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Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

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

Improving Knowledge about the Build-up of Large Earthquakes/Tsunamis from Geodetic Observations

Francisco Ortega-Culaciati, Marcos Moreno, Joaquín Hormazábal, Daniel Melnick, Vanessa Carrillo-Barra, Vicente Yañez-Cuadra, Roberto Benavente, Juan Carlos Báez, Andrés Tassara, Javier Ruiz, Natalia Díaz, Lorenzo Jara, Juan Pablo Merino, Dietrich Lange, Heidrun Kopp, Shoichi Yoshioka, Diana Comte, Daniel Carrizo

August 22, 2023

NLHPC
National Laboratory for High Performance Computing
Chile

Instituto Milenio de Oceanografía

Motivation: Earthquake and Tsunami Hazard?

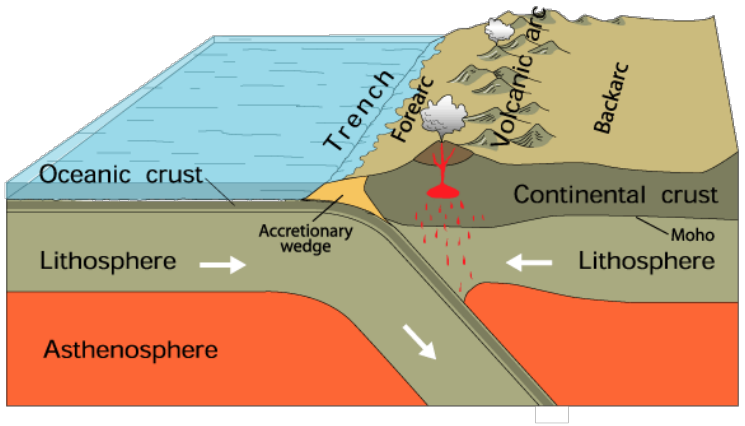
- Discussion on regional and global implications (Scientific/research) and Intro to local tectonic situation:
  - How will this work impact our understanding of the **hazard** and risk?
  - What are the impacts on science and research?
  - What are the constraints?

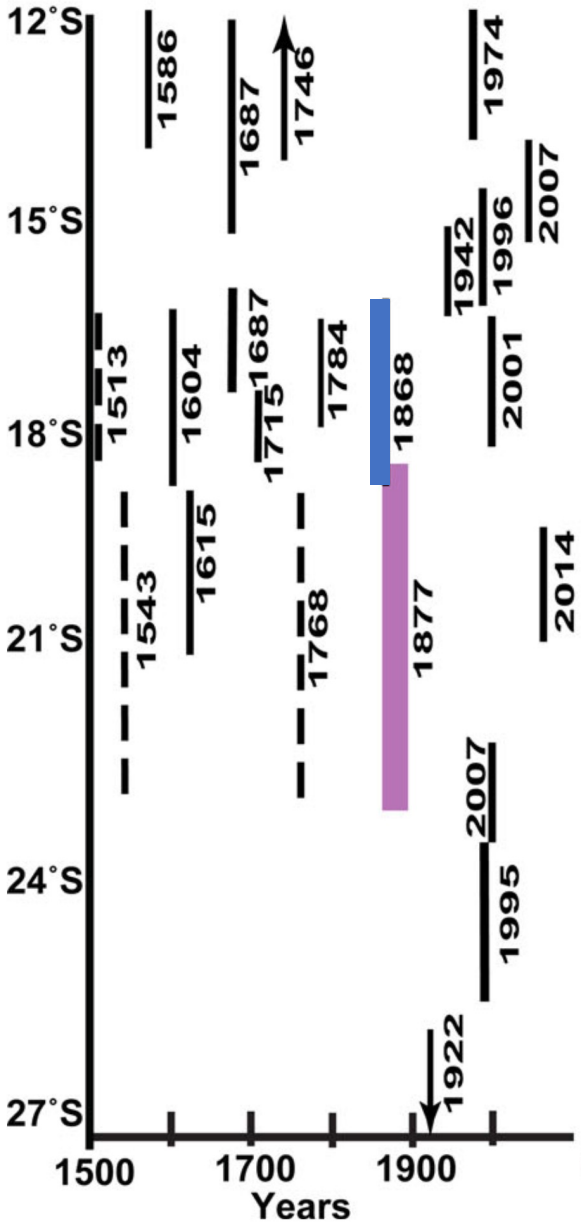
Seismotectonics of South-Peru and North-Chile

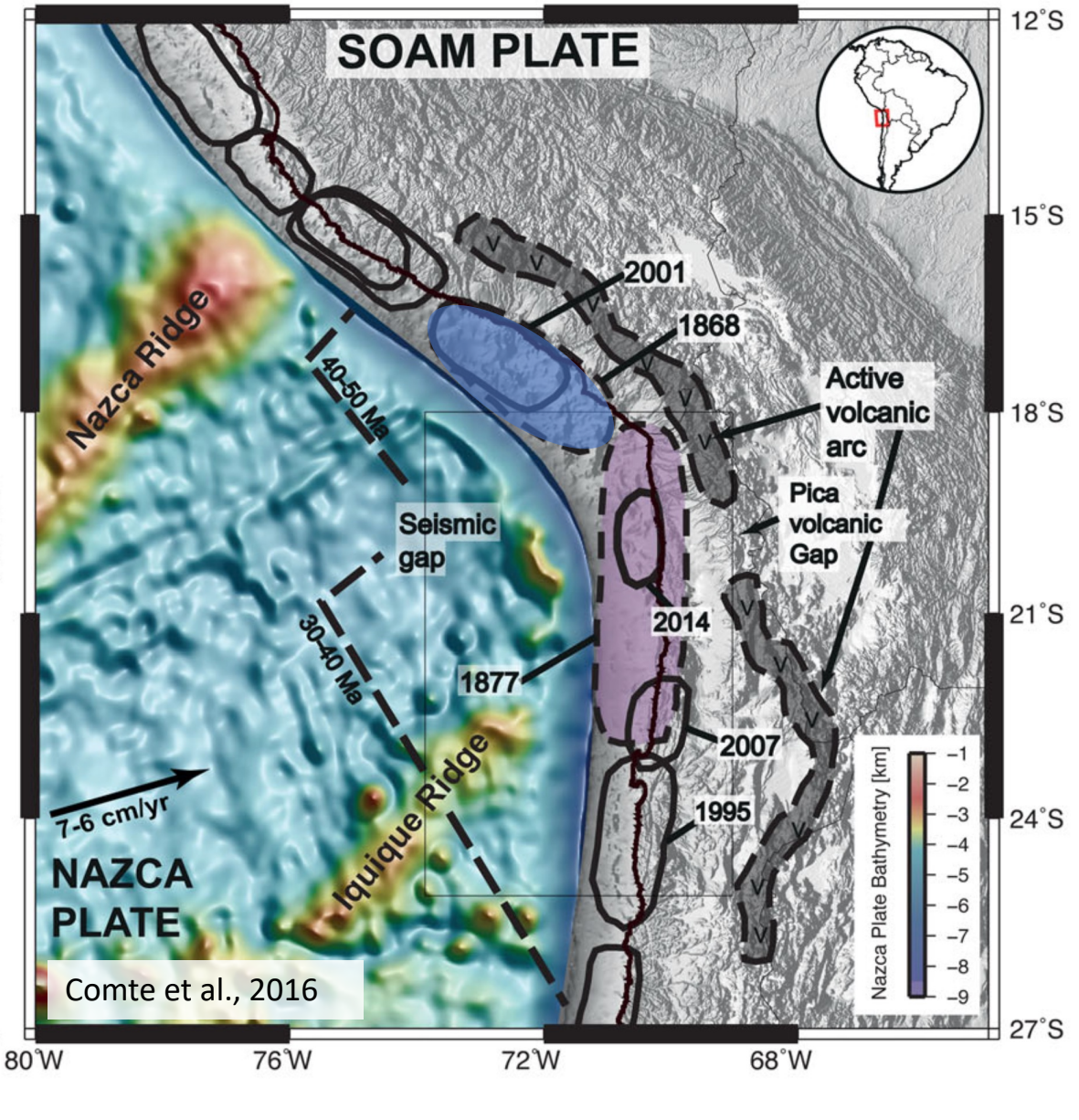
Chile and Perú are located in the subduction between Nazca and South American plates.

Struck by great devastating earthquakes and Tsunamis.

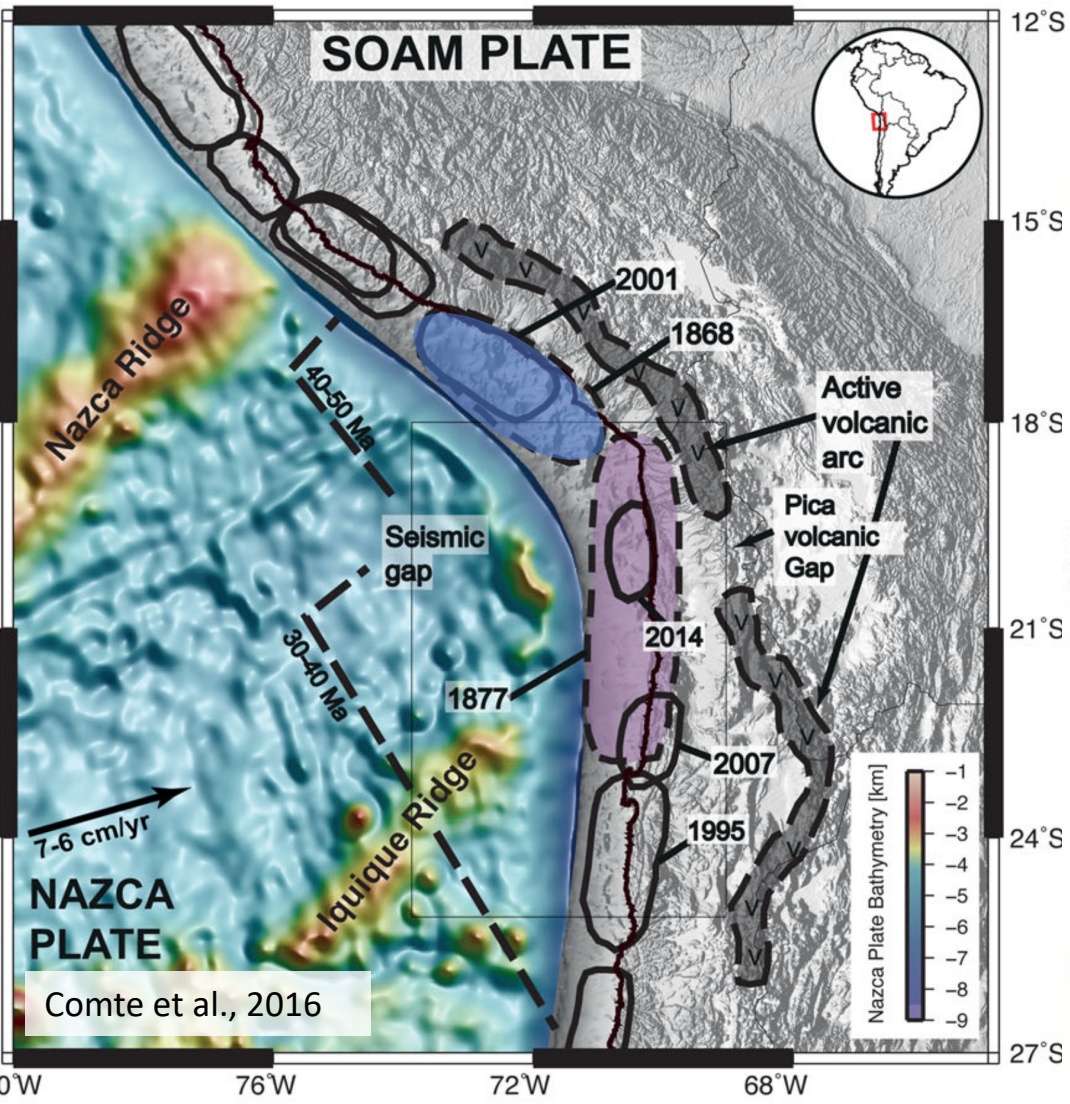
Sometimes preceded by anomalous seismicity or deformation





