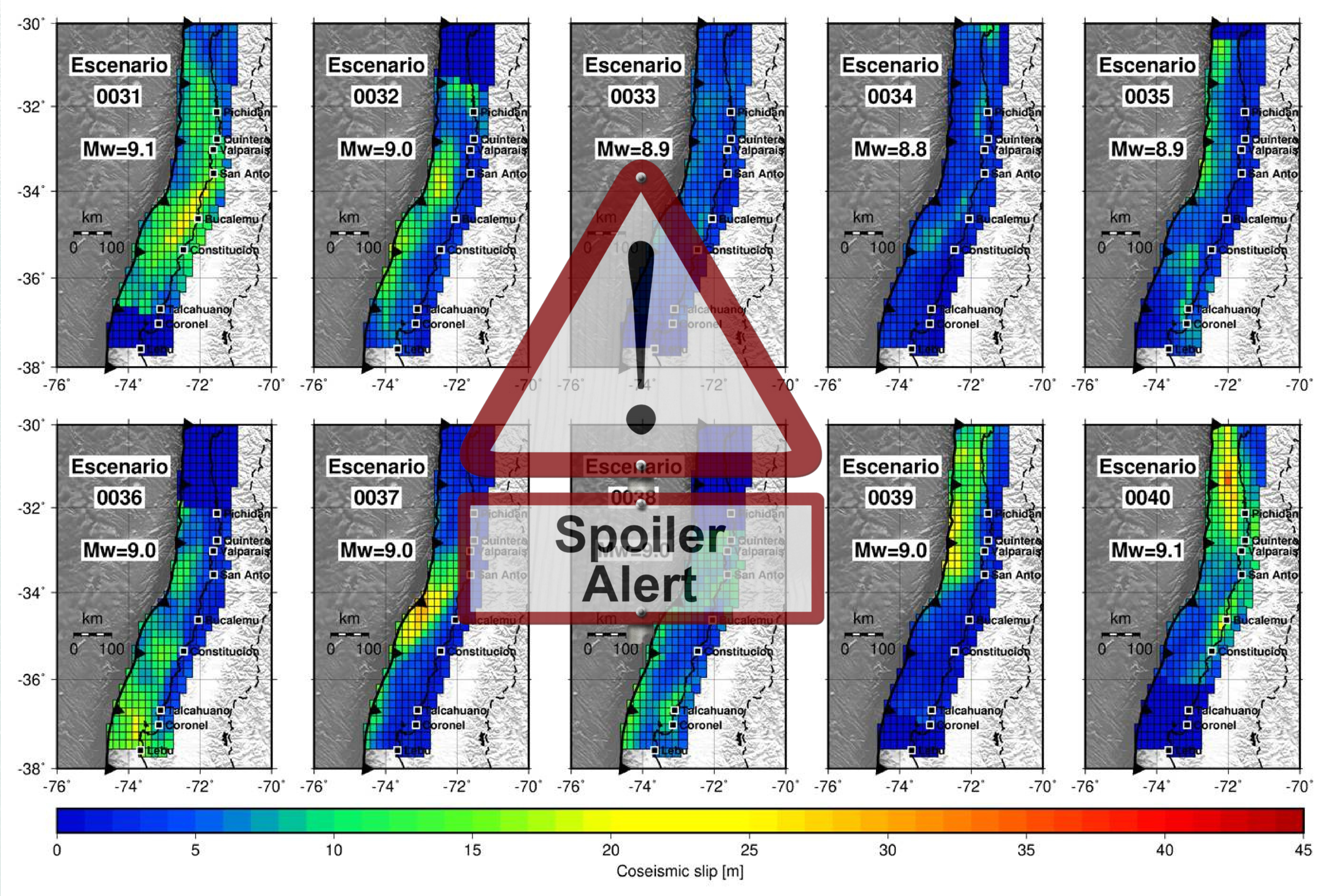
Tsunamigenic source approaches





[Historical scenarios]

[Stochastic scenarios]

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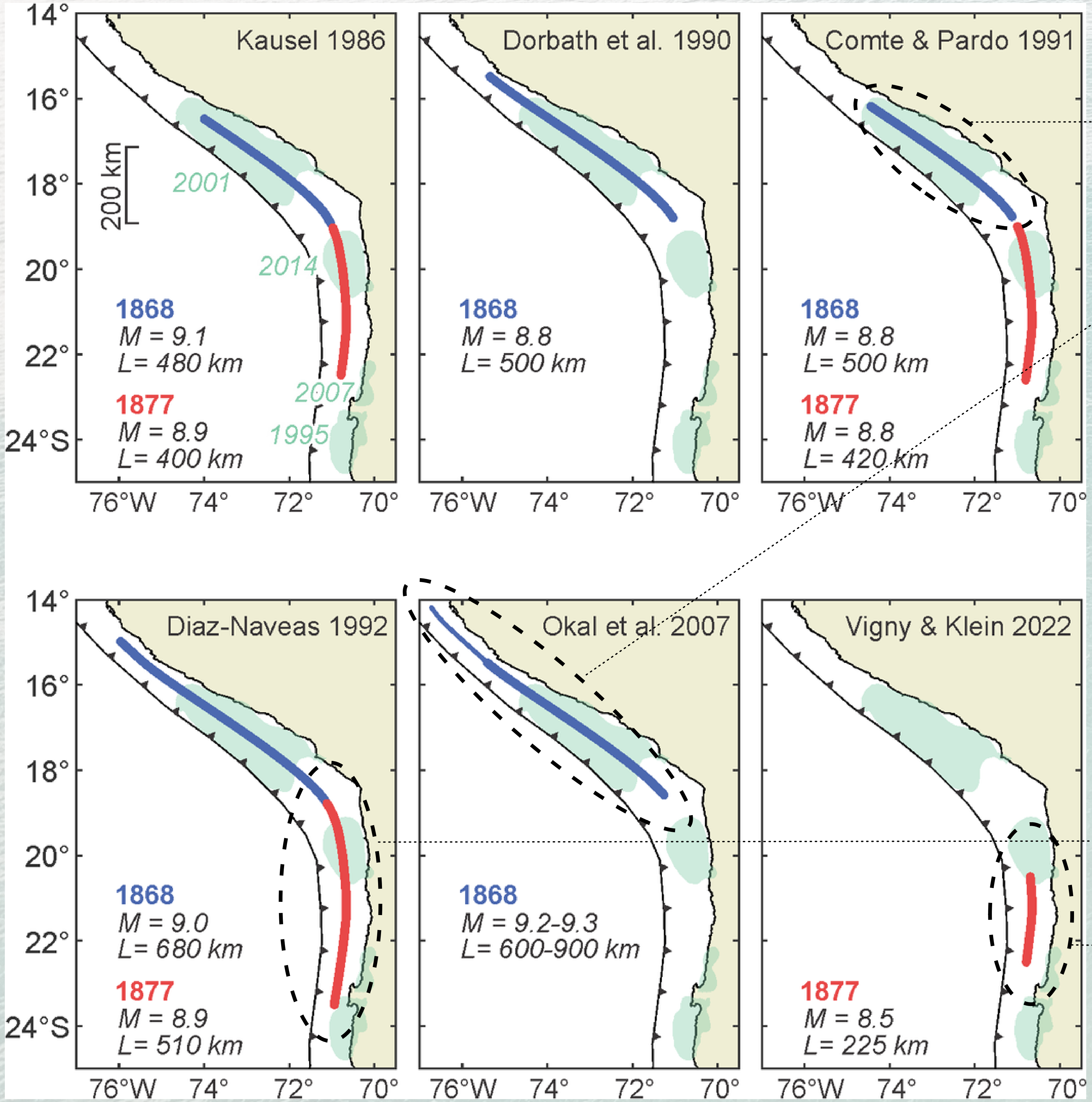
Historical approach

Rupture mode of historical megathrust earthquakes



Mw=8.8; L =480 km *(Kausel 1986)*

Mw=9.3; L =900 km *(Okal et al. 2007)*

Mw=8.9; L =510 km *(Diaz-Naveas 1992)*

Mw=8.5; L =225 km *(Vigny and Klein 2022)*

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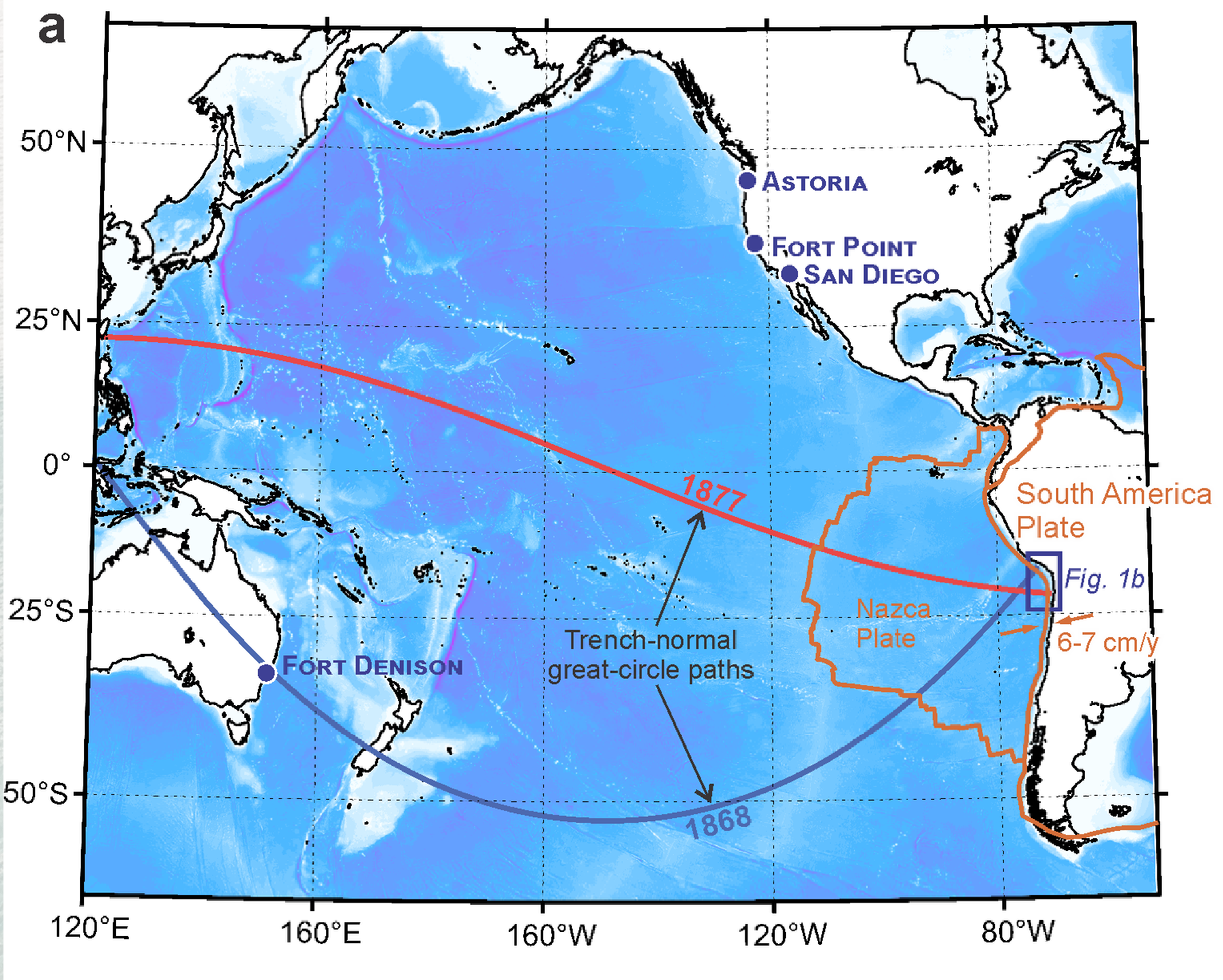
How can we constrain historical earthquake ruptures?

