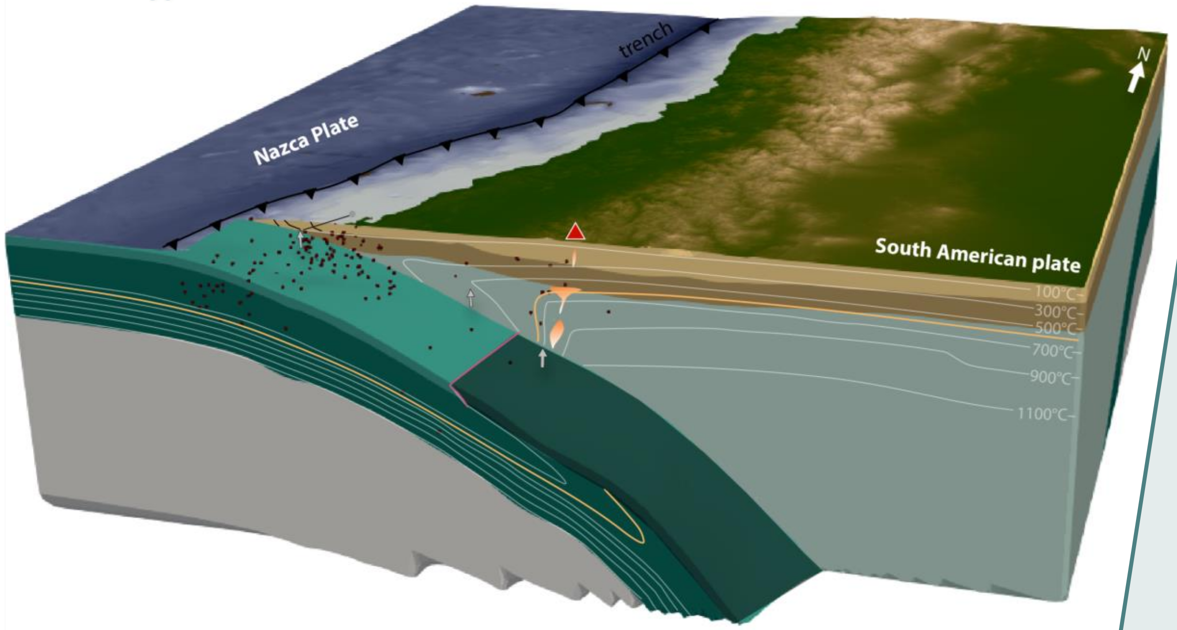
EGU General Assembly 2022

Session TS7.1: Inter- and intraplate seismicity in subduction zones

This presentation participates in OSPP
Outstanding Student Poster & PICO Contest



How does lithospheric strength, mantle hydration and slab flexure relate to seismicity in the southern Central Andes?

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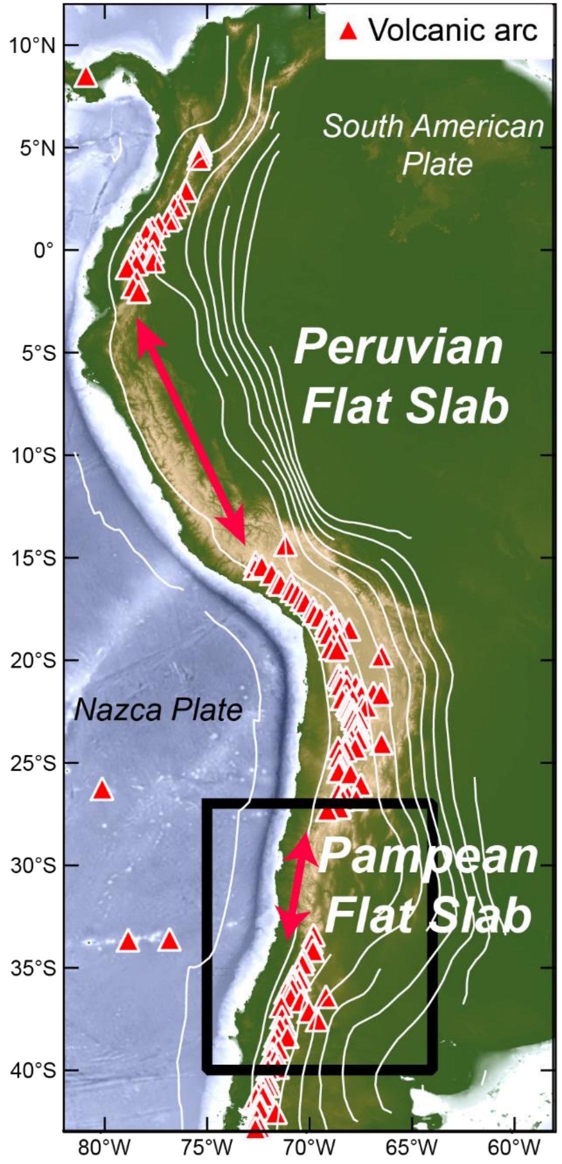
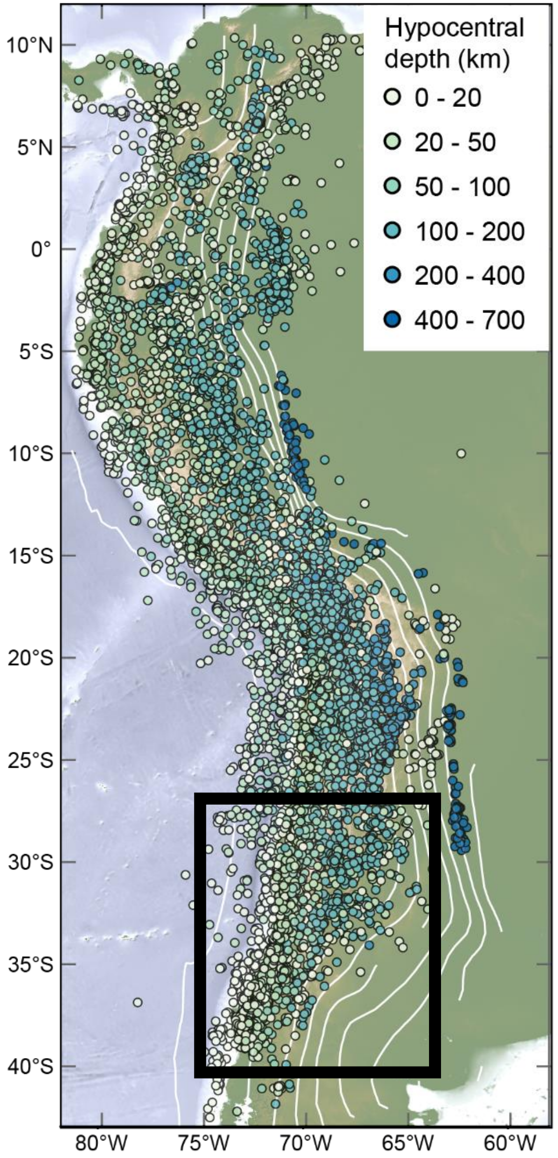
Vienna, May 24th 2022 *Contact: piceda@gfz-potsdam.de*

Motivation



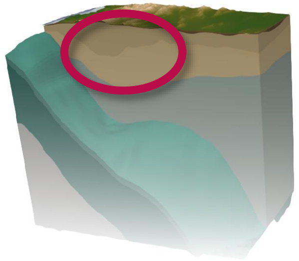