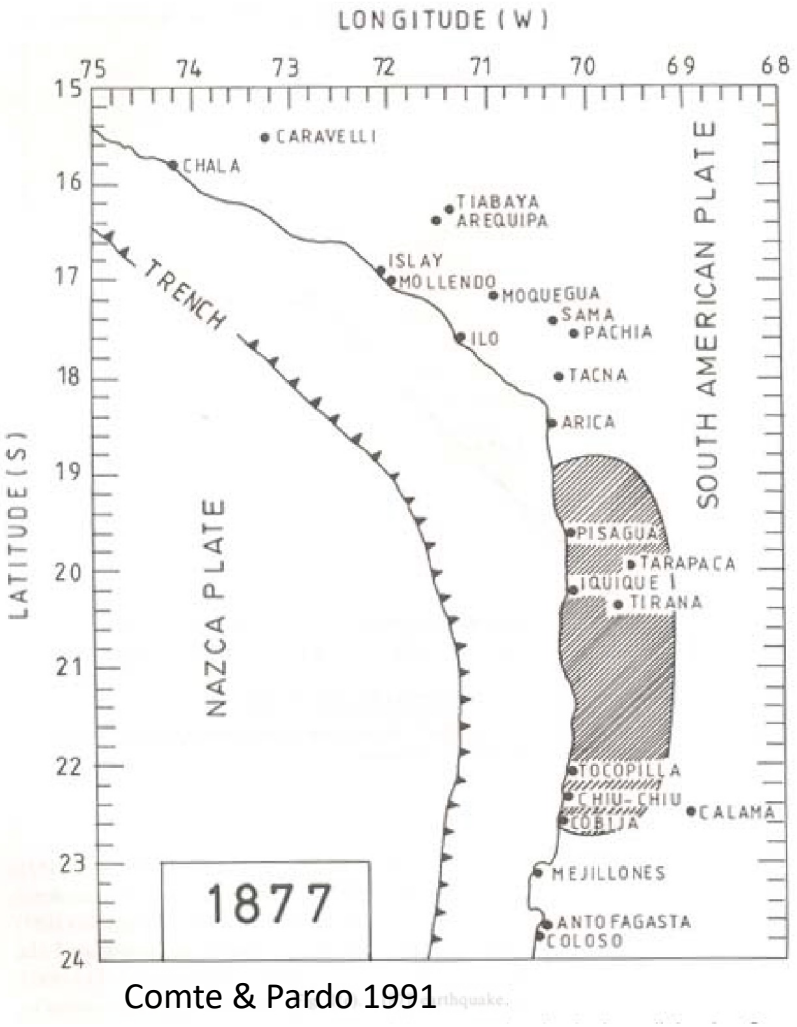


Understanding Seismic & Tsunami Hazard



Comte et al., 2016

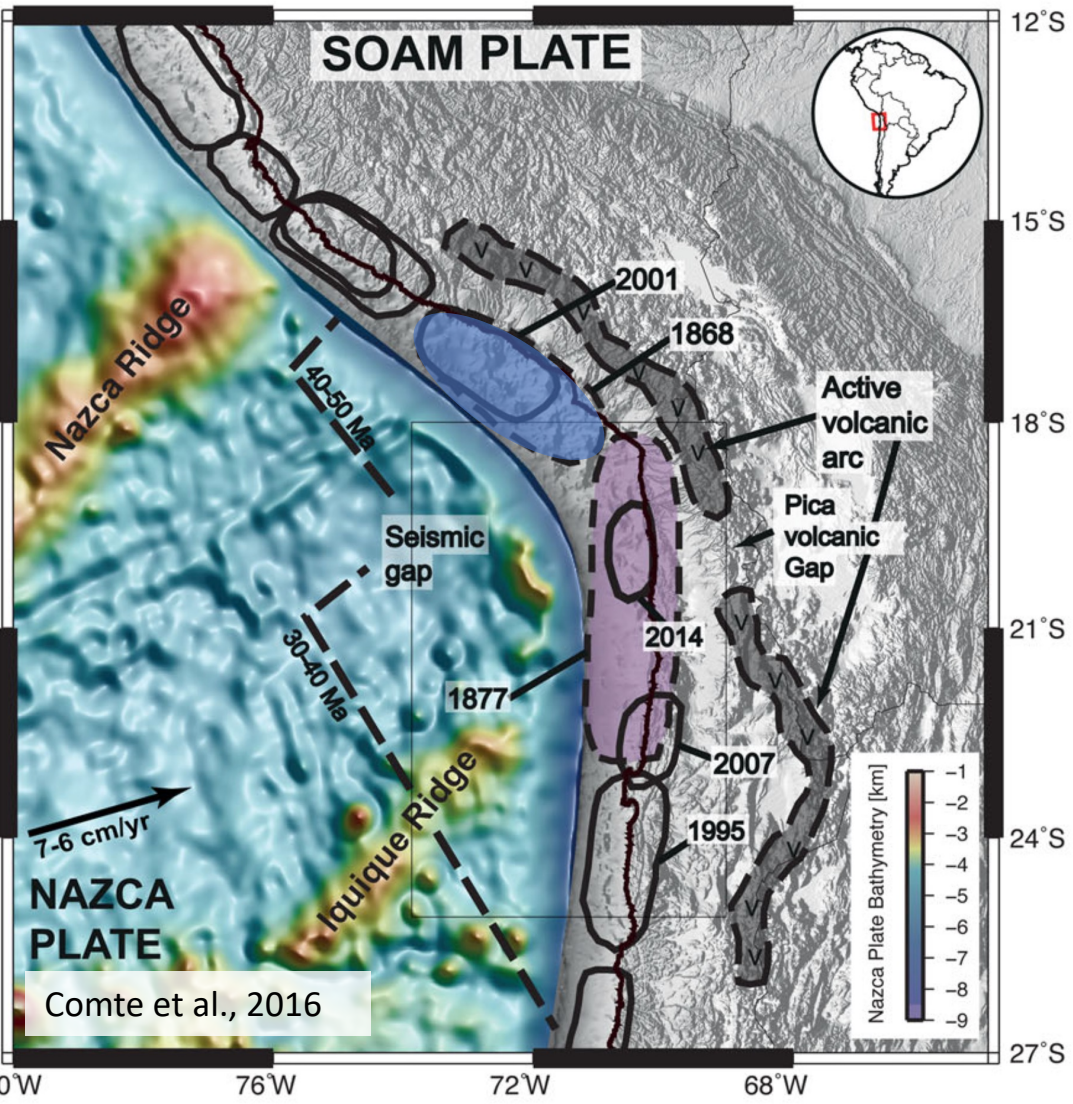
Northern Chile
May 10, 1877



Comte & Pardo 1991

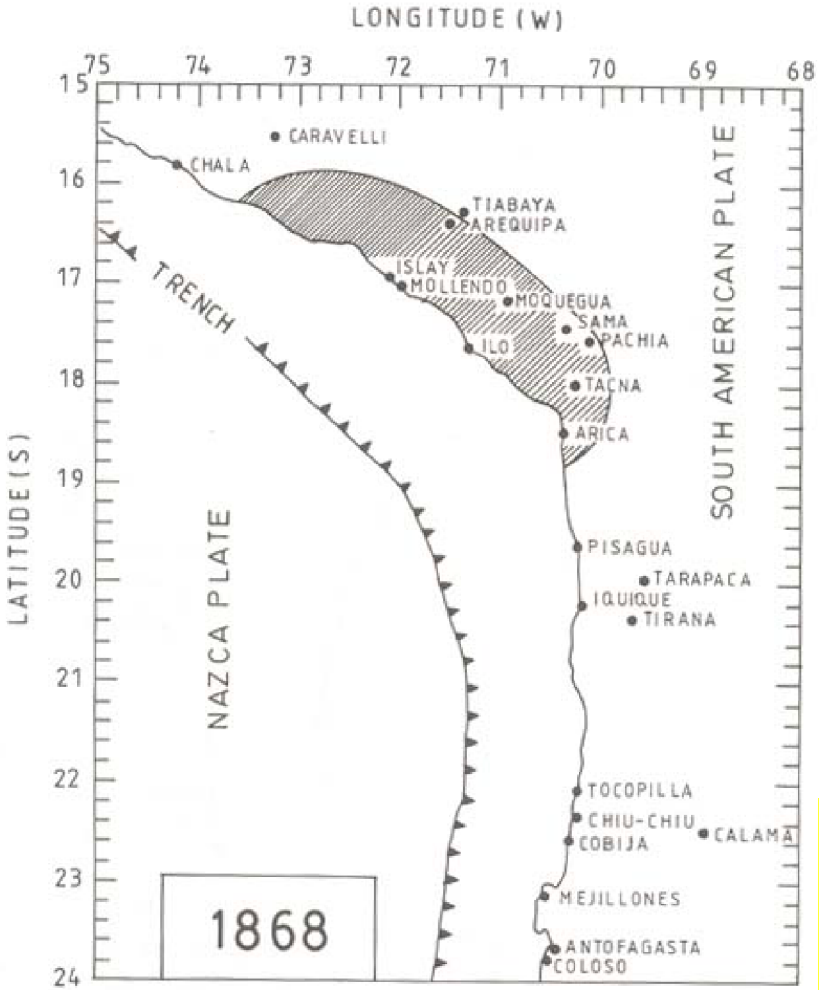
Magnitude		
Ms	8.0 – 8.5	Lomnitz (1971)
mt	9.0	Abe (1979)
Mw	8.9	Kausel (1986)
Mw	8.7-8.8	Ramirez (1988)
Ms mL	8.8 8.7	Comte & Pardo (1991)
Mw	~8.5	Vigny & Klein (2022)