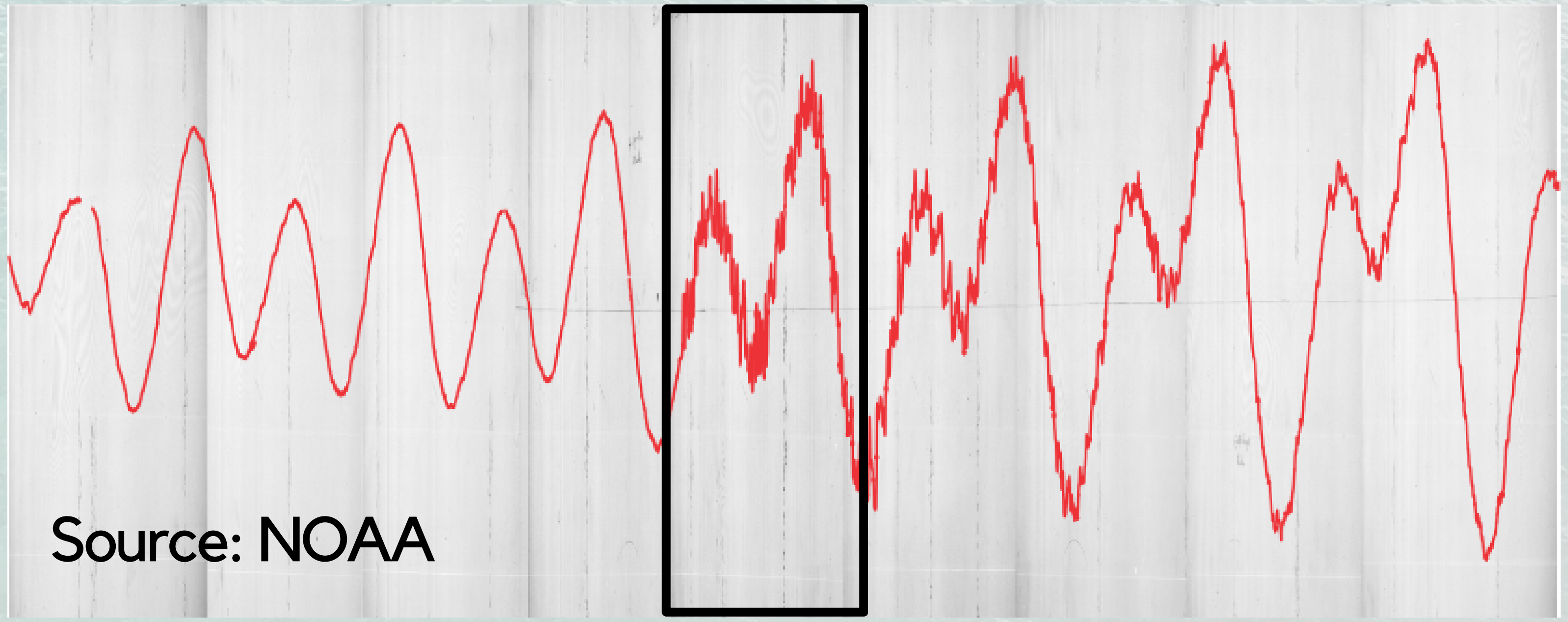


1868 marigrams

- Astoria, USA.
- San Diego, USA.
- Fort Point, San Francisco, USA.
- Fort Denison, Sydney, Australia.

1877 marigrams

- Fort Point, San Francisco, USA.
- Fort Denison, Sydney, Australia.



An example: 1877 marigram recorded at Fort Point, SF, USA

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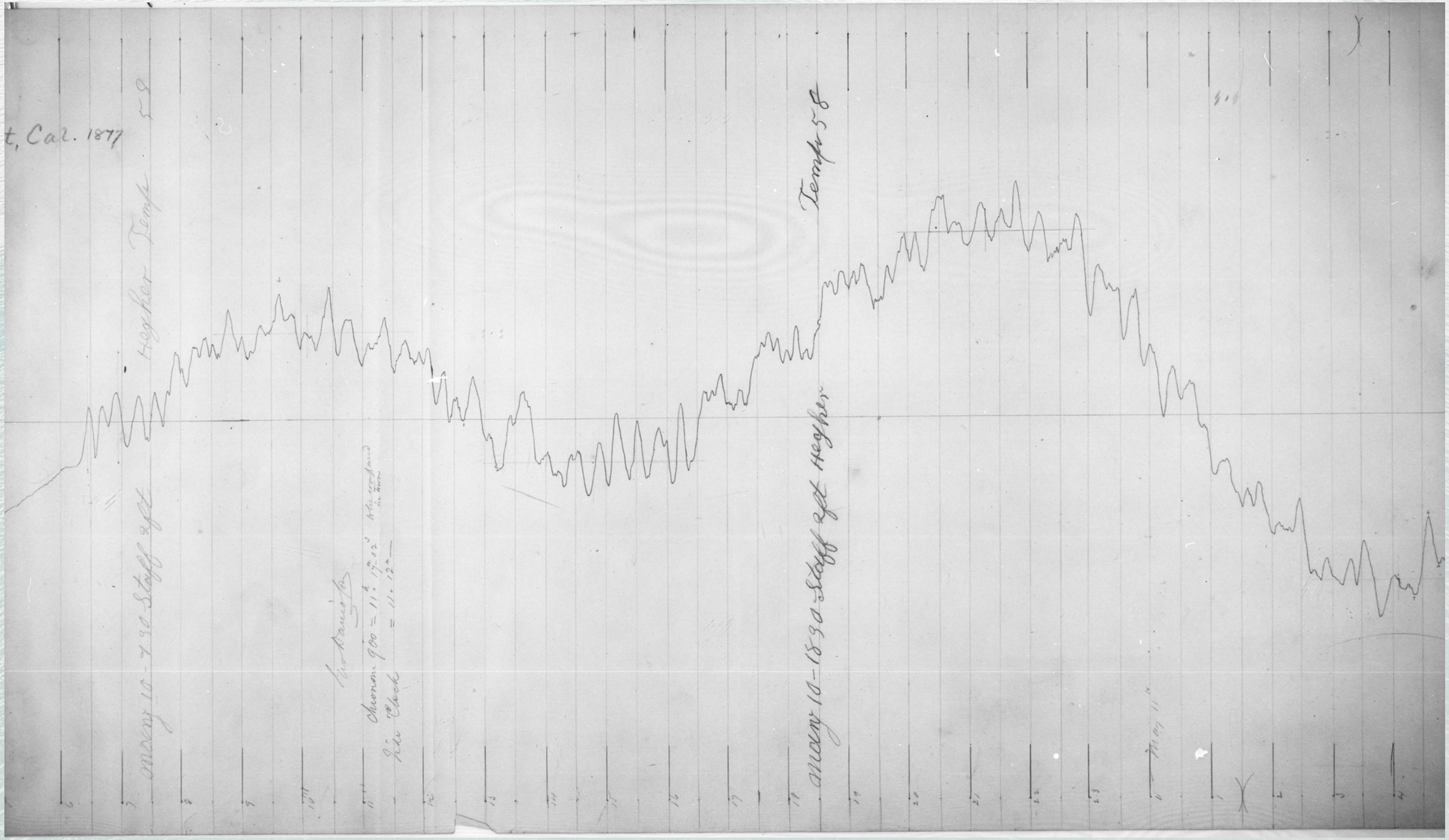
Some issues in old marigrams data

- Lack of an amplitude scale.
- Large time errors.
- Uncertainitities.



An example: 1877 marigram recorded at Fort Point, SF, USA

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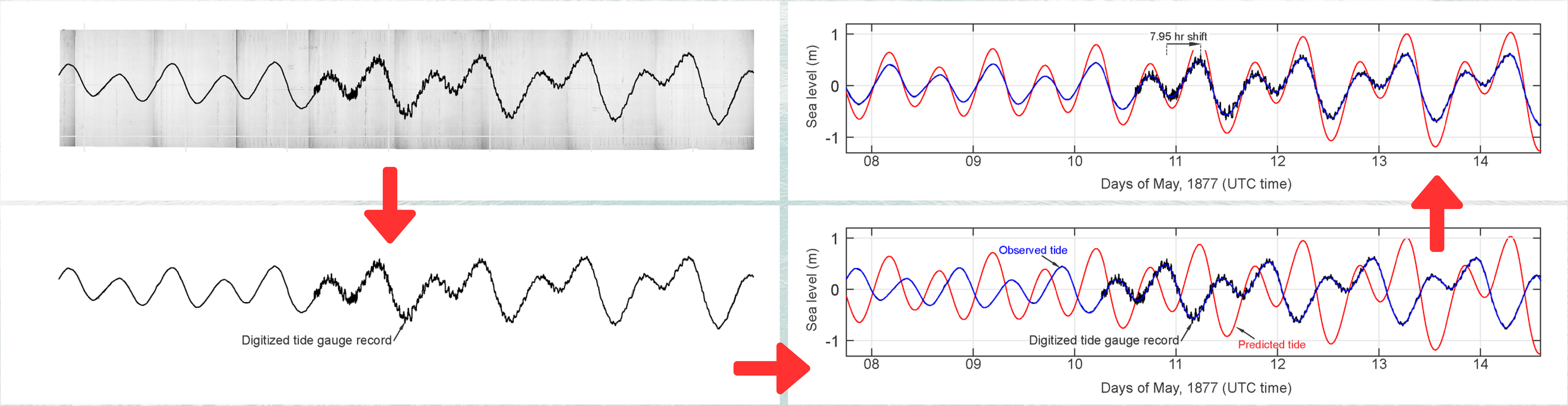
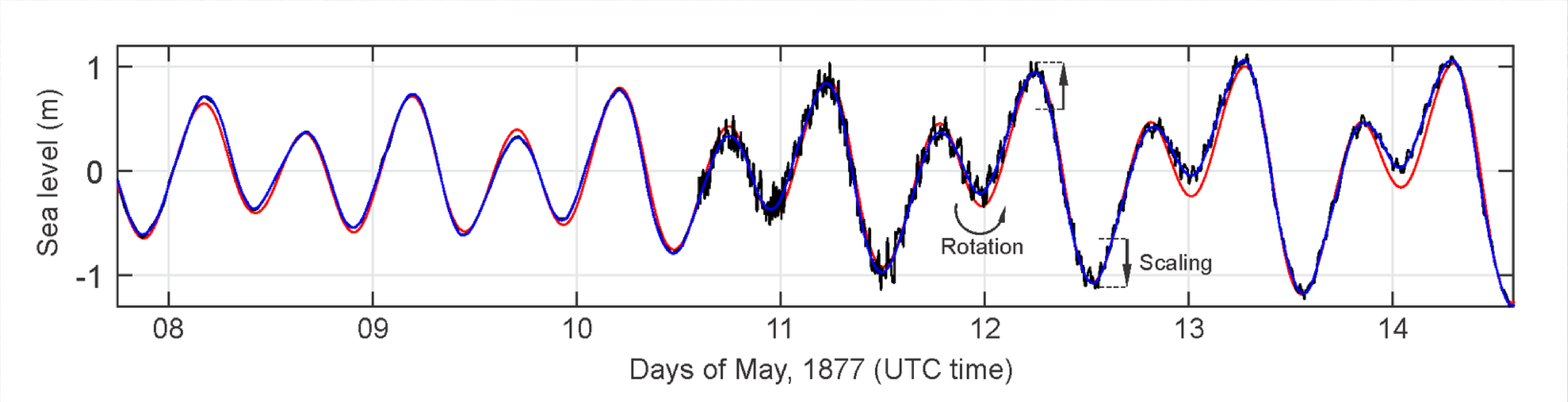
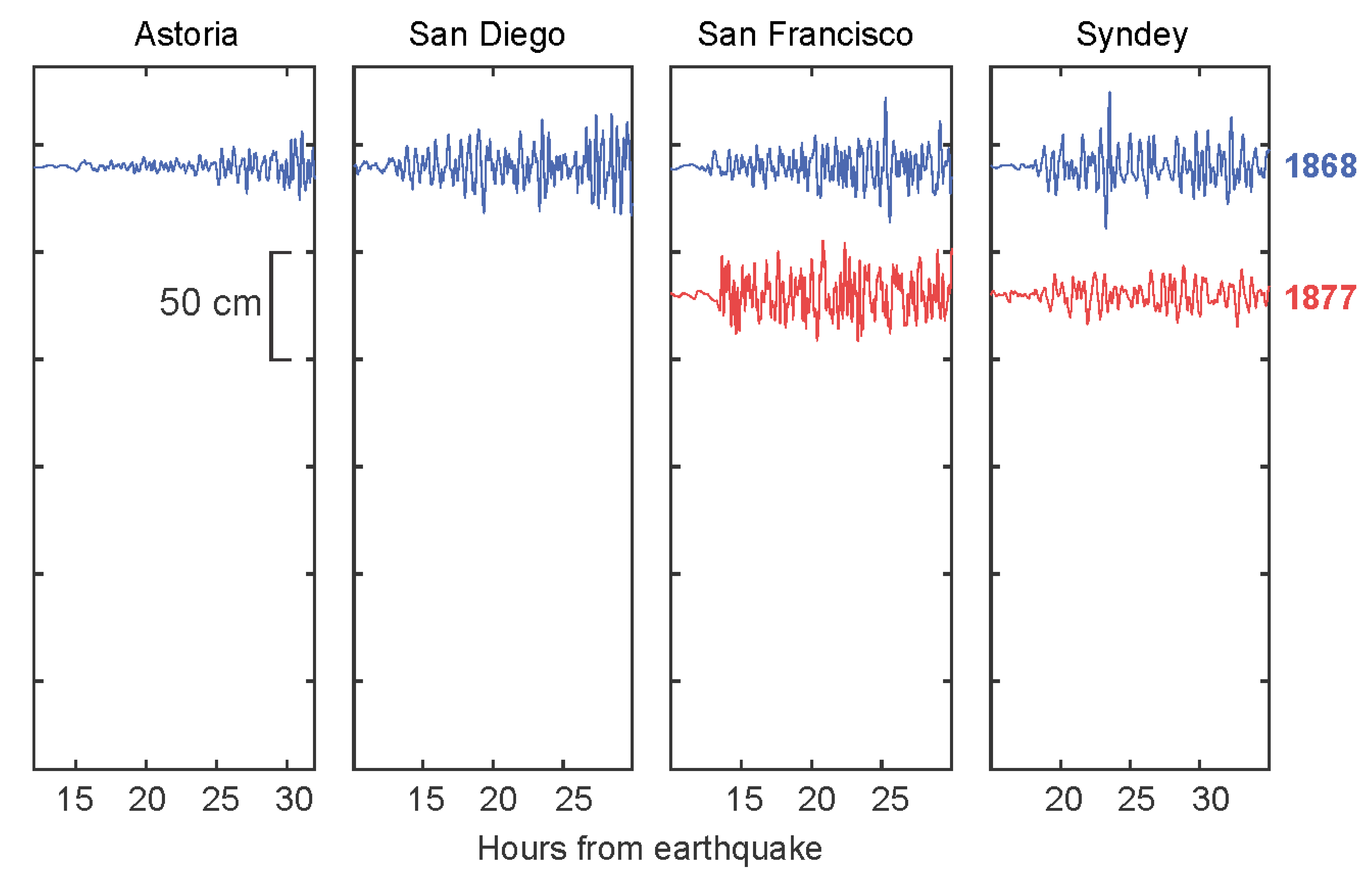
Reconstructed old marigrams