Understanding Seismic & Tsunami Hazard



Comte et al., 2016

Southern Peru
August 13, 1868



Comte & Pardo 1991

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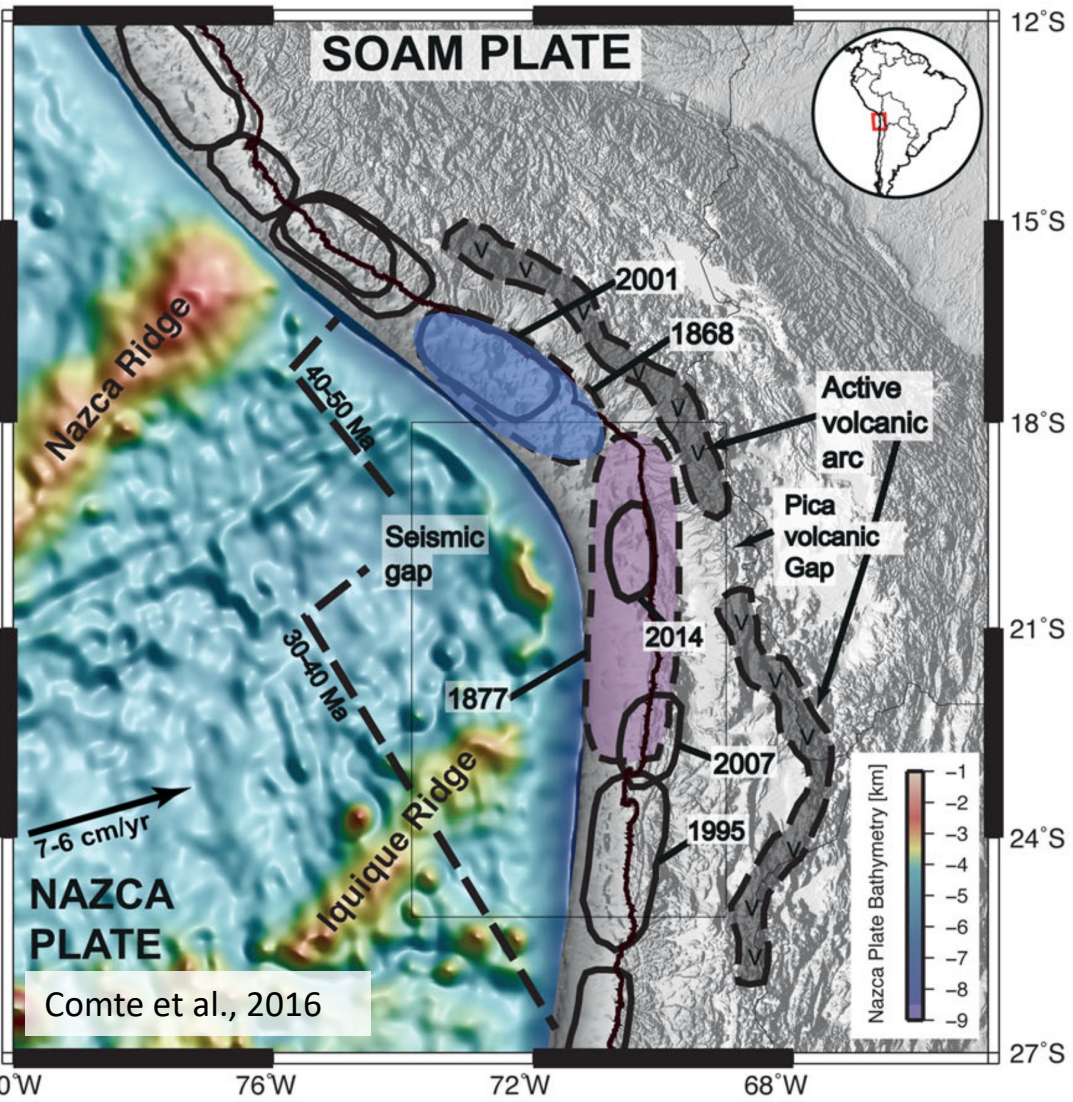
Mw	8.5-8.8	Ramirez (1988)
mL mt	8.8 8.9	Dorbath et al. (1990)
mL	8.8	Comte & Pardo (1991)

Not mentioning all historic earthquakes in southern Perú (time constraints)

Understanding Seismic & Tsunami Hazard



Comte et al., 2016

Ultimate Goal:
Improvement of Seismic/Tsunami Hazard knowledge

Statistical approach

Learn from the past: Historic- and Paleo-tsunami research

Modeling Approach

Improve understanding of the Seismic Cycle in subduction environment

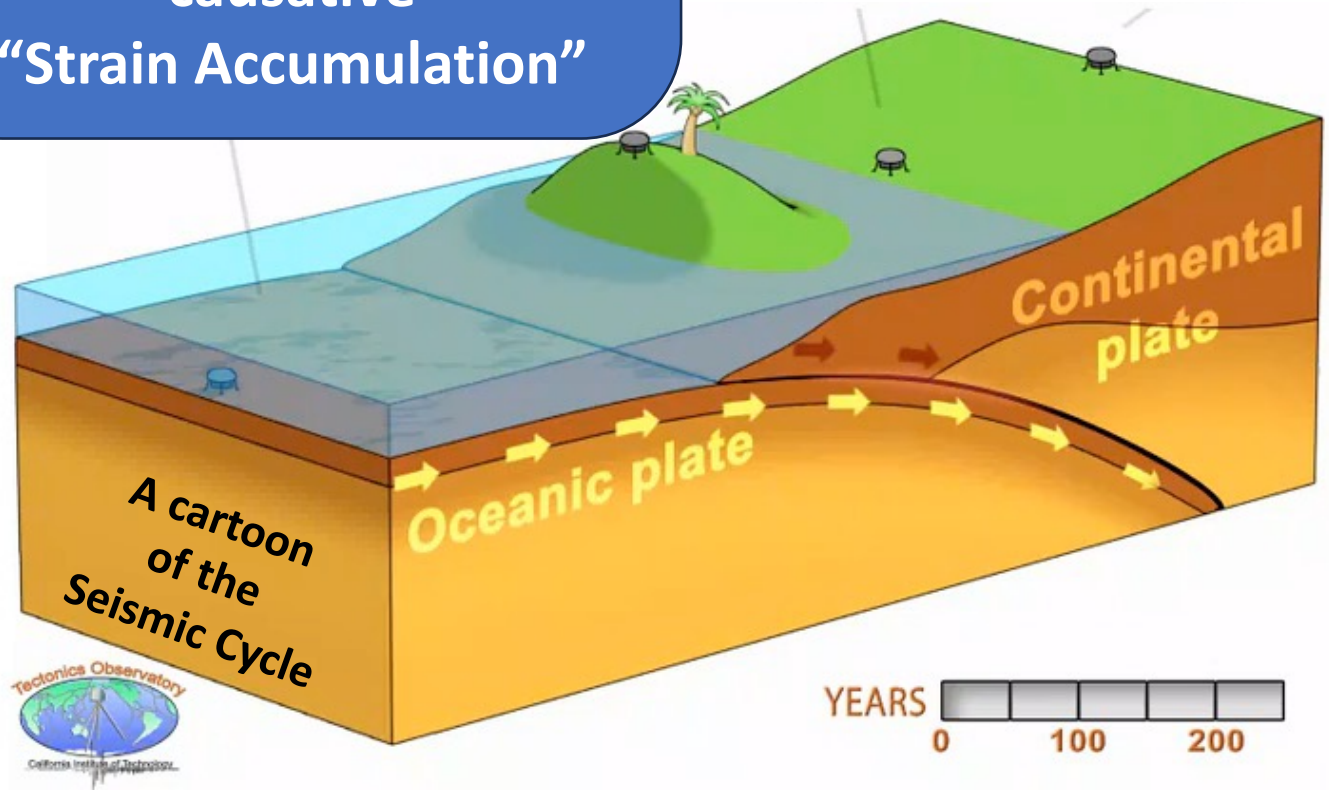
causative "Strain Accumulation"

Geodetic observations of Seismic Cycle

Modeling Approach

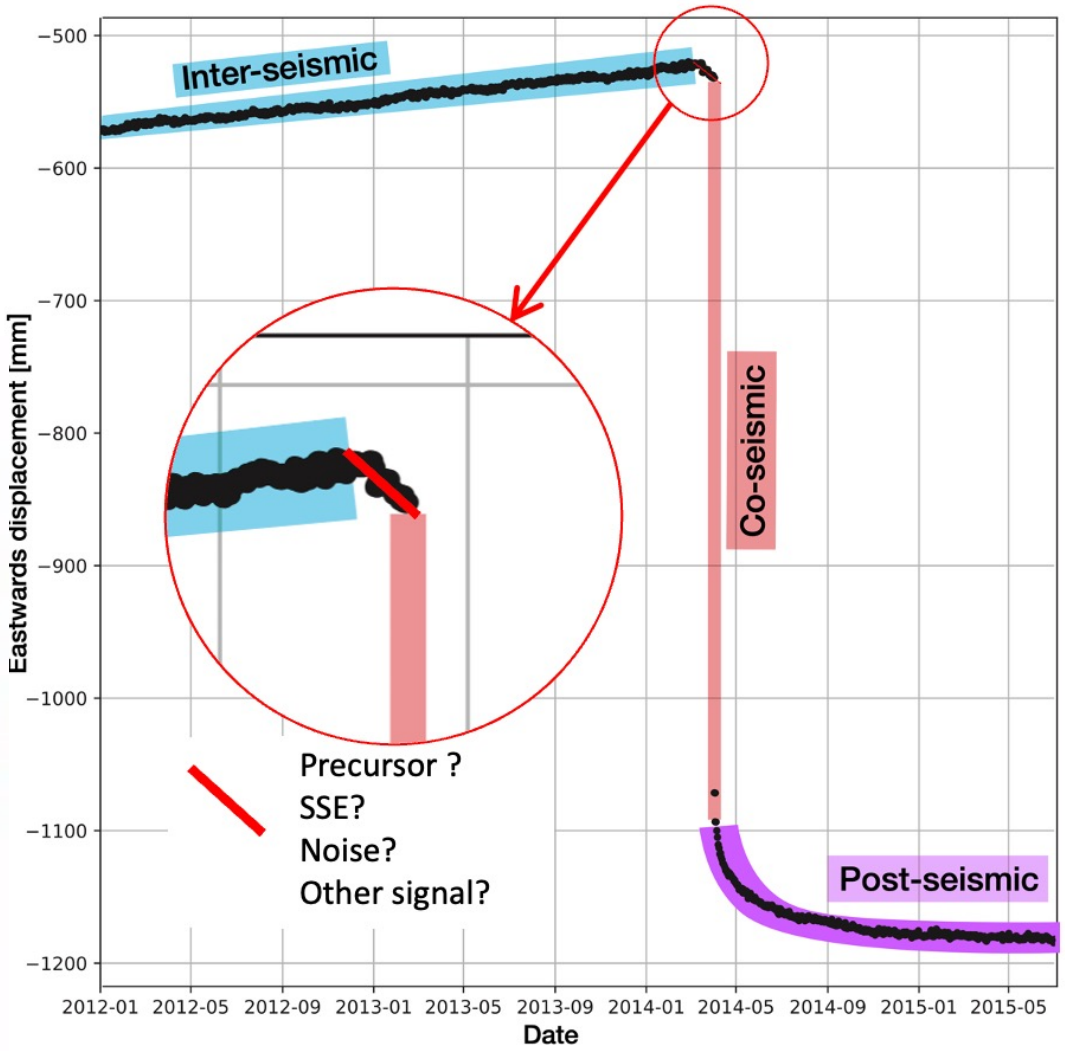
Improve understanding of the Seismic Cycle in subduction environment

causative
"Strain Accumulation"



A cartoon of the Seismic Cycle

GNSS positional time series



Geodetic observations of Seismic Cycle

Modeling Approach

Improve understanding of the Seismic Cycle in subduction environment

causative
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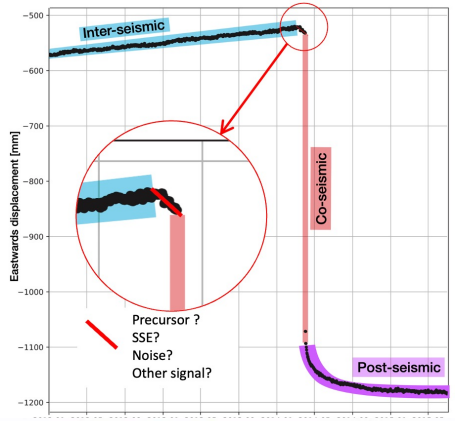
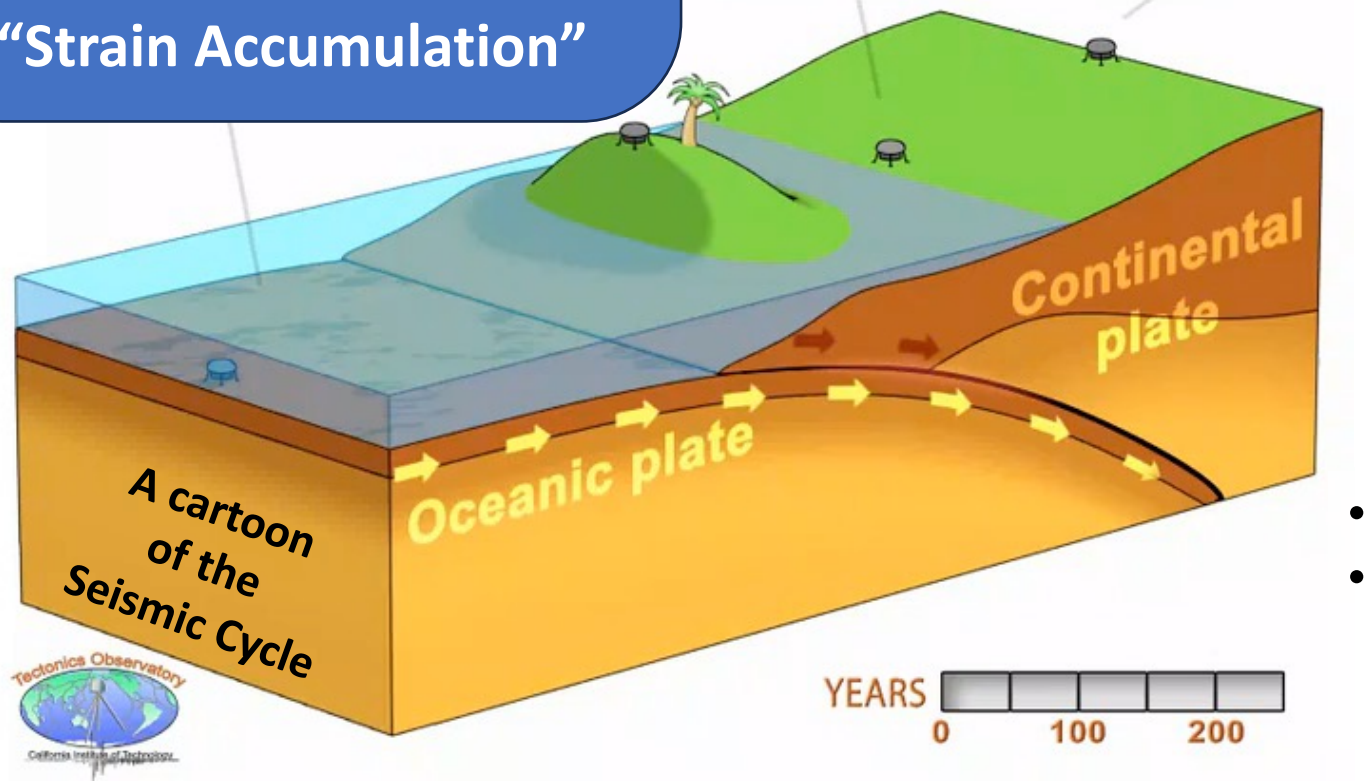
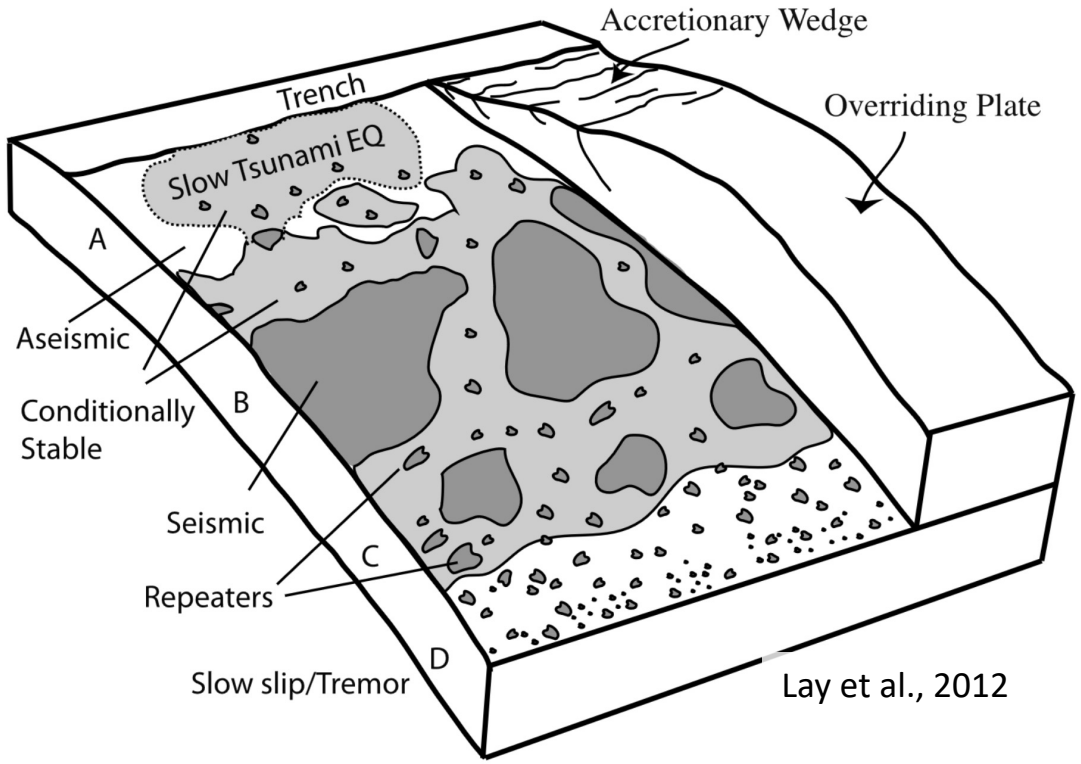


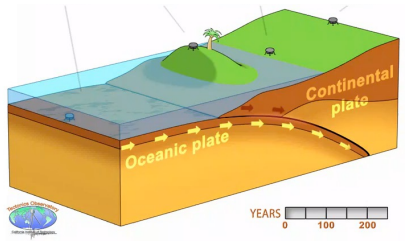


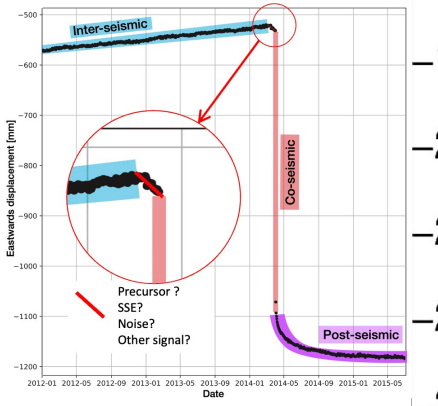
Illuminating megathrust mechanical (fricitional) behavior

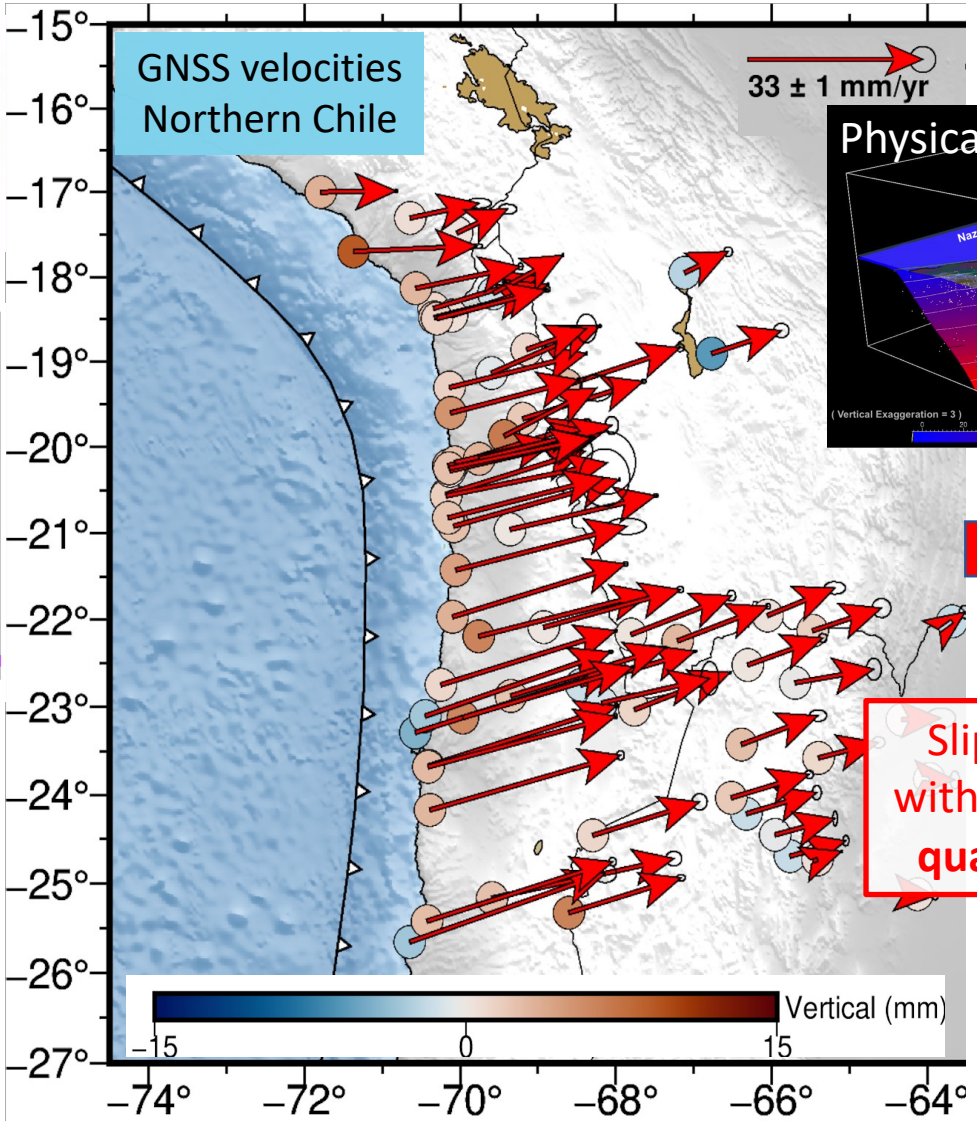


- **Where is elastic crustal strain accumulating?**
- **Where is stress building up at the megathrust?**
  →Location and extent of future earthquakes?
  → Separation of brittle and ductile regions.