Adjusted historical marigram

The 1868 and 1877 tsunami records



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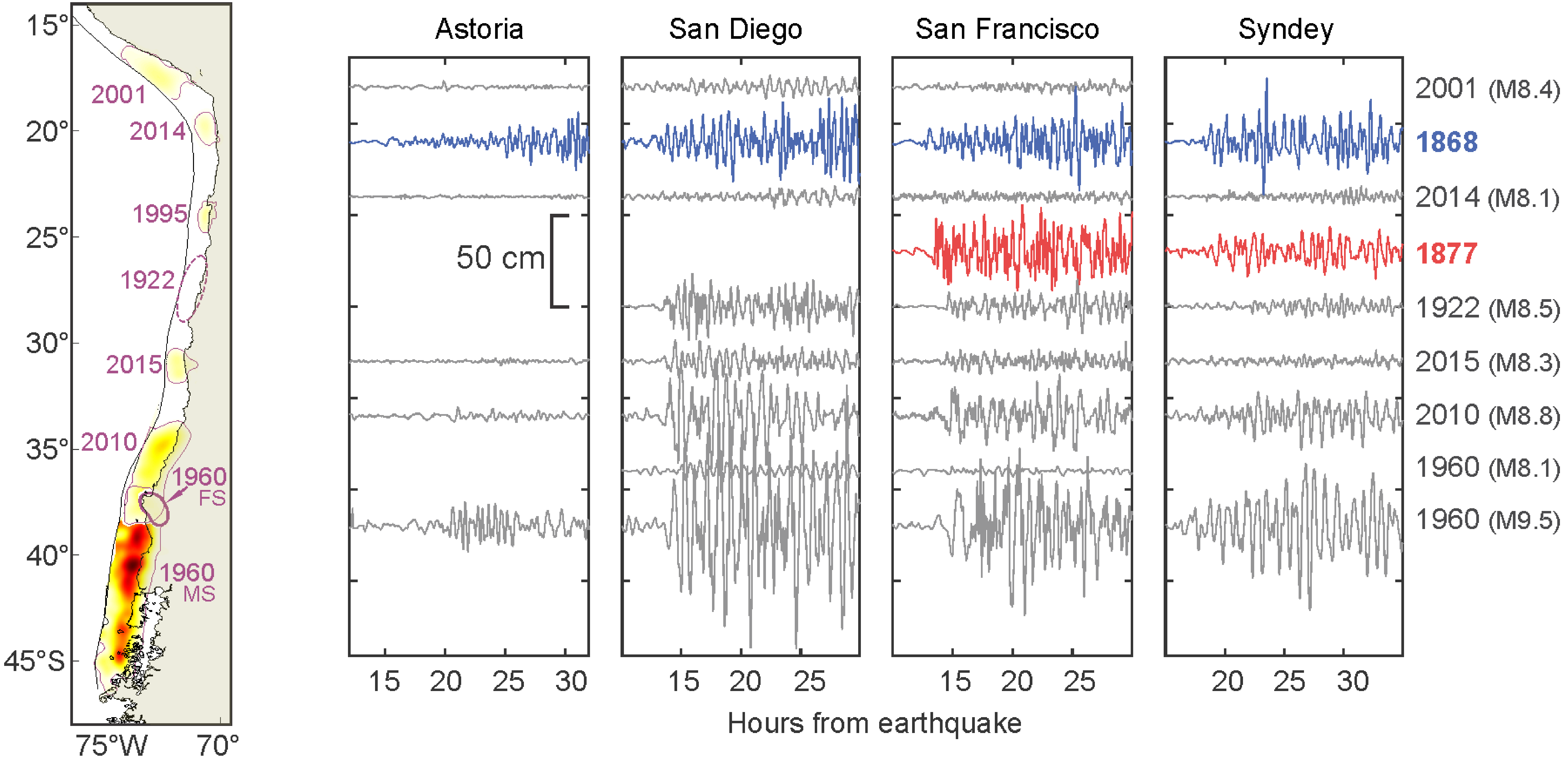
Comparison with Chilean tsunamis in far-field sites

Sydney records were kindly provided by Gareth Davies (Geoscience Australia)



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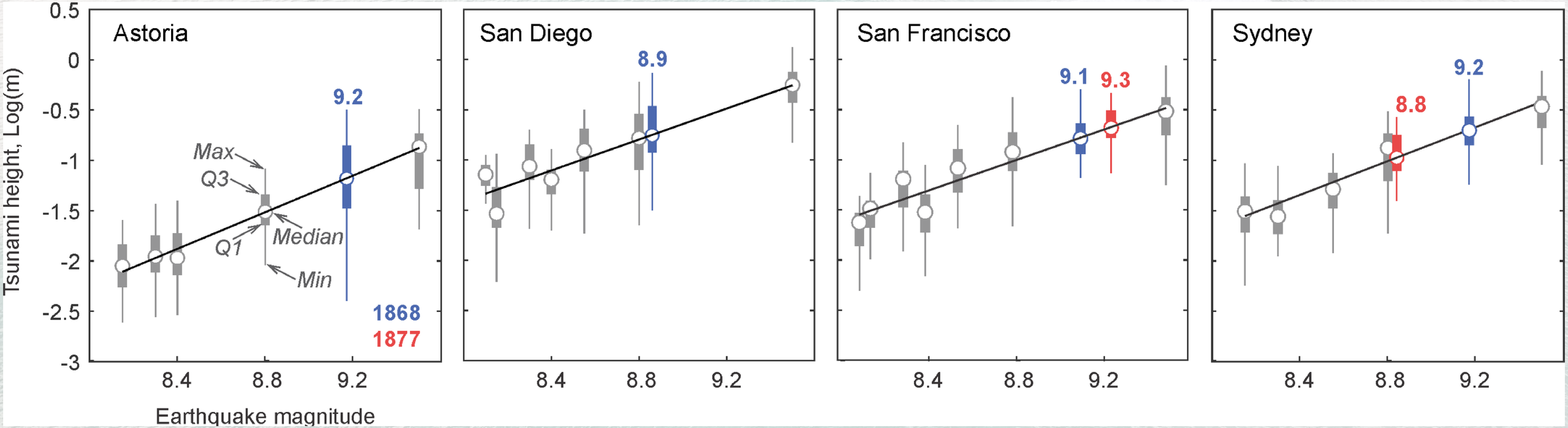
Inferred tsunami magnitudes