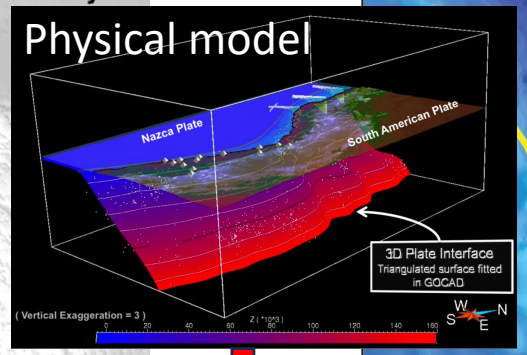
Inferring Coupling models



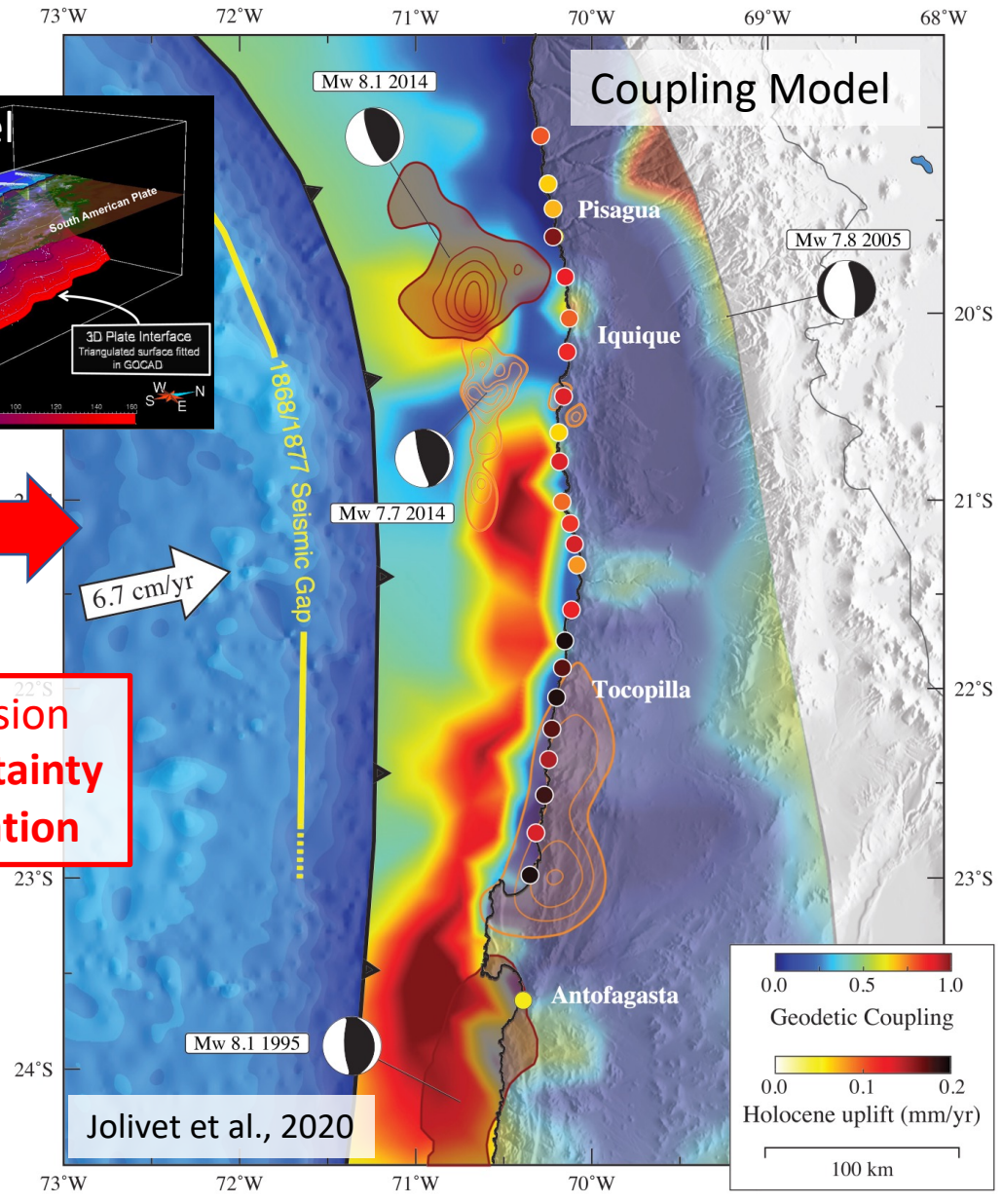




Hormazabal, J. et al (in prep)



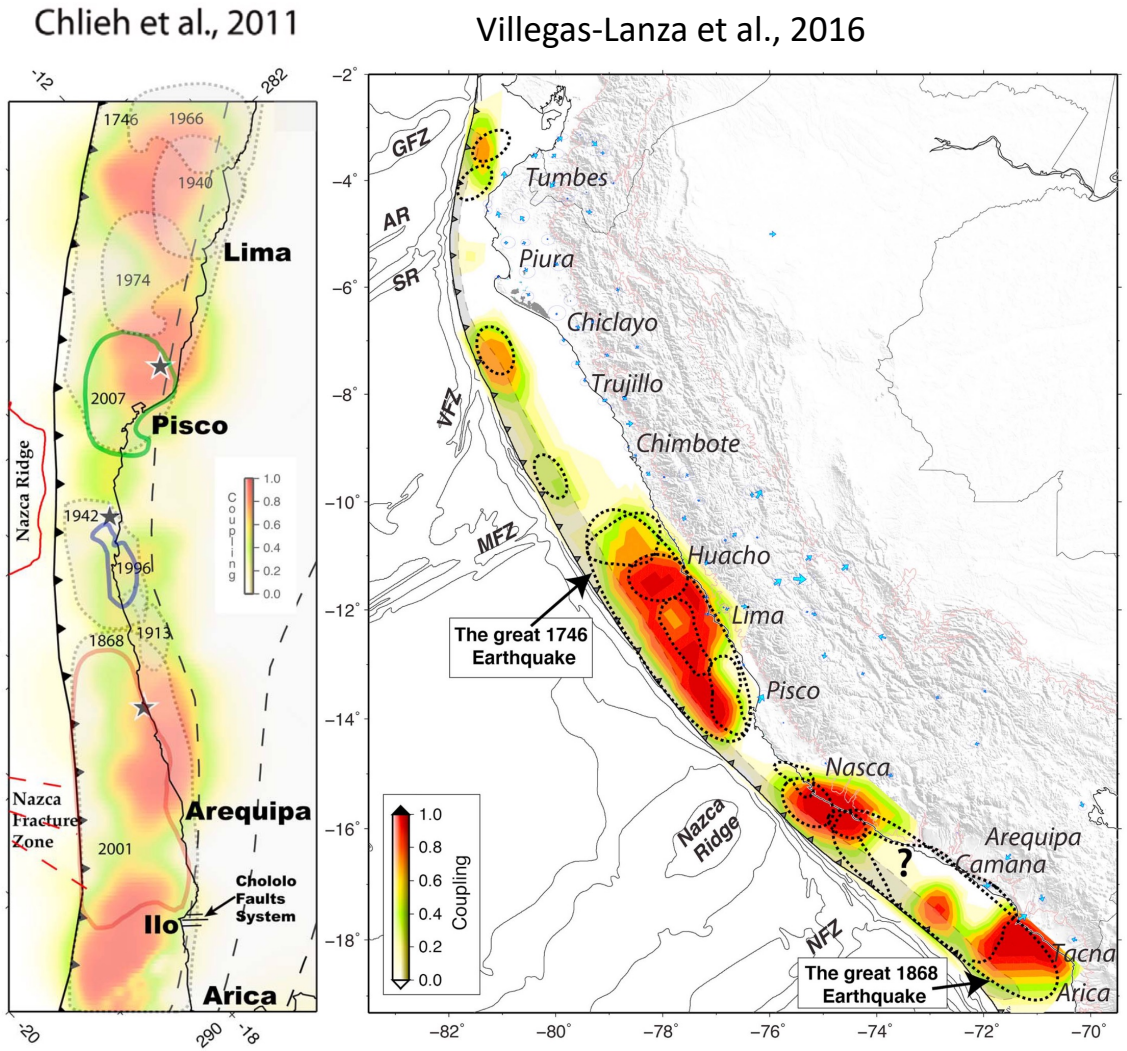
Slip Inversion with **uncertainty quantification**



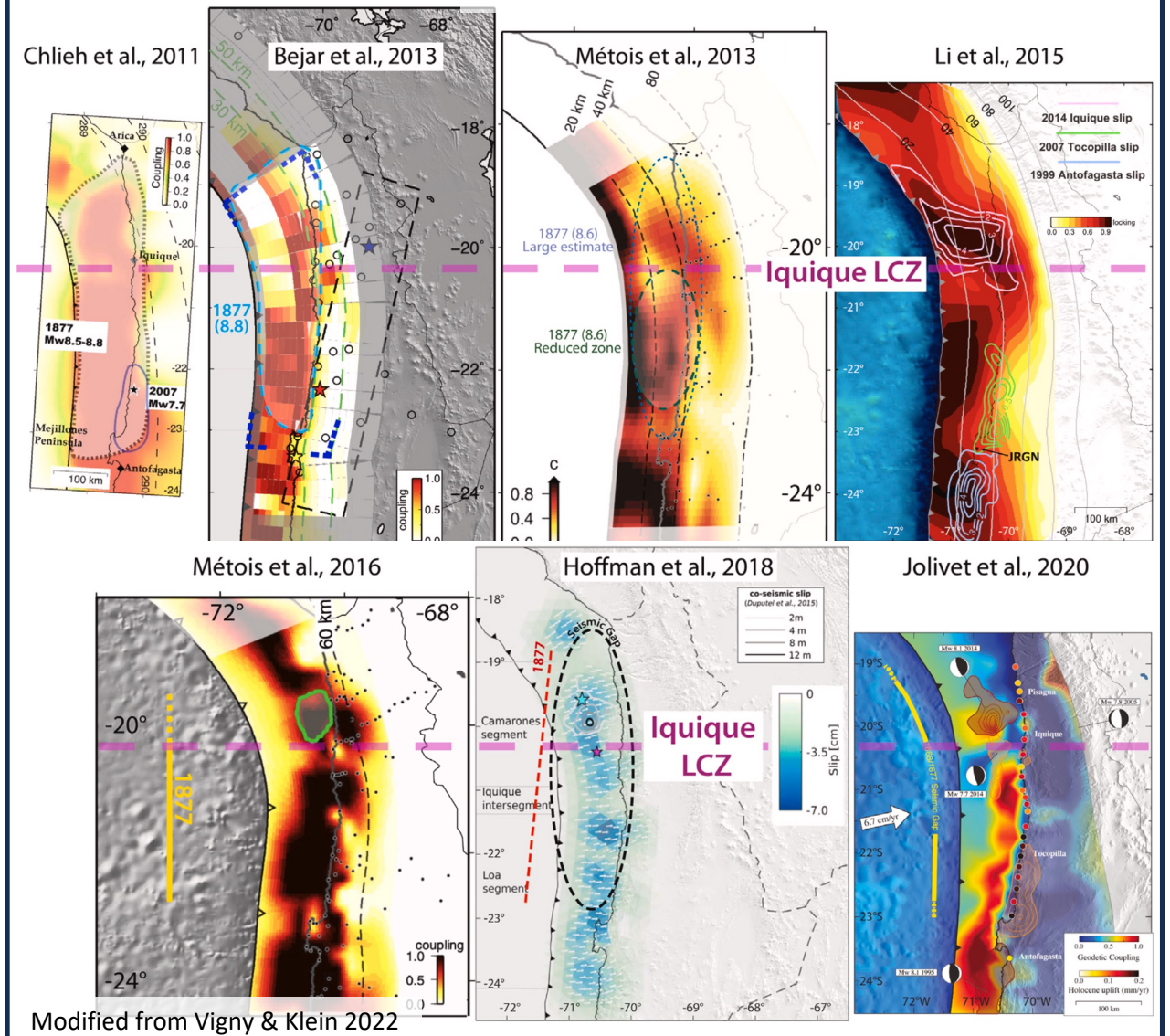
Jolivet et al., 2020

A few coupling models available Perú-Chile

Southern Perú

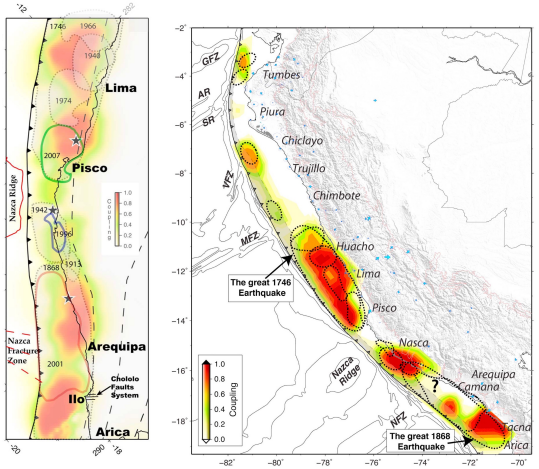


Northern Chile

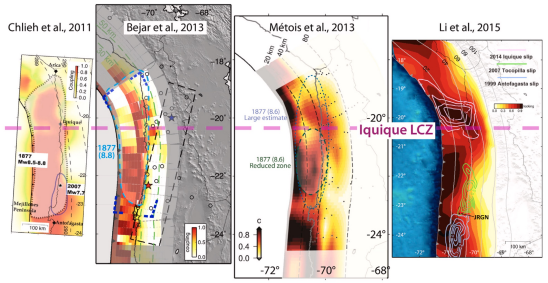


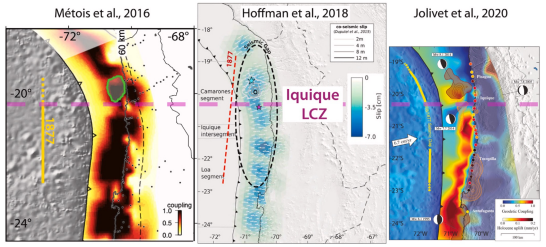
A few coupling models available Perú-Chile

Southern Perú



Northern Chile



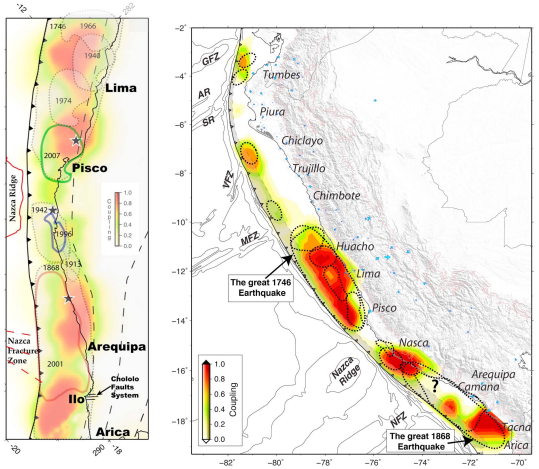


Differences in Coupling Models

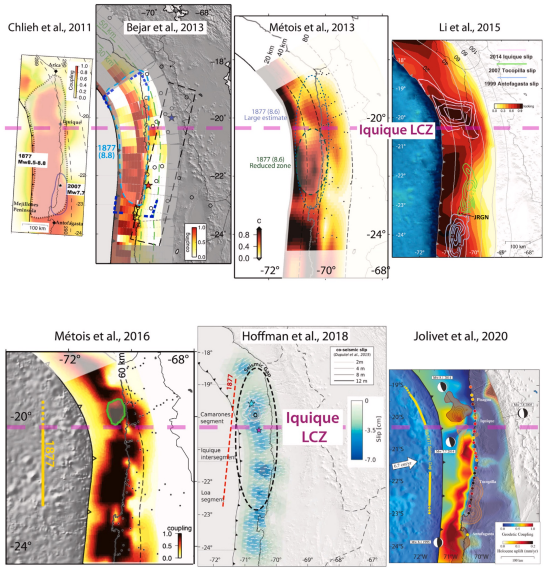
- Inverse Methodology
- Choice of prior information
- Type (GNSS, InSAR) and amount of observations

A few coupling models available Perú-Chile

Southern Perú



Northern Chile



Differences in Coupling Models

- Inverse Methodology
- Choice of prior information
- Type (GNSS, InSAR) and amount of observations

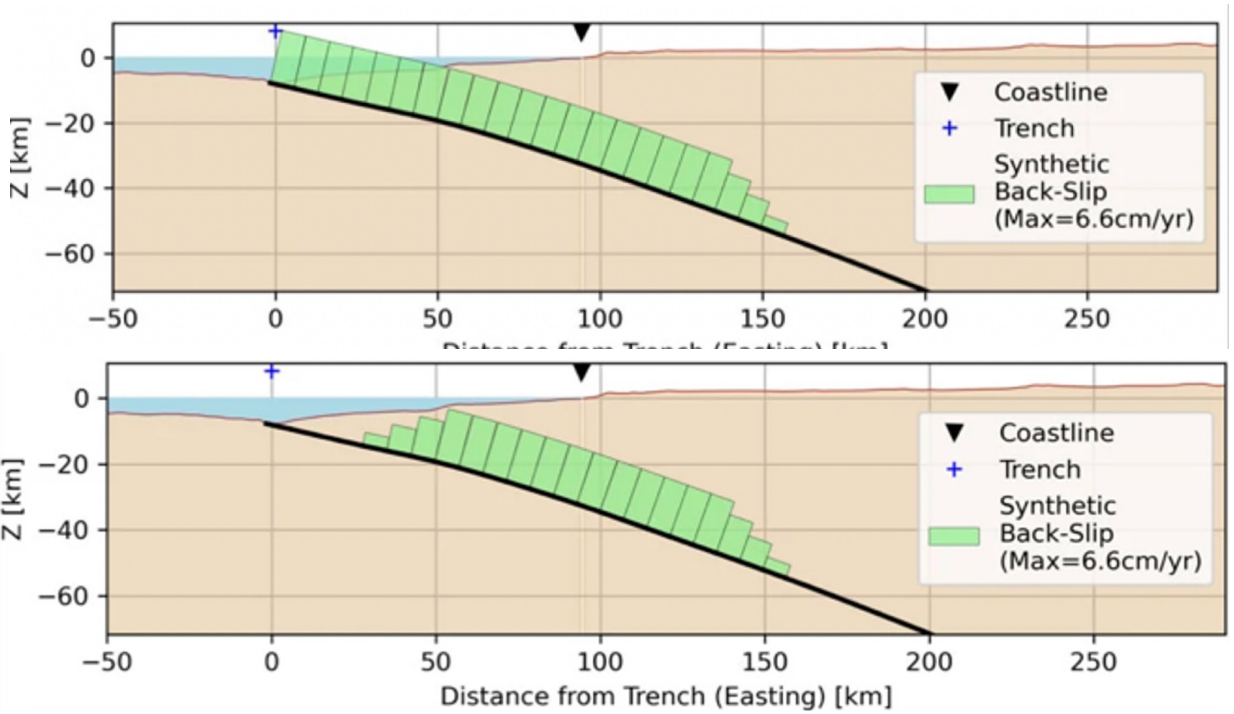
An important common factor

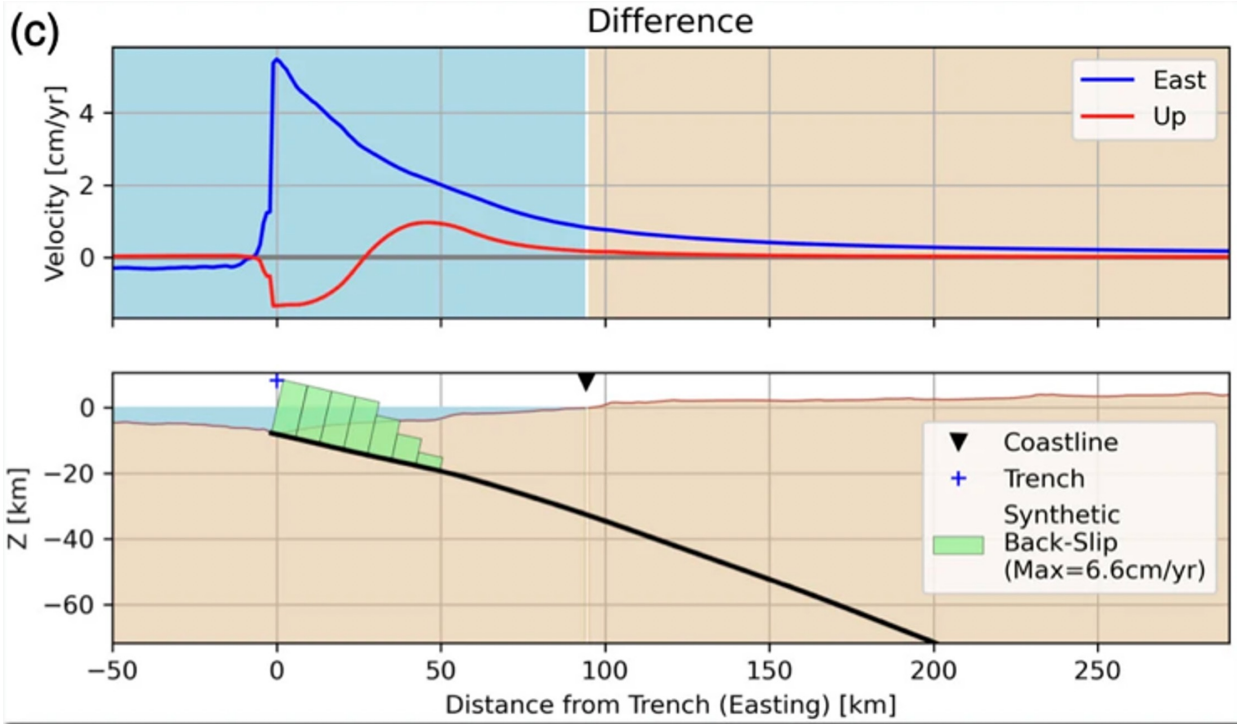
- Onland crustal strain observations to constrain offshore megathrust slip behavior

Poor resolution of shallow megathrust slip behavior

Translates into high uncertainty in shallow coupling and tsunami hazard

Shallow slip complexity manifest at seafloor





(Ortega-Culaciati et al., In Preparation)

Improving imaging of shallow megathrust slip behavior: Selecting the location of Absolute Pressure Gauge sensors off-shore Taltal (~ 25°S) Chile

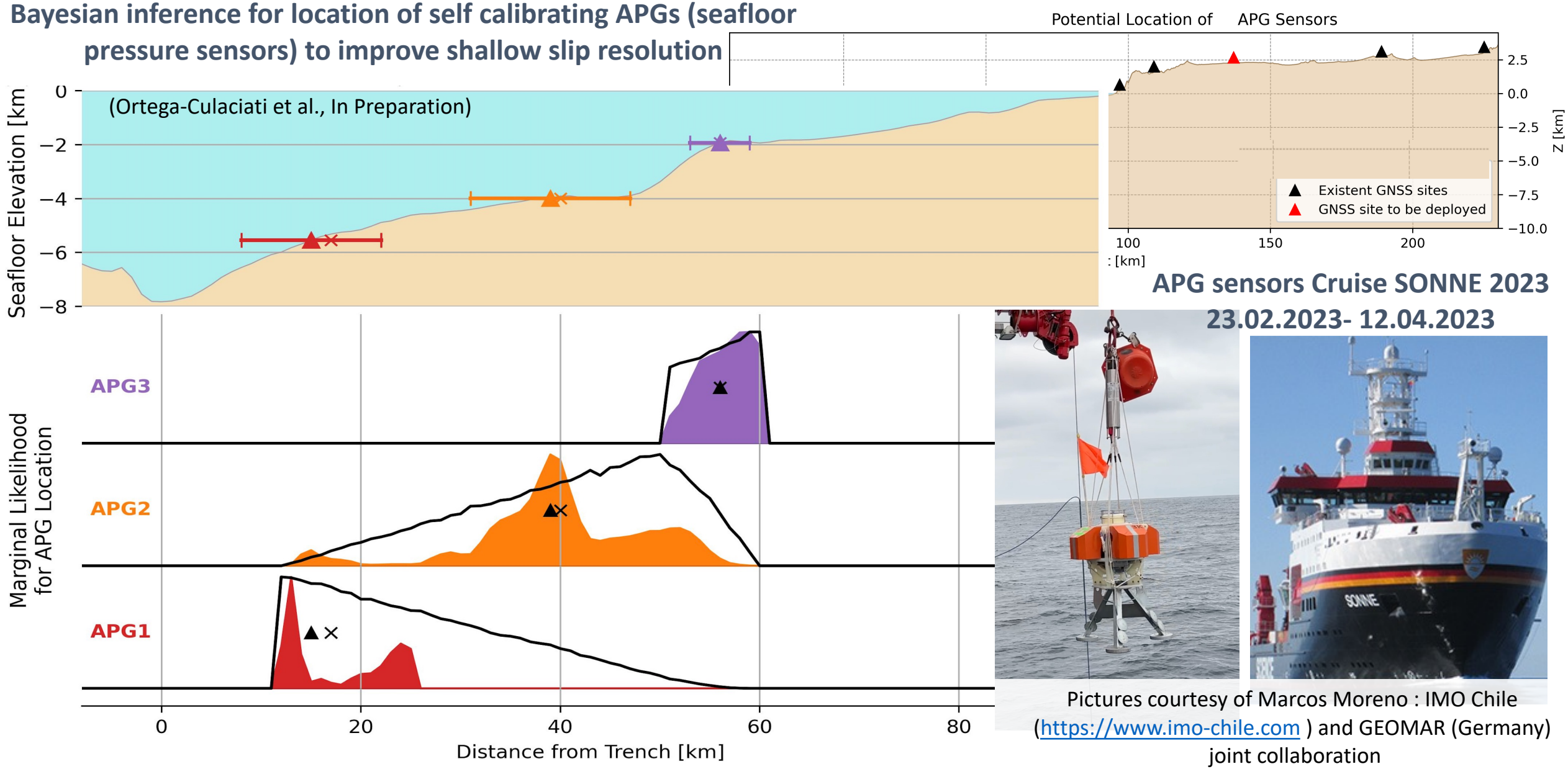
Francisco Ortega-Culaciati[1,*], Marcos Moreno[2,+], Dietrich Lange[3,+], Heidrun Kopp[3,4,+], Juan Pablo Merino[1], Lorenzo Jara[5], Javier Ruiz[1], Shoichi Yoshioka[6,7], Daniel Melnick[8], and Roberto Benavente[9,10]

The complexities of shallow megathrust slip can only be observed at the seafloor

Need to observe seafloor deformation!