1868: Mt ~ 8.9 to 9.2

1877: Mt ~ 8.8 to 9.3

Good agreement with upper limit proposed in literature

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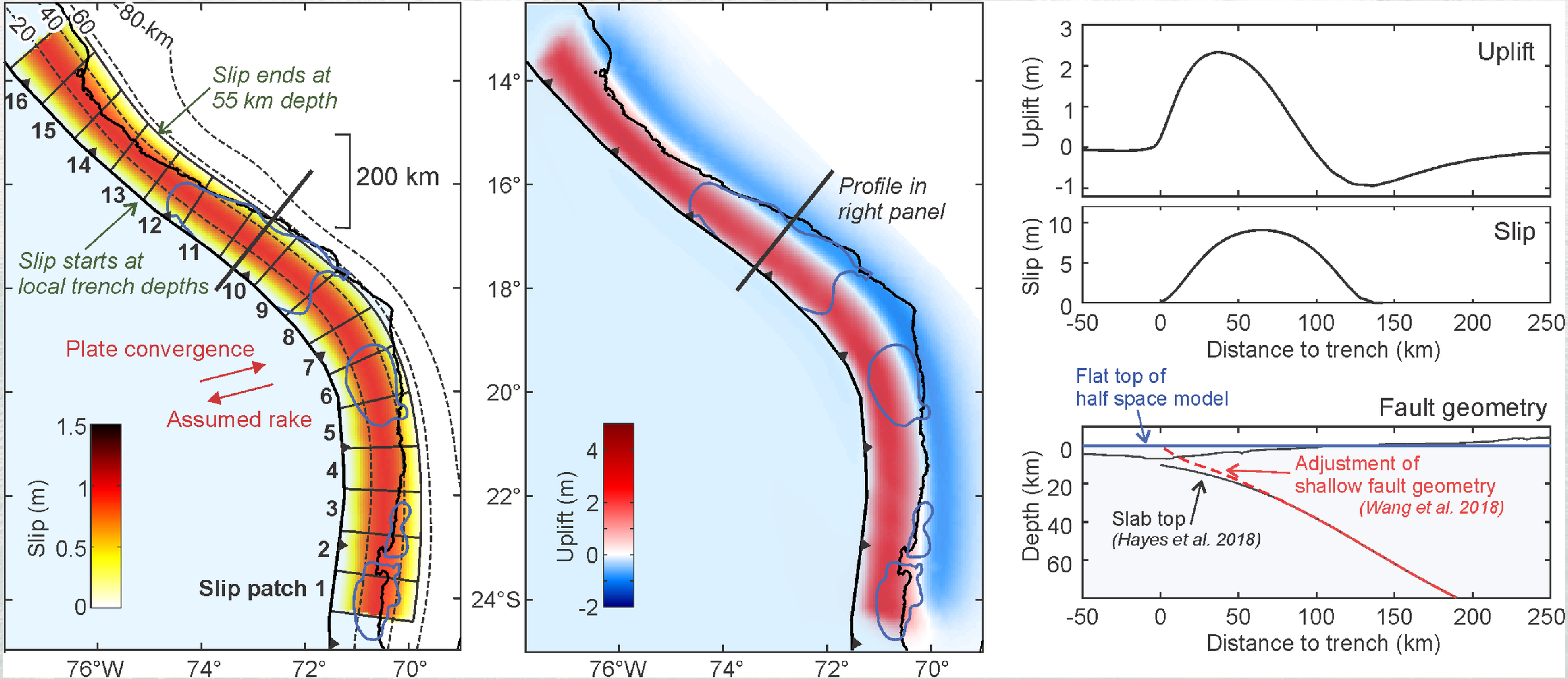
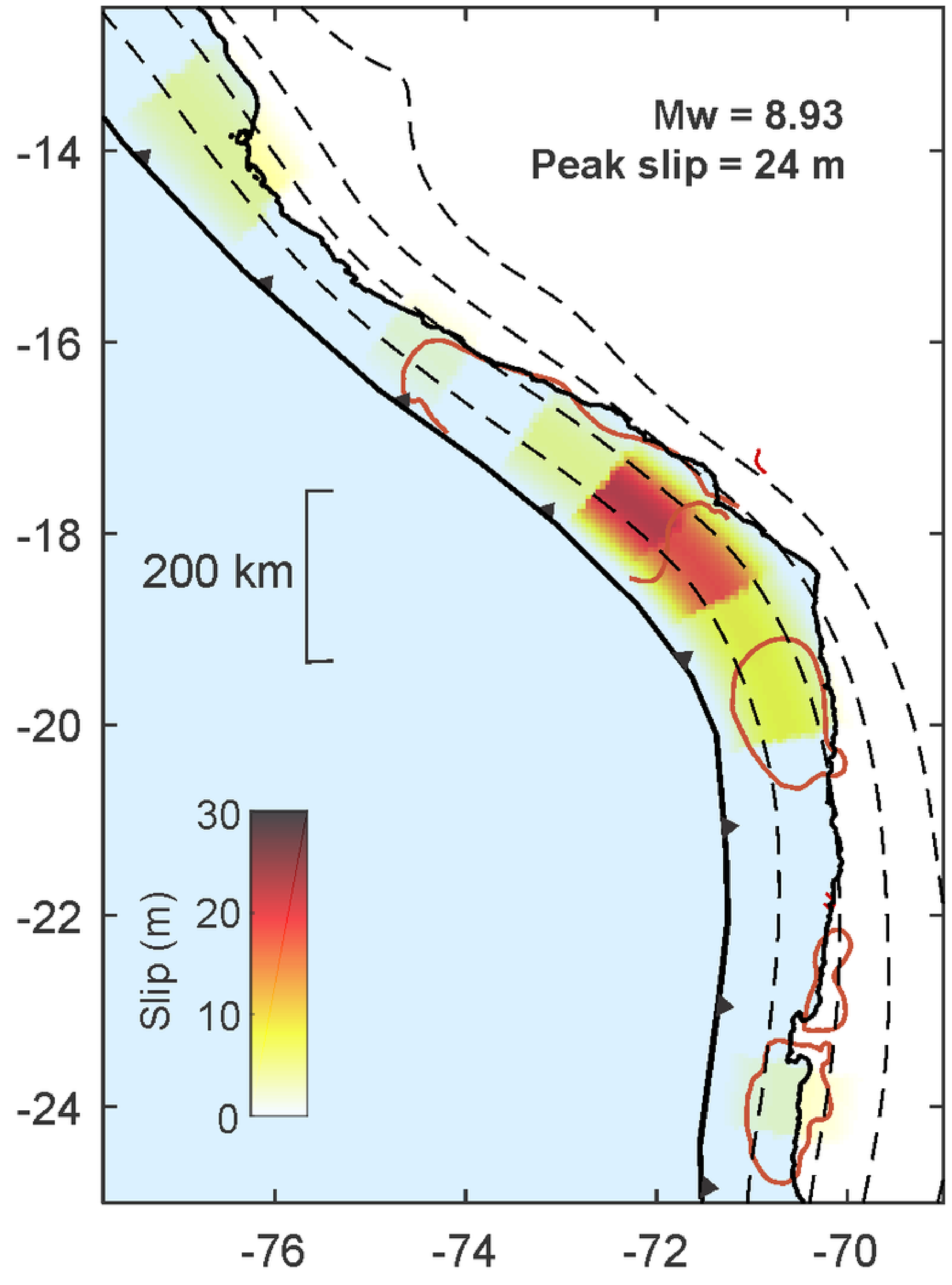
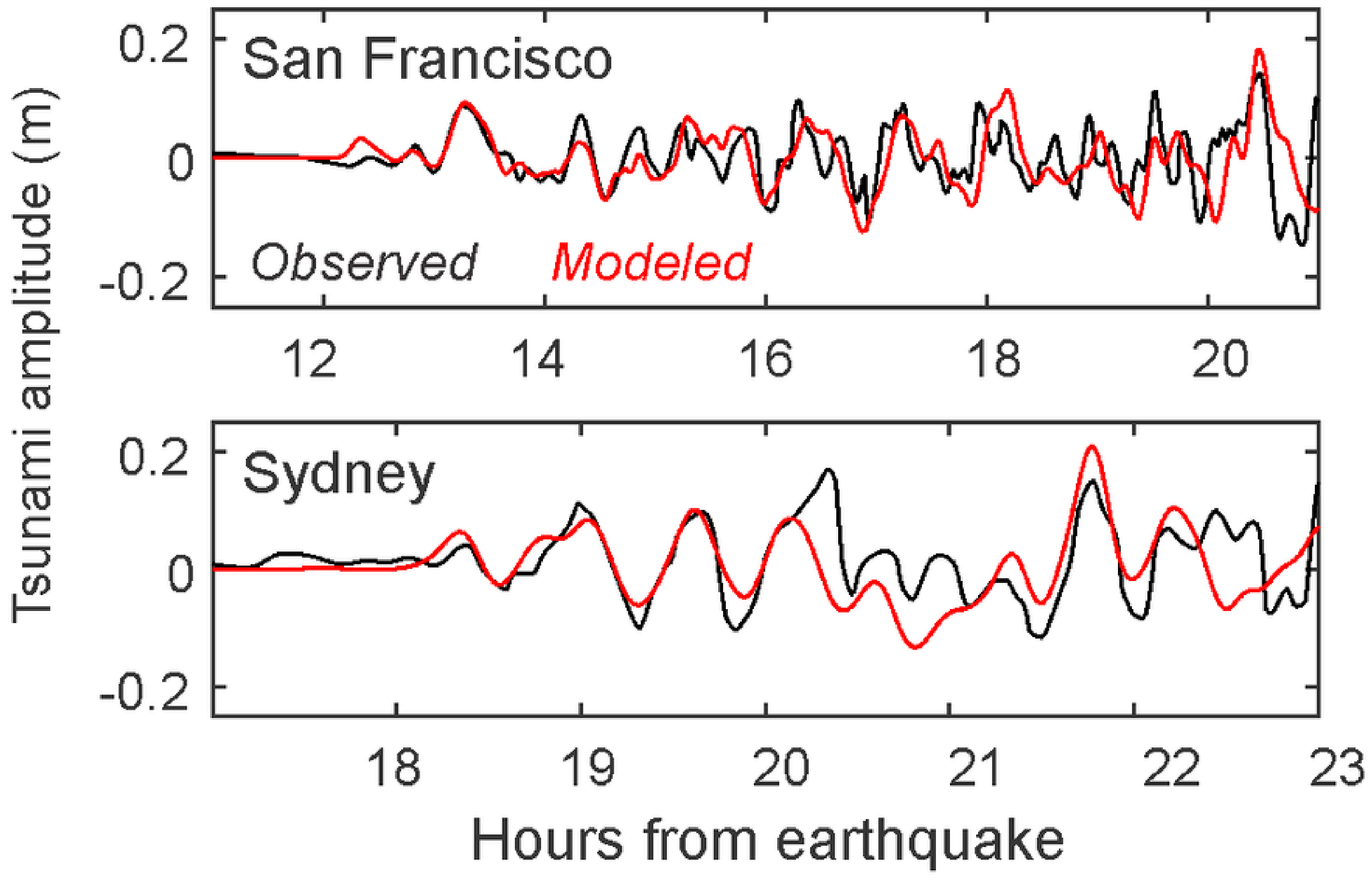
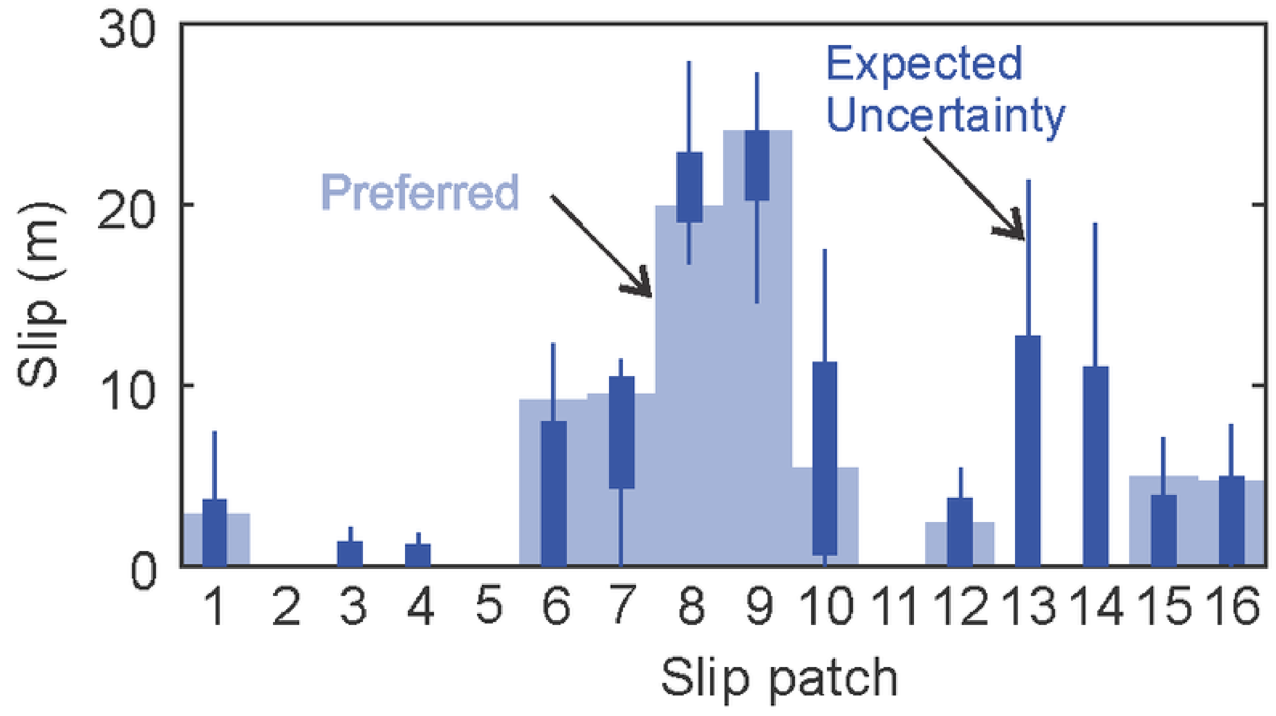
Formal inversion of old marigrams



Some results: the 1868 earthquake







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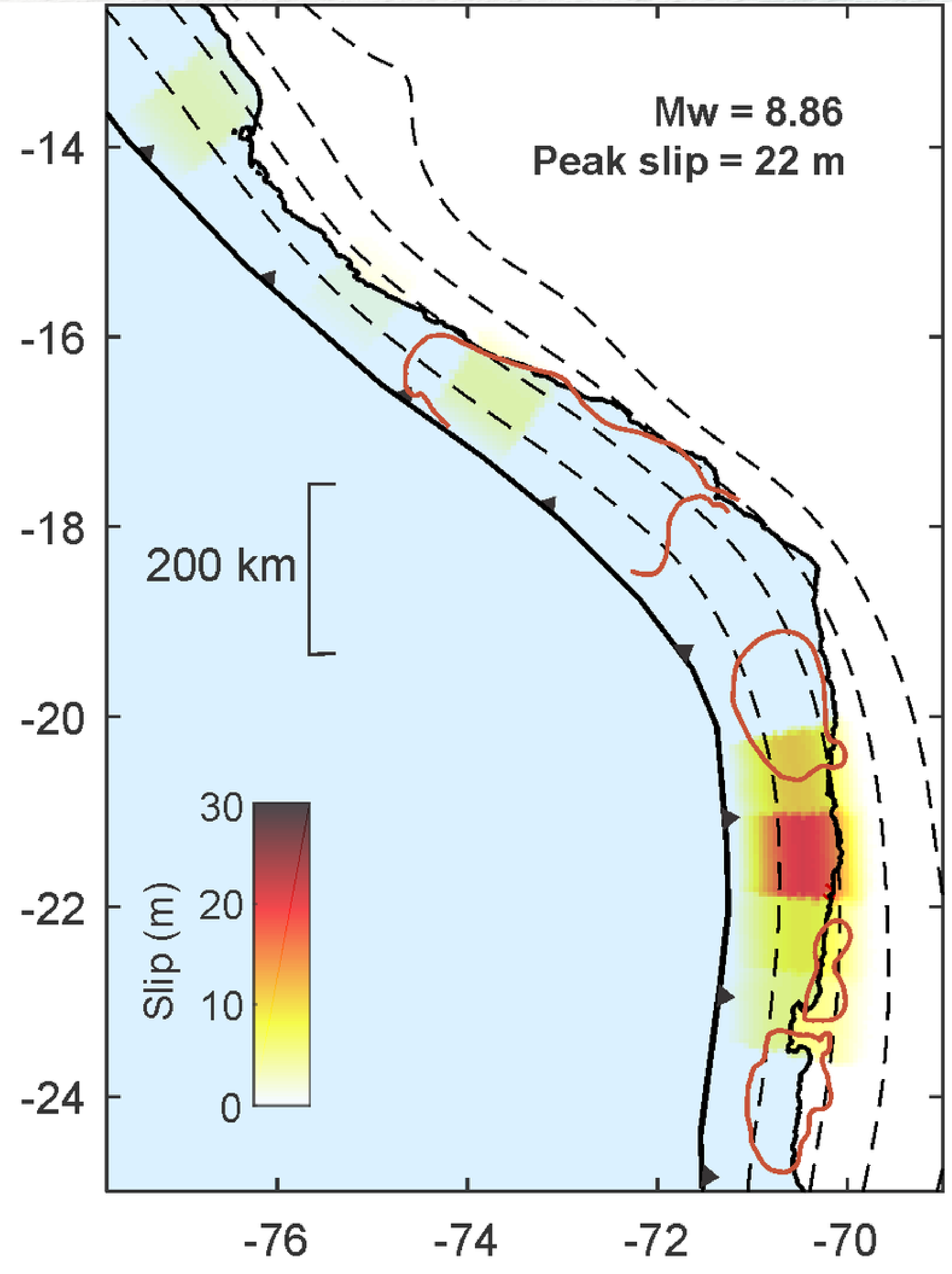
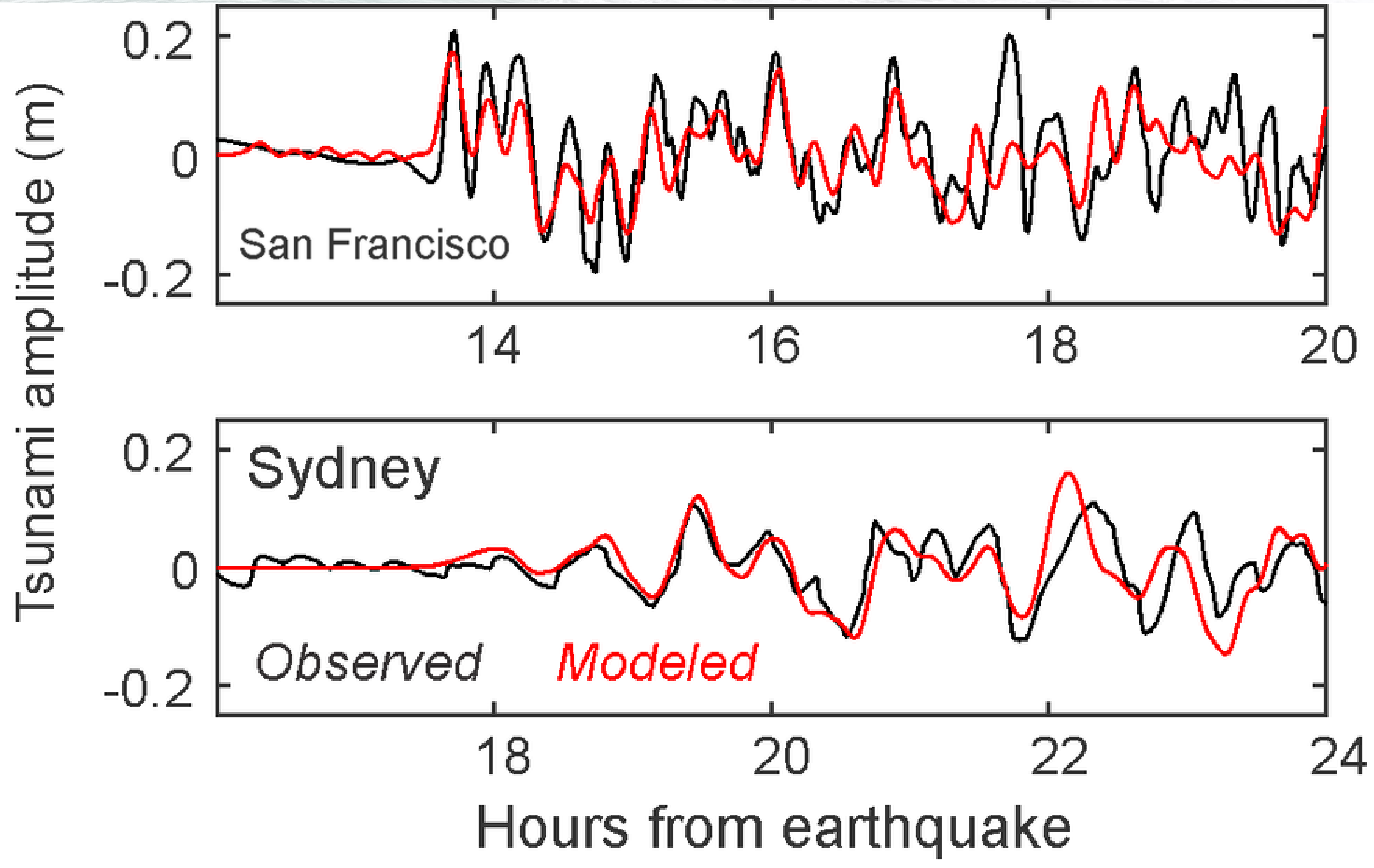
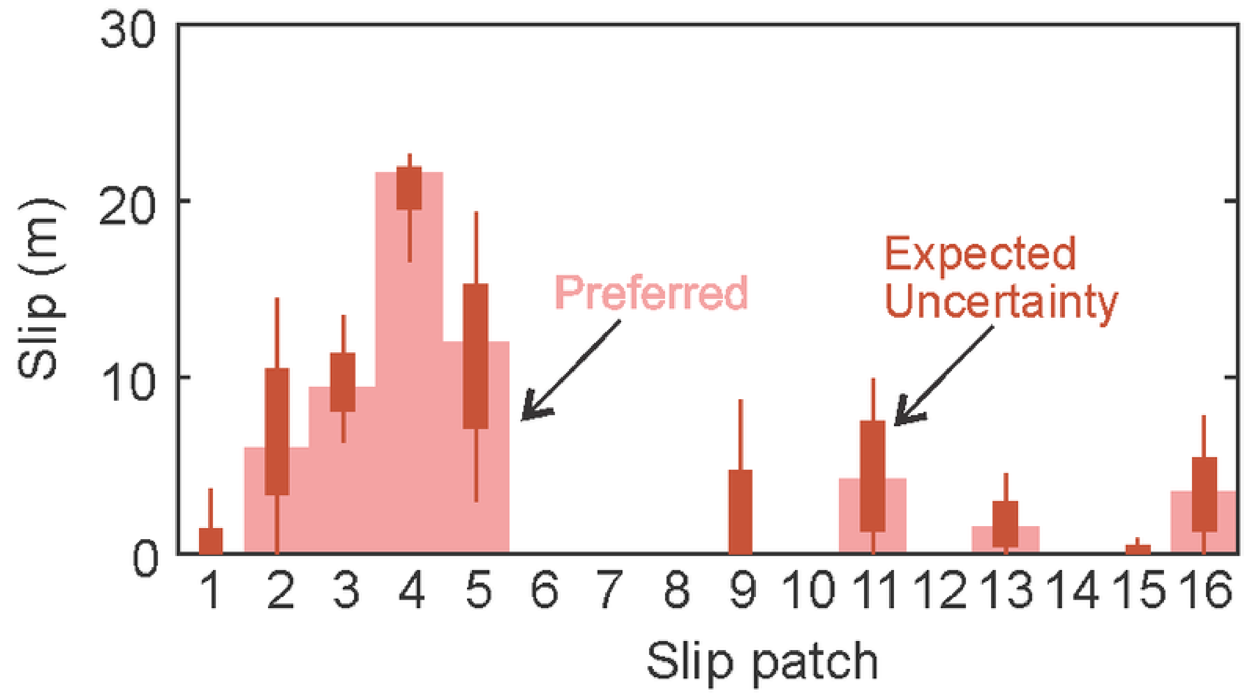
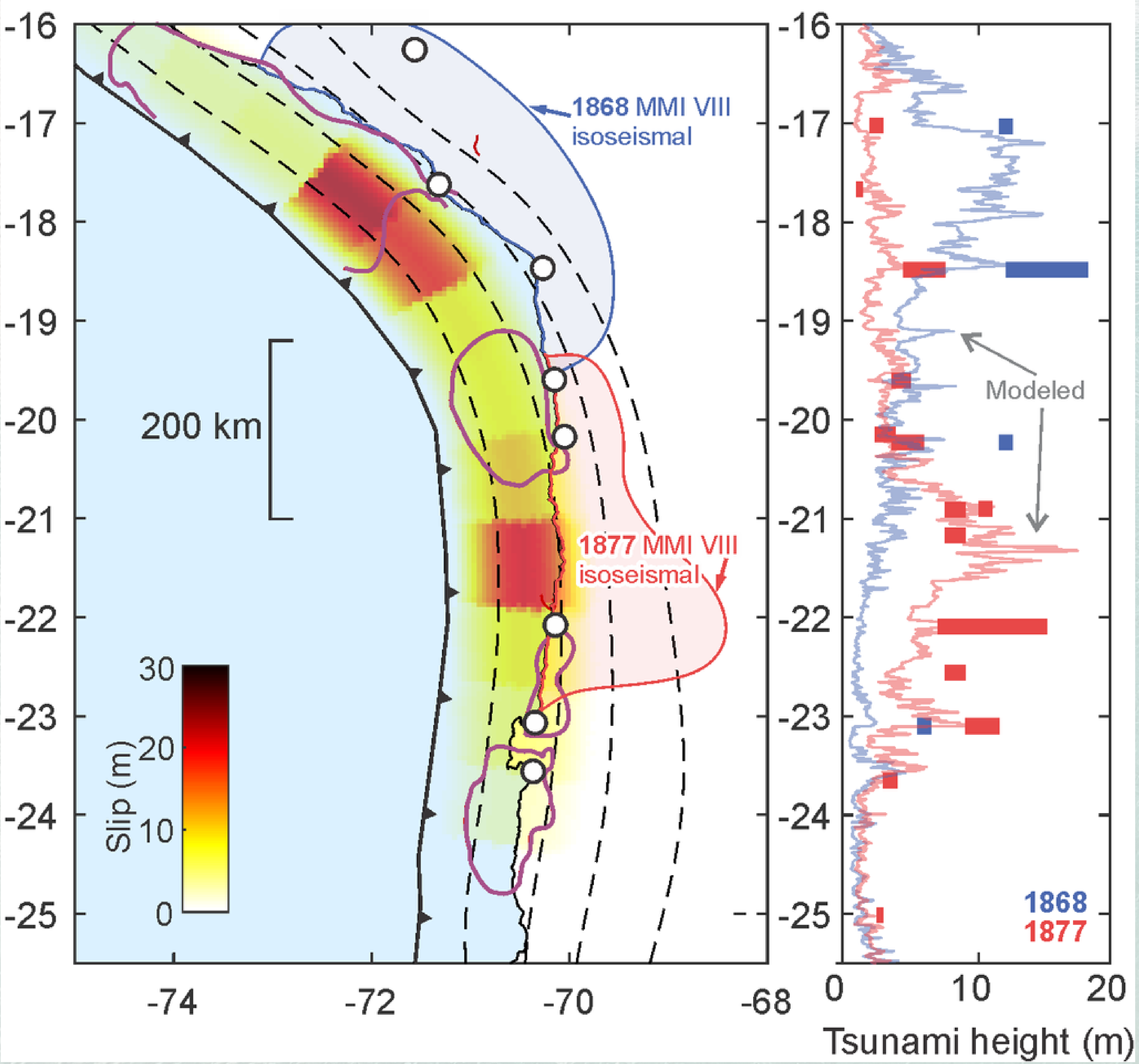
Some results: the 1877 earthquake

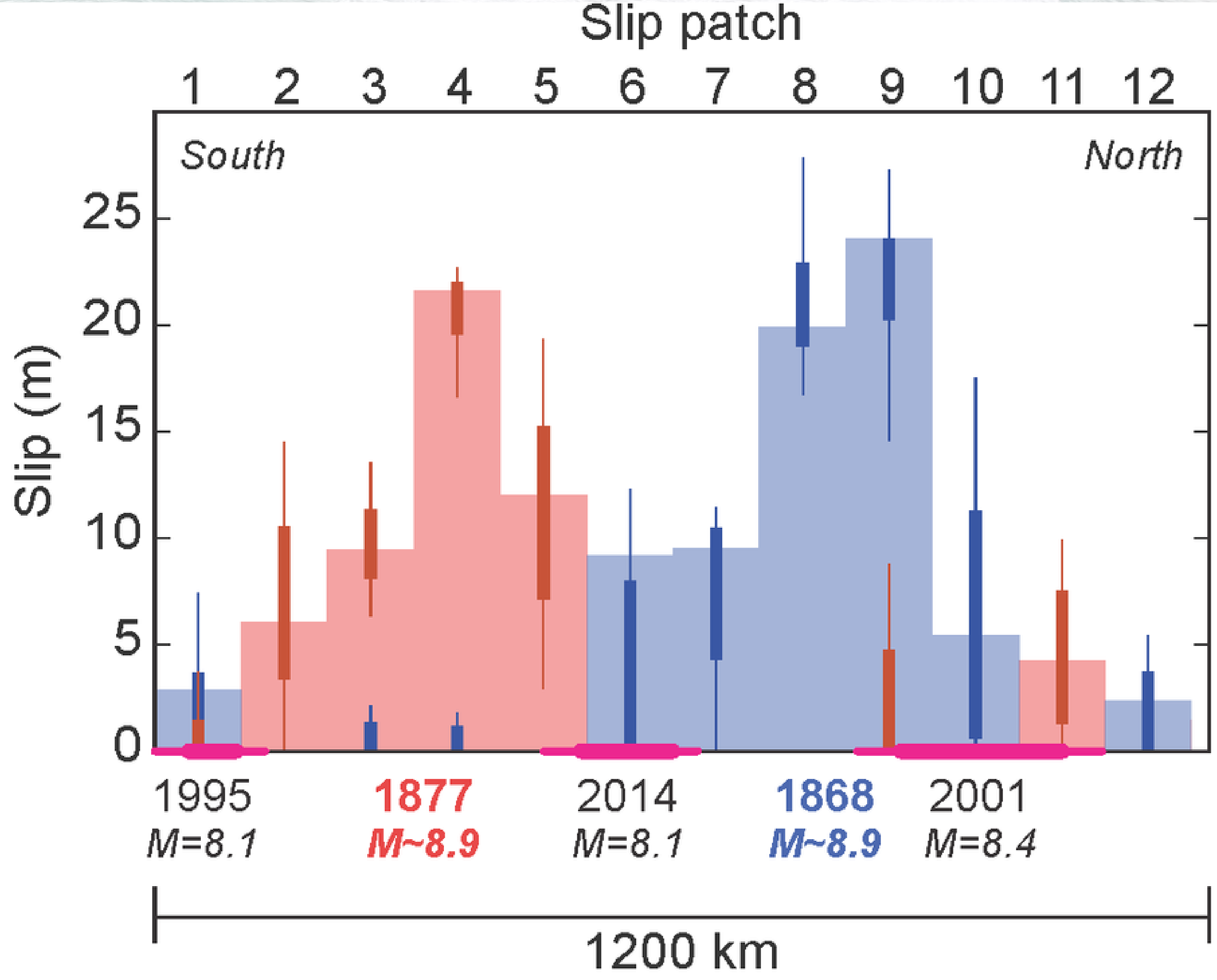


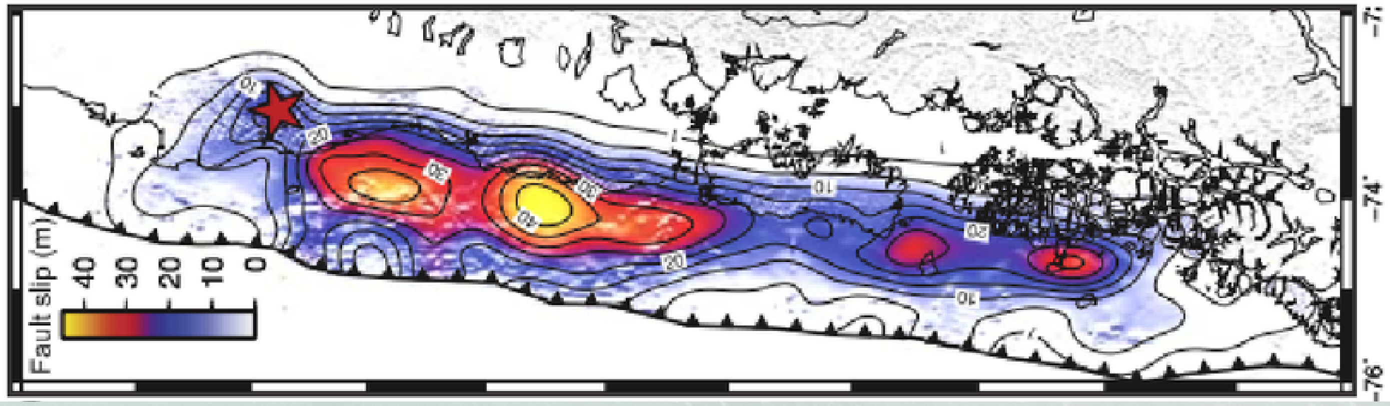




Rupture mode of southern Peru and northern Chile seismic gap







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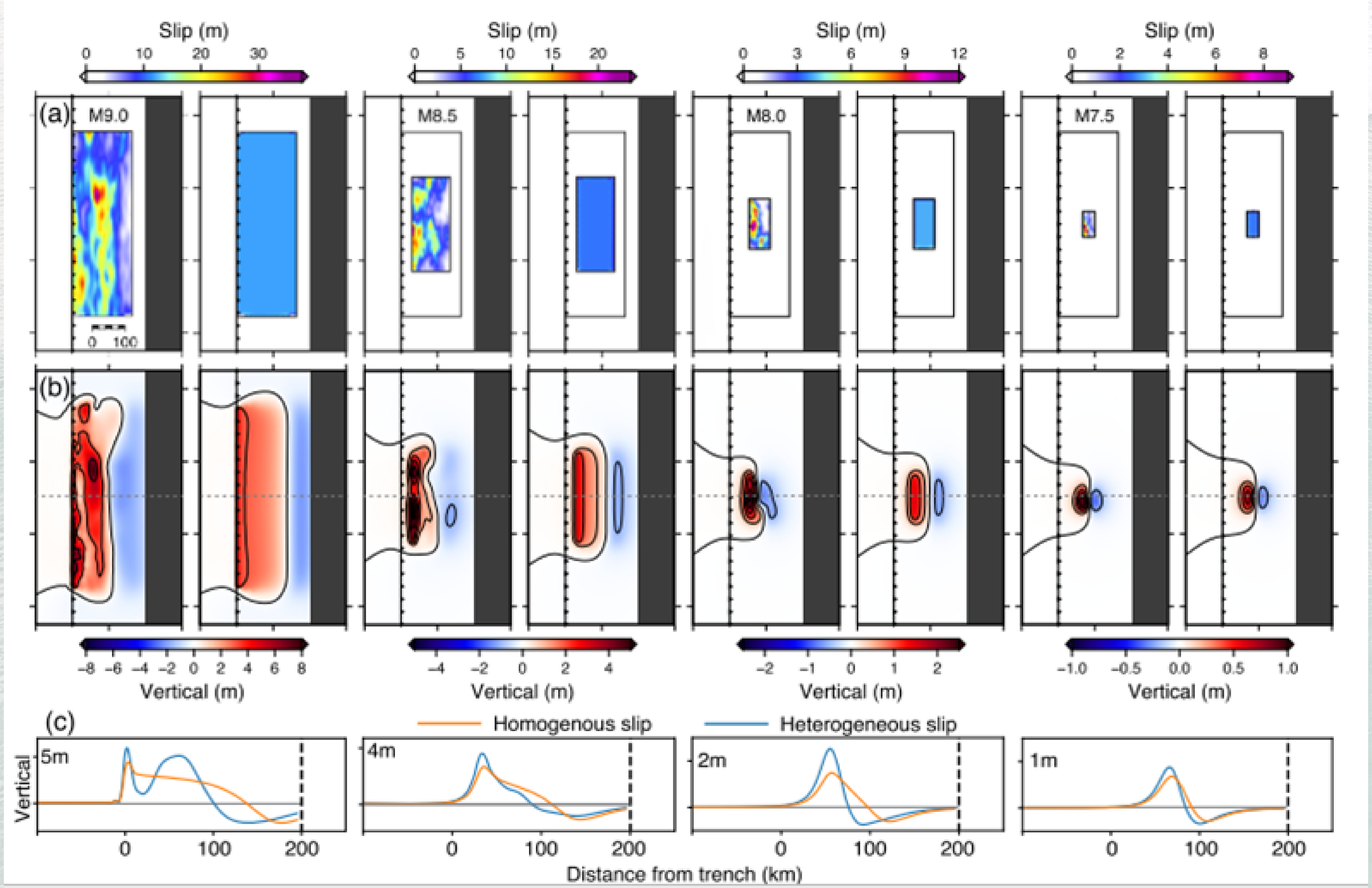
Stochastic approach

Multi-scenario stochastic deterministic approach



Melgar *et al*, 2019

Rupture complexity

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Generation of stochastic seismic sources

Karhunen-Loève expansion (K-L)

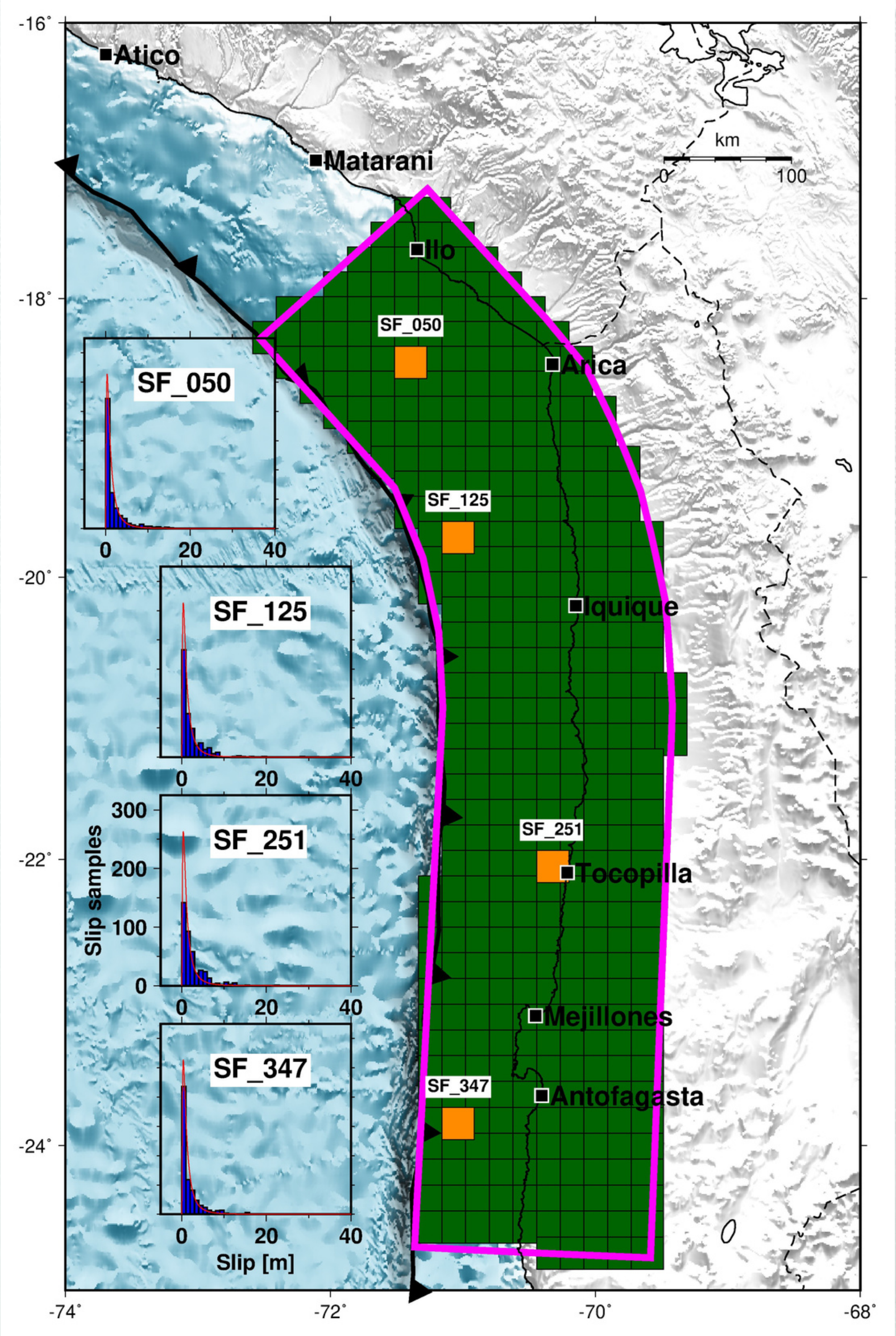
The Karhunen-Loève expansion (e.g. Karhunen, 1947; Loève, 1977; Schwab & Todor, 2006) is a standard approximation to represent a **gaussian random field** as a linear combination of a presumed covariance matrix $\hat{C}$.

The K-L expansion expresses the slip vector as:

$$s = \mu + \sum_{k=1}^{N} z_k \sqrt{\lambda_k} v_k .$$

Leveque *et al*, 2016

where zk are independent normally distributed random numbers with mean 0 and standard deviation 1.



González *et al*, 2020

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Tsunami numerical modelling

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = f(hv) + h\tau_{sx} - gh\frac{\partial \eta}{\partial x} + c_f u\sqrt{u^2+v^2}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (hv^2)}{\partial y} + \frac{\partial (huv)}{\partial x} = f(hu) + h\tau_{sy} - gh\frac{\partial \eta}{\partial y} + c_f v\sqrt{u^2+v^2}$$

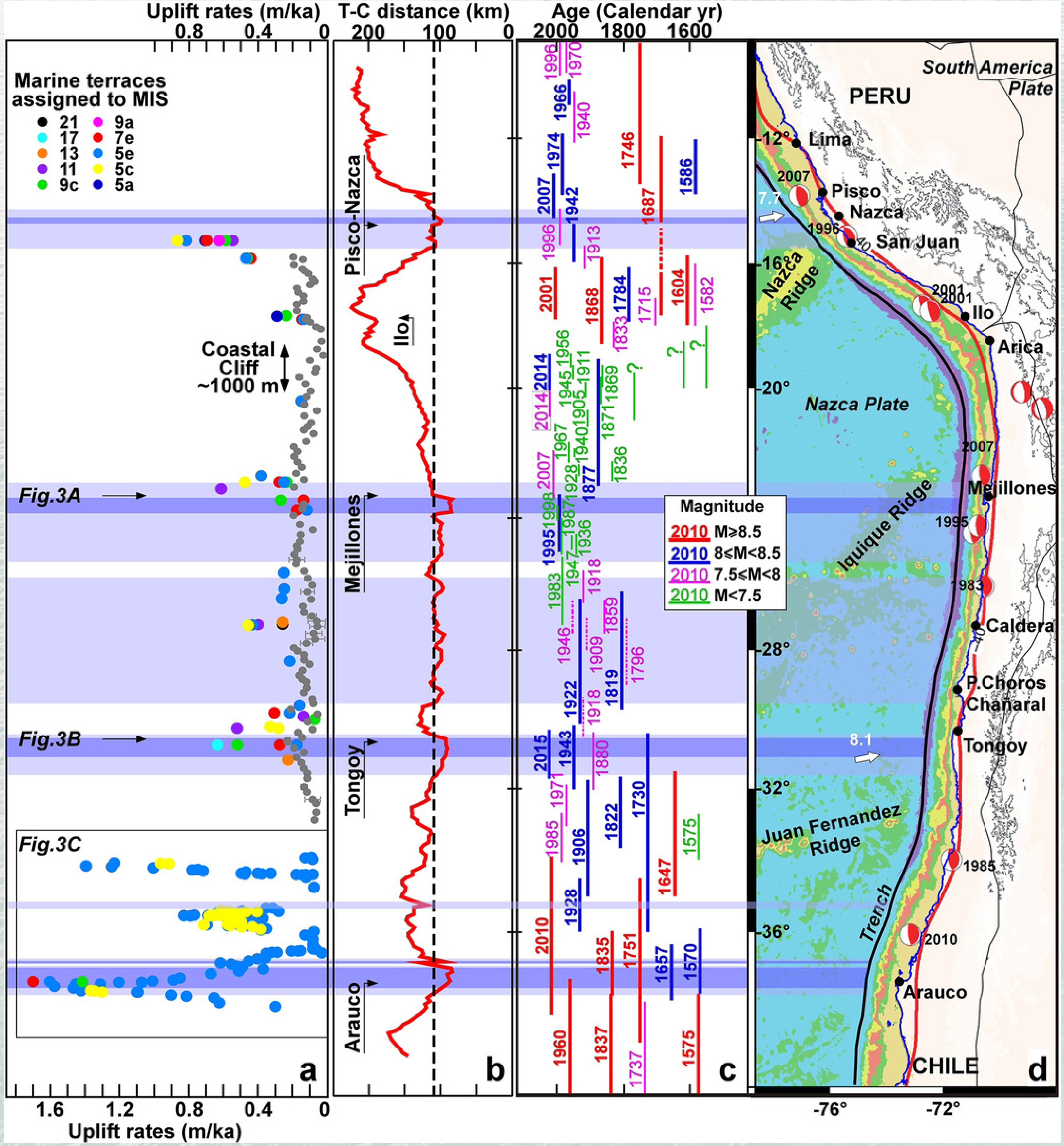
Non Linear Shallow Water Equations

- Neowave2D model.
- Okada algorithm.
- Topobathymetric model in nesting scheme.
- Non-hydrostatic approach

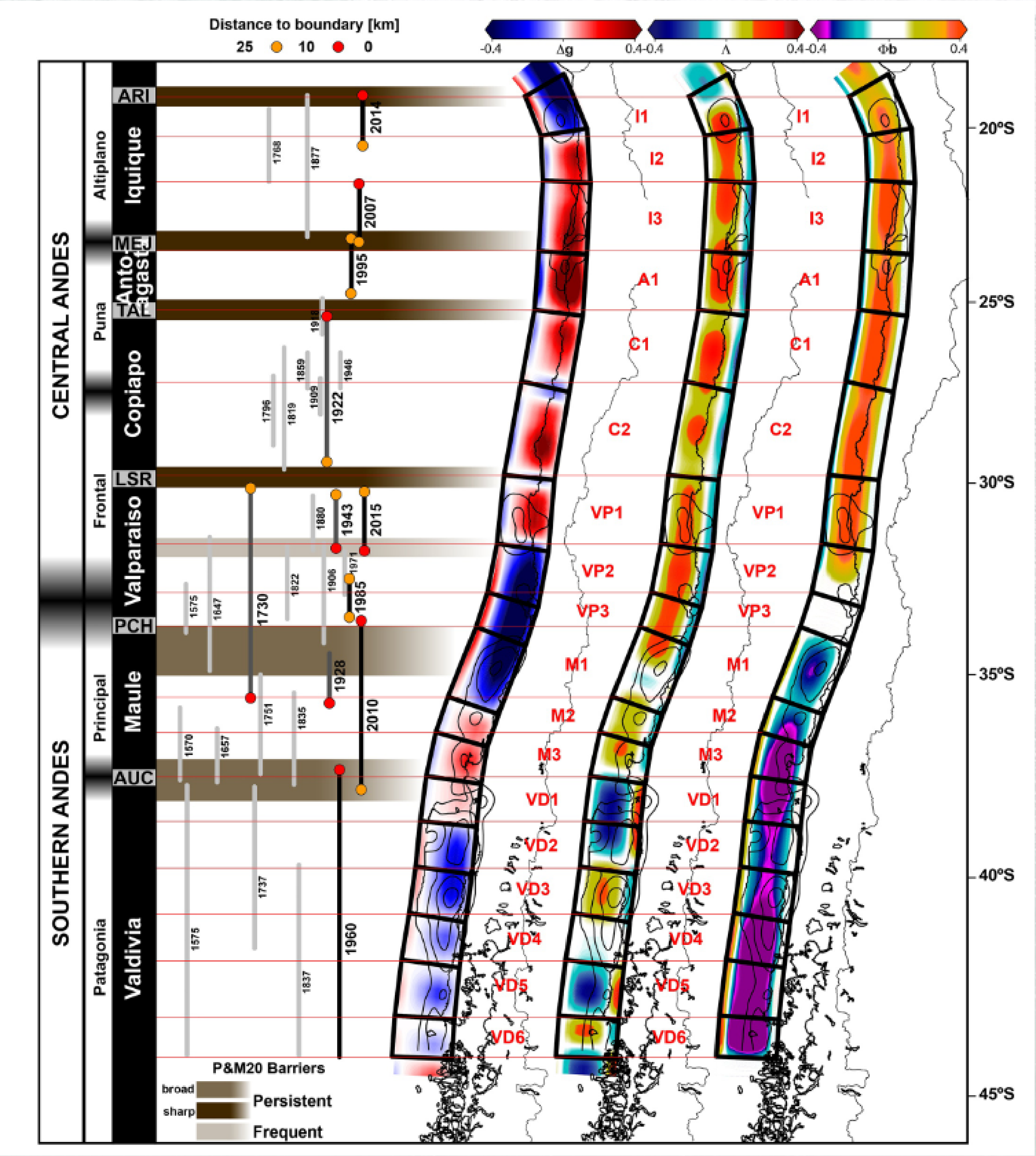
Use a cluster infrastructure (NLHPC):

- ~50.000 computing hours.
- 3 Tb of storage.
- ~88 processors
- All required software (e.g. Intel Fortran compiler, GMT, Python, etc.).

Tectonic segmentation: along strike

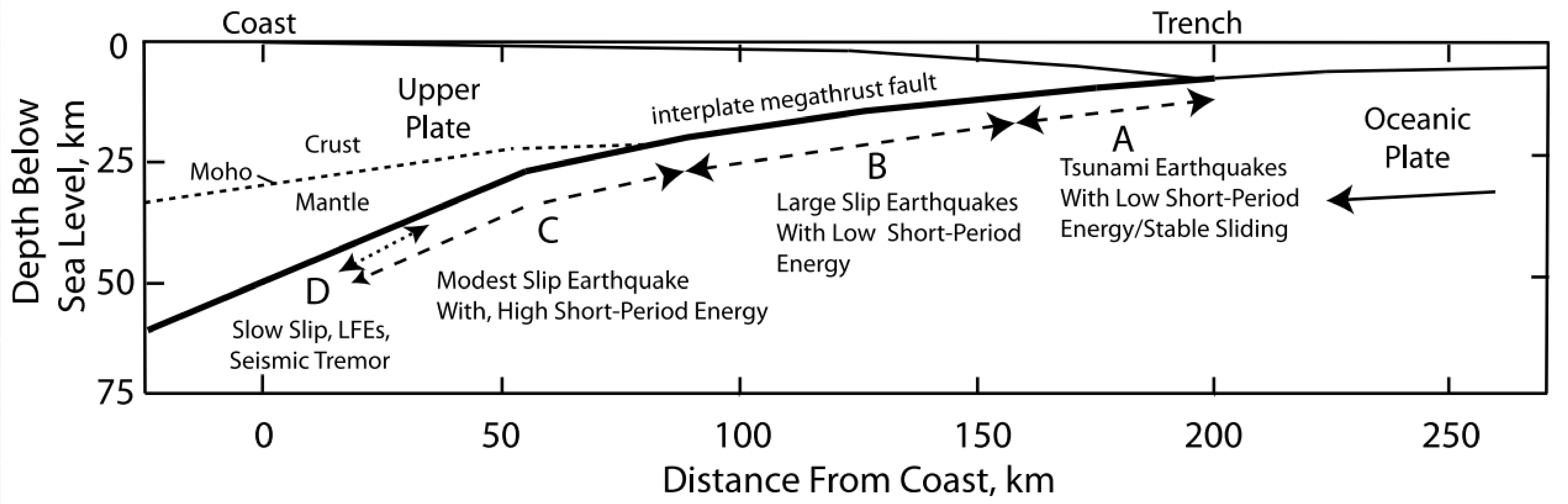


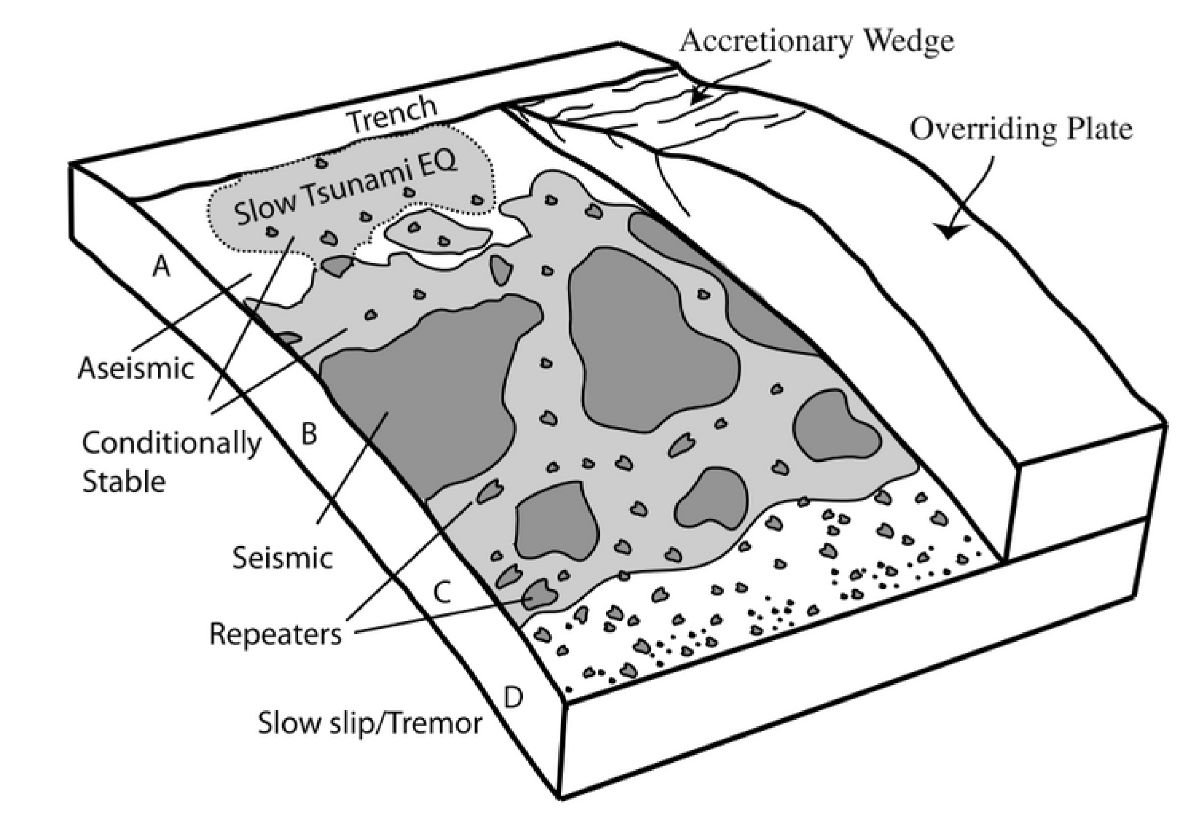
Saillard *et al*, 2017



Molina *et al*, 2021

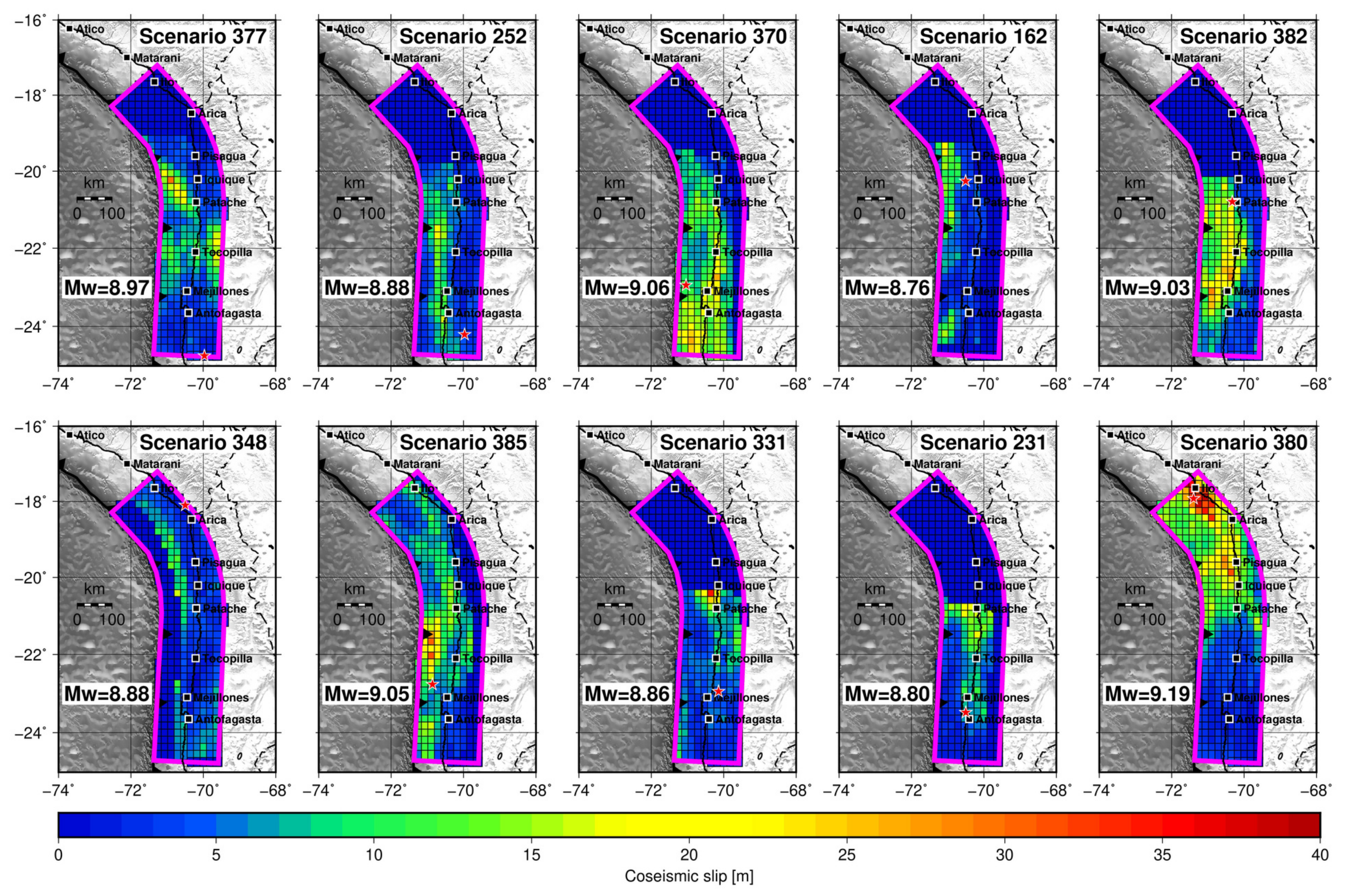
Tectonic segmentation: down dip





Lay *et al*, 2012

Results: northern Chile



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González *et al*, 2020

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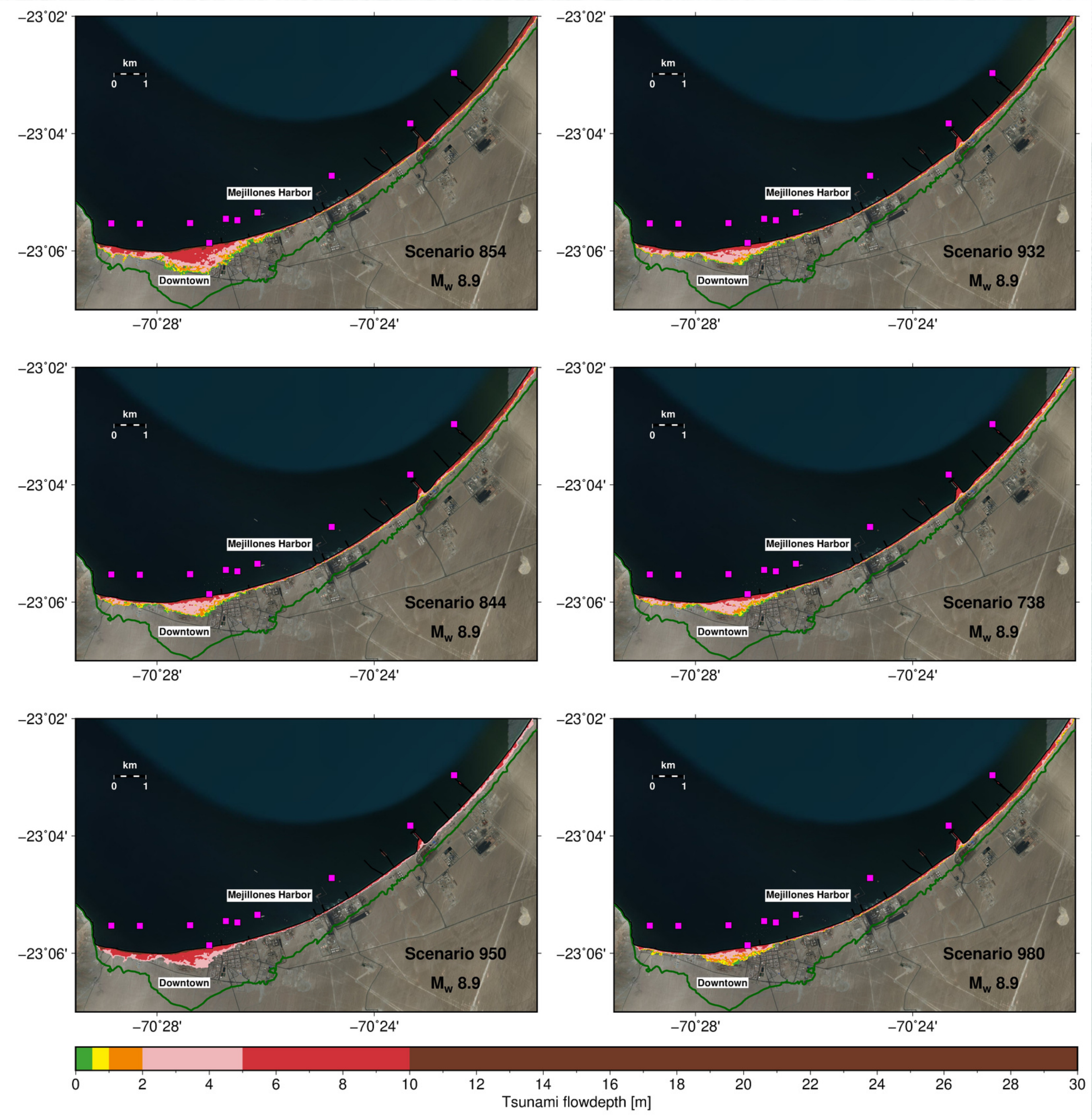
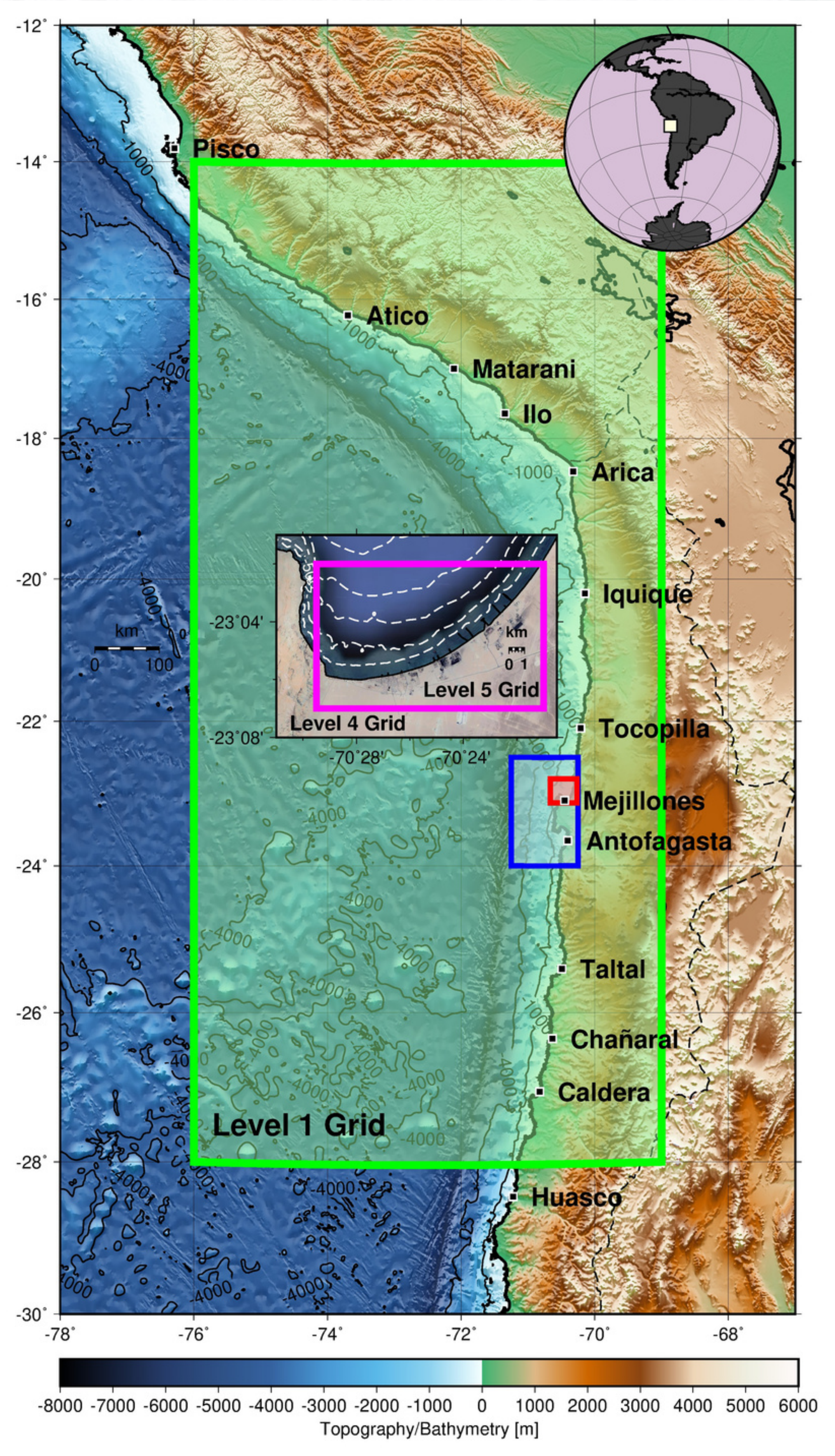
Results: northern Chile

Mejillones
~1000 Scenarios





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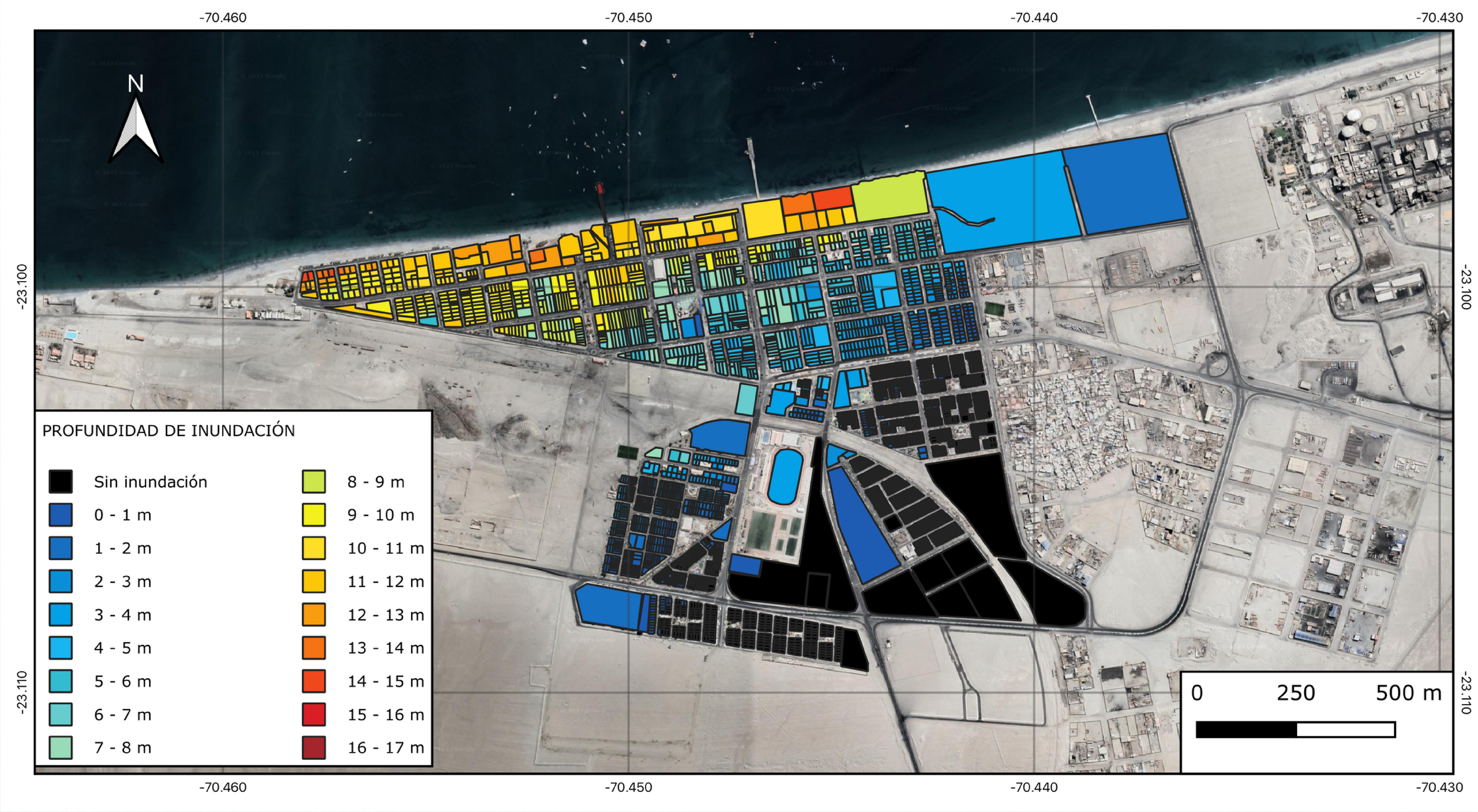
Results: northern Chile



Results: northern Chile

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Some conclusions

- The slip models for the 1868 and 1877 earthquakes are consistent with far-field marigrams records, and near-field reports of both tsunami heights and shaking intensities derived from historical accounts.

- Both earthquakes had magnitudes of ~8.9 and produced large tsunamis. The maximum slip areas are coupled and show a seismic quiescence from 1877.

Some conclusions

- Comprehensive database for stochastic earthquake scenarios can be applied to active seismic gaps in subduction zones, including slip distribution and other rupture parameters.
- Uncertainty analysis.
- Cascading hazards (megathrust earthquakes versus active faults, volcanoes and landslides).
- Training systems, evacuation plans and critical infrastructure location.

Guide questions

- How this work will impact our understanding of the hazard and risk?
- What are the impacts of science research?
- What are the constraints?

Thanks you
for your attention