An ongonig example of seafloor geodesy (APGs)

Bayesian inference for location of self calibrating APGs (seafloor pressure sensors) to improve shallow slip resolution



APG sensors Cruise SONNE 2023

23.02.2023- 12.04.2023

Pictures courtesy of Marcos Moreno : IMO Chile (https://www.imo-chile.com) and GEOMAR (Germany) joint collaboration

Cutting-edge inversion and uncertainty quantification

An EPIC Tikhonov Regularization: Application to Quasi-Static Fault Slip Inversion

F. Ortega-Culaciati[1], M. Simons[2], J. Ruiz[1], L. Rivera[3], and N. Díaz-Salazar[1]

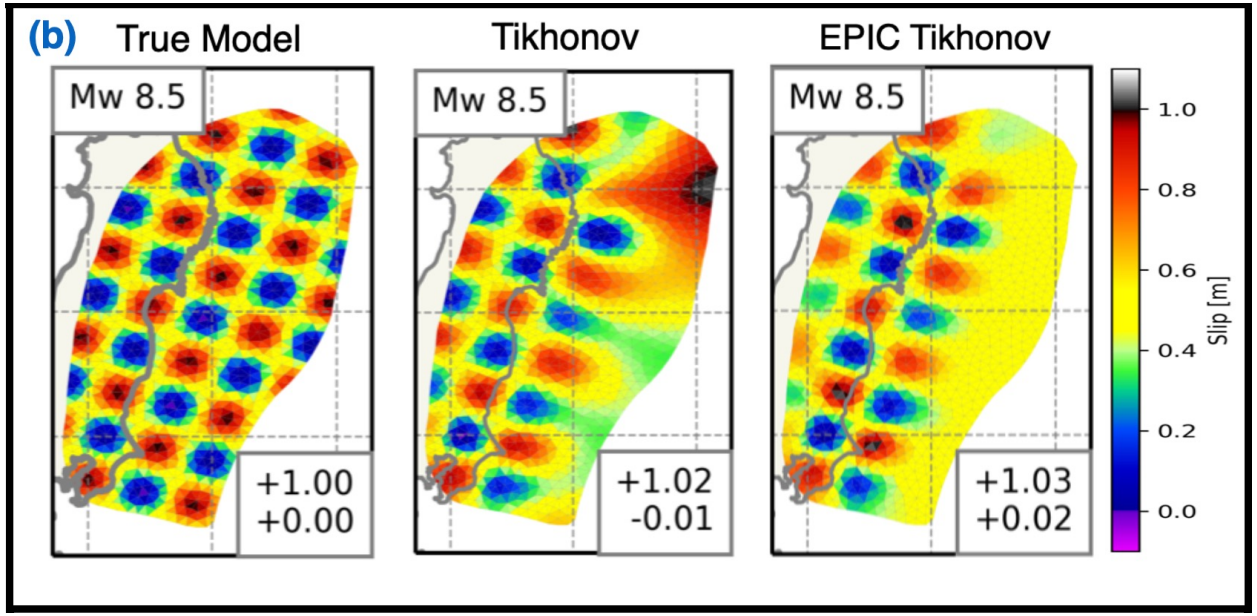
JGR Solid Earth

Ortega-Culaciati et al. (2021)

EPIC:

Equal a **P**osteriori **I**nformation **C**ondition

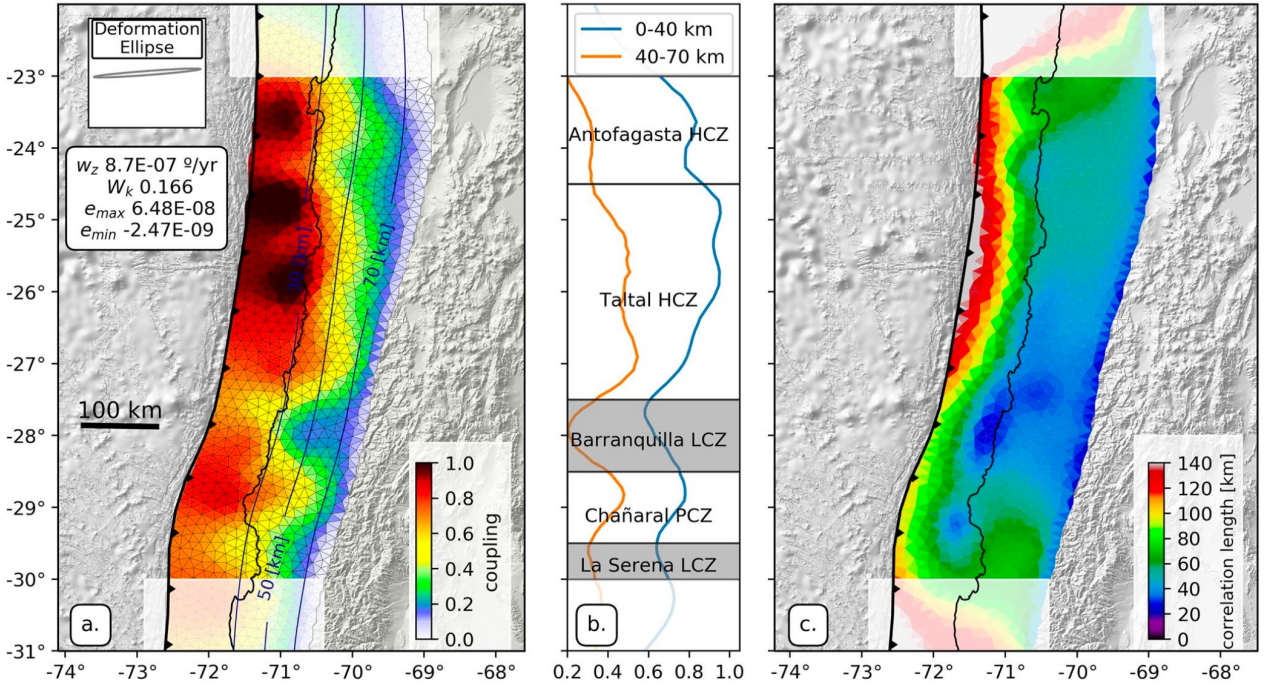
→ Spatially variable smoothing for slip



(2022) Geophysical Research Letters

Interplate Coupling and Seismic Potential in the Atacama Seismic Gap (Chile): Dismissing a Rigid Andean Sliver

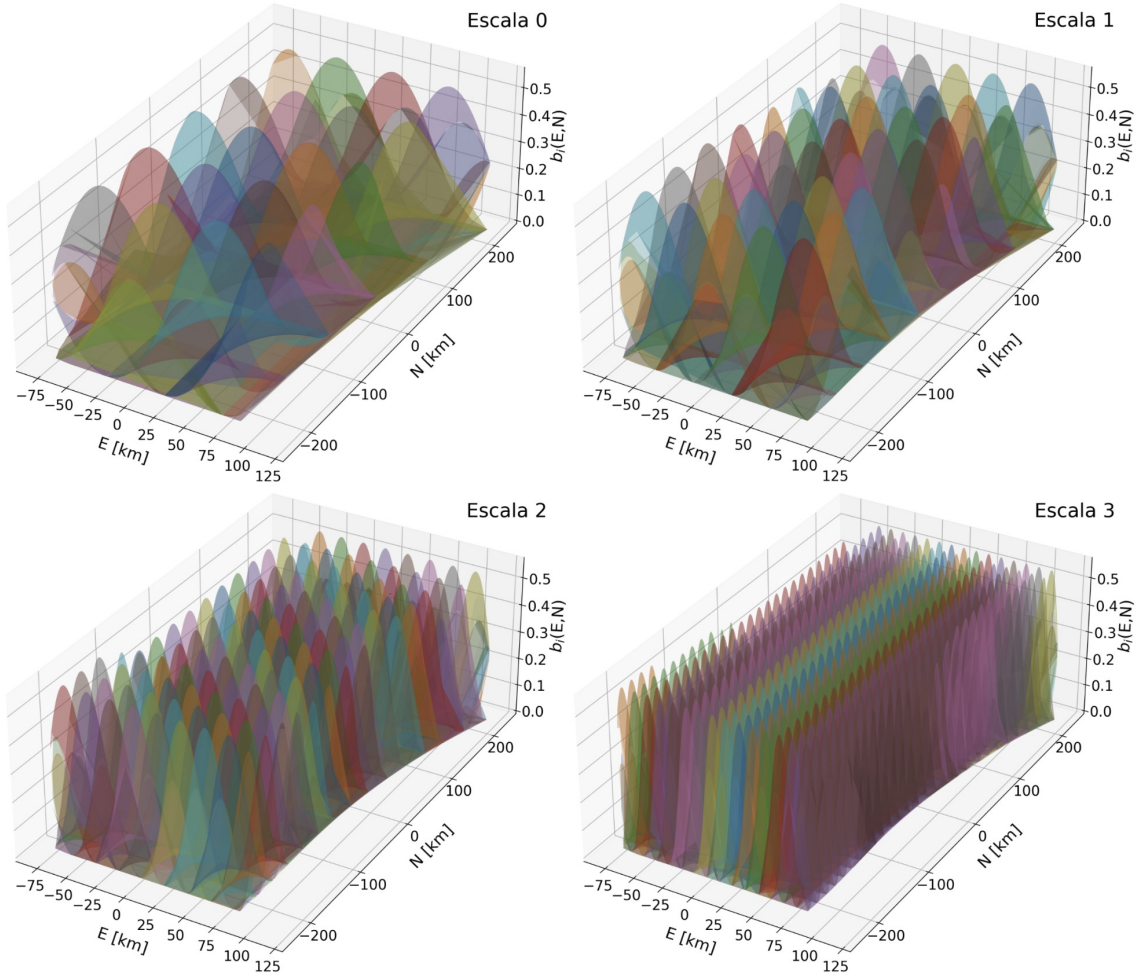
V. Yáñez-Cuadra[1,2], F. Ortega-Culaciati[1], M. Moreno[2], A. Tassara[3], N. Krumm-Nualart[4], J. Ruiz[1], A. Maksymowicz[1], M. Manea[5,6], V. C. Manea[5], J. Geng[7], and R. Benavente[8,9]



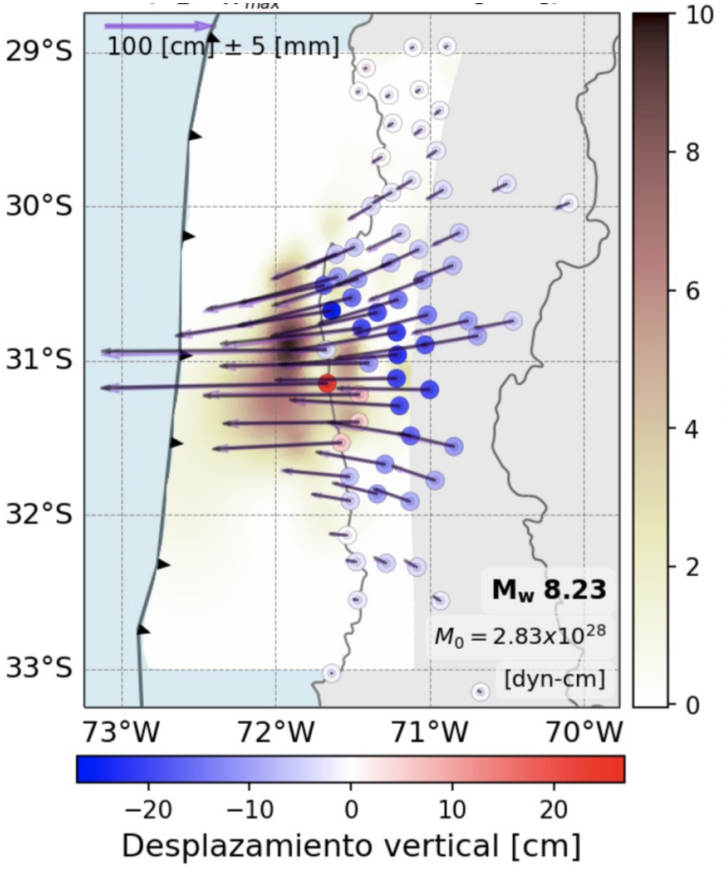
Cutting-edge inversion and uncertainty quantification

MUSE: MUltiscale Sparse Estimation of slip (Ortega-Culaciati, Carrillo-Barra, et al., in preparation)

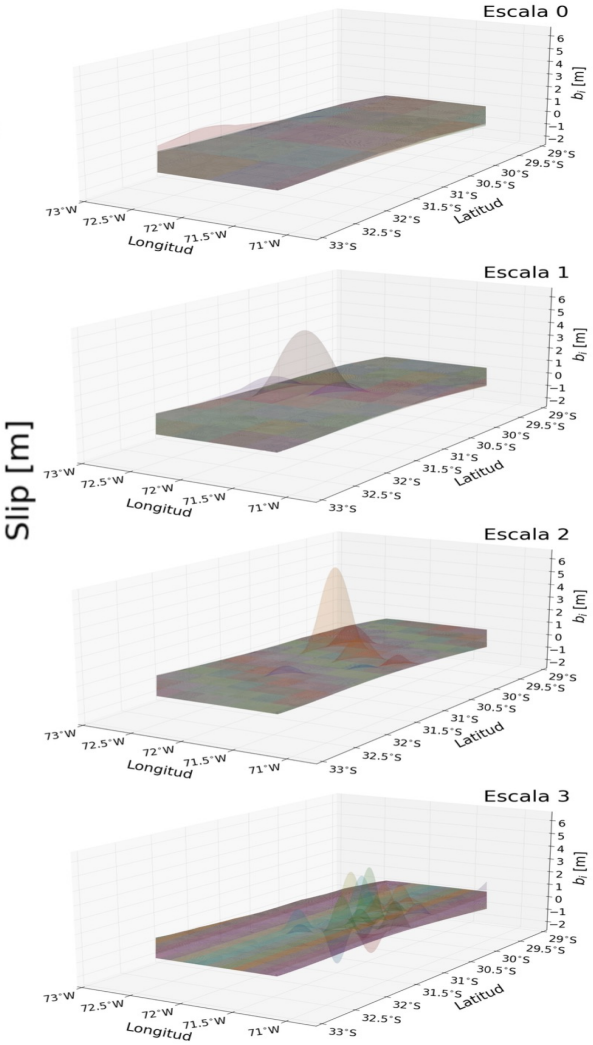
Slip parameterized using redundant set of basis functions



Slip Illapel (2015) earthquake (constrained by GNSS data)



Selected basis functions



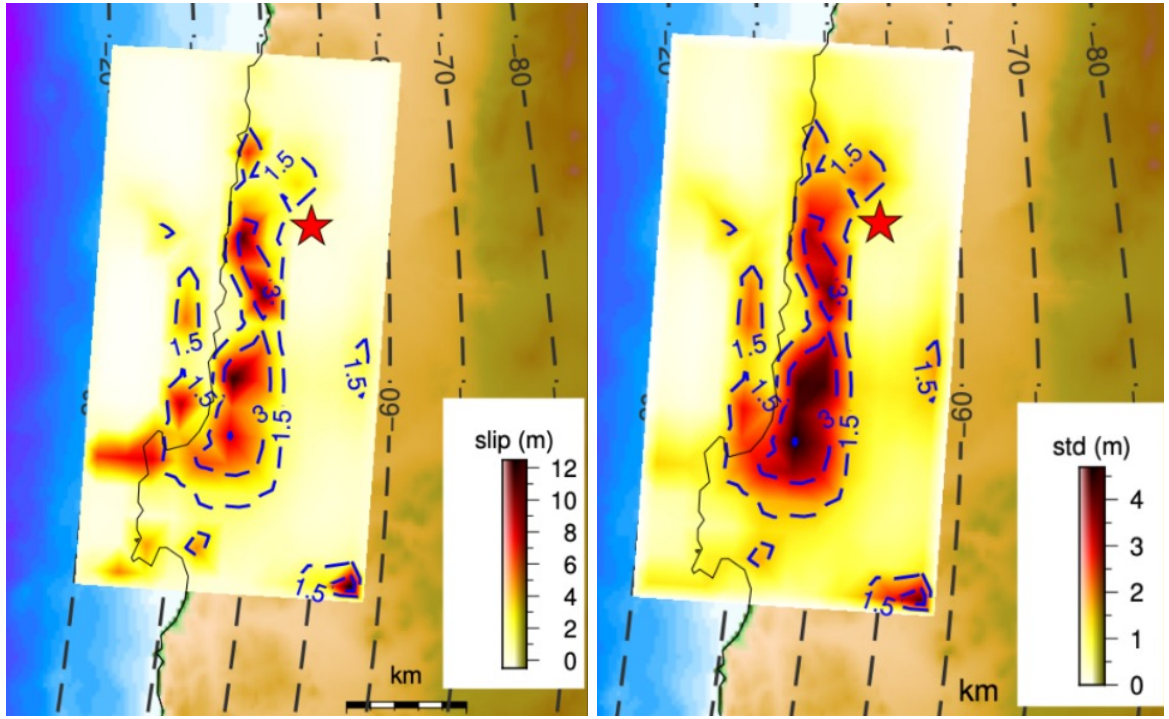
Cutting-edge inversion and uncertainty quantification

Bayesian Sampling Schemes

A Bayesian perspective of the 2007 M_W 7.7 Tocopilla, Chile, Earthquake using geodetic data and accounting for epistemic uncertainties.

(in preparation)

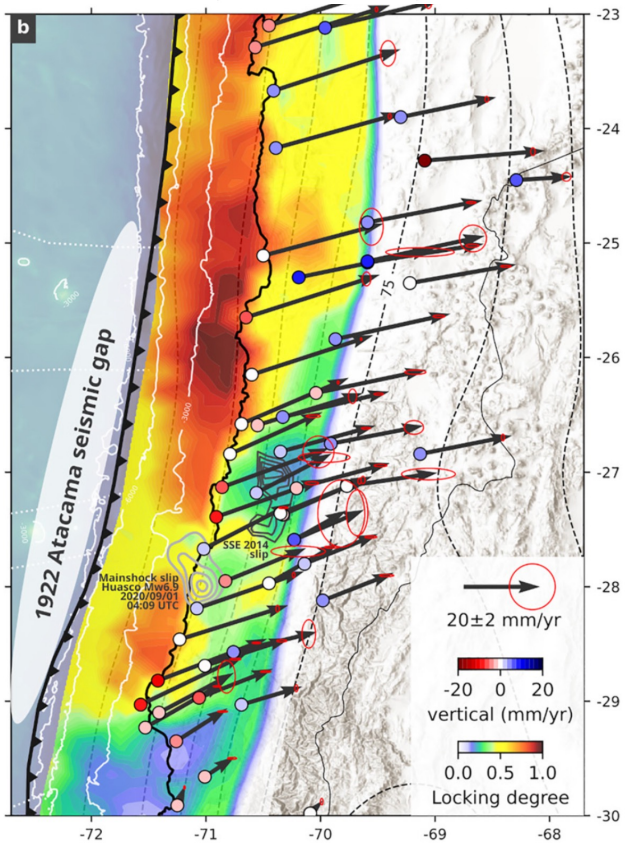
Natalia Díaz-Salazar [1], Francisco Ortega [1], Javier Ruiz [1], Mark Simons [2], Sarah Minson [3], Joaquín Hormazábal [1]



Transdimensional Sampling

Relation Between Oceanic Plate Structure, Patterns of Interplate Locking and Microseismicity in the 1922 Atacama Seismic Gap Geophysical Research Letters

Diego González-Vidal[1], Marcos Moreno[2], Christian Sippl[3], Juan Carlos Baez[4], Francisco Ortega-Culaciati[5], Dietrich Lange[6], Frederik Tilmann[7,8], Anne Socquet[9], Jan Bolte[10], Joaquin Hormazabal[5], Mickael Langlais[9], Catalina Morales-Yáñez[11], Daniel Melnick[1], Roberto Benavente[11,12], Jannes Münchmeyer[9], Rodolfo Araya[13], and Benjamin Heit[7]



Summary: Improvements for Tsunami Hazard

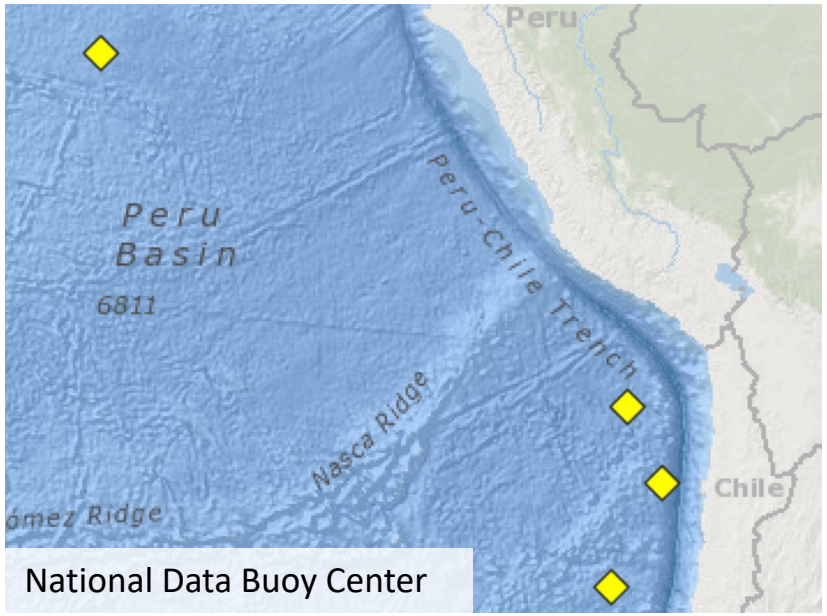
- **Improve geodetic observations**
  - Seafloor Geodesy
  - Absolute Pressure Gauge sensors for vertical seafloor displacements?
  - Acoustic GNSS?
  - OBS for robust seismicity
  - Submarine cables: DAS? Deformation? (see Diane Rivet's Project in Chile with fiber optics and DAS)
  - **Expensive:** requires external fostering for international research projects and funding acquisition

- **Improve Modeling**
  - Use Inverse method with less bias on the solution and allows to explore all solutions (e.g., Bayesian sampling ideally)
  - Physical forward model: account for topography/bathymetry and media heterogeneities (need tomography), viscoelasticity, etc.
  - Account for uncertainties in physical forward model
  - Quantify uncertainties of results

Summary: Improvements for Tsunami Hazard

- **Paleo Tsunamis? (lots of presentations!)**
- **Tsunami Hazard characterized by causative "earthquakes" (or other fenomena).**
  - Only Chlieh et al (2011) did joint Southern-Peru and Northern-Chile coupling.
  - Should we update such coupling with updated datasets and state-of-the-art inference techniques? What about stress shadows? (working on it!)
  - Coupling derived tsunami scenarios (Drápela, Calisto, Moreno, 2019)

- **Early Warning efforts?**
  - Do we need more DART Buoys?



  - What about coastal mareographs?
  - Development of instrumentation with broader spatial coverage?

Earthquakes/Tsunamis do not know about geographical borders → We need to recommend international collaboration and fudraising for ad-hoc research projects

Thank you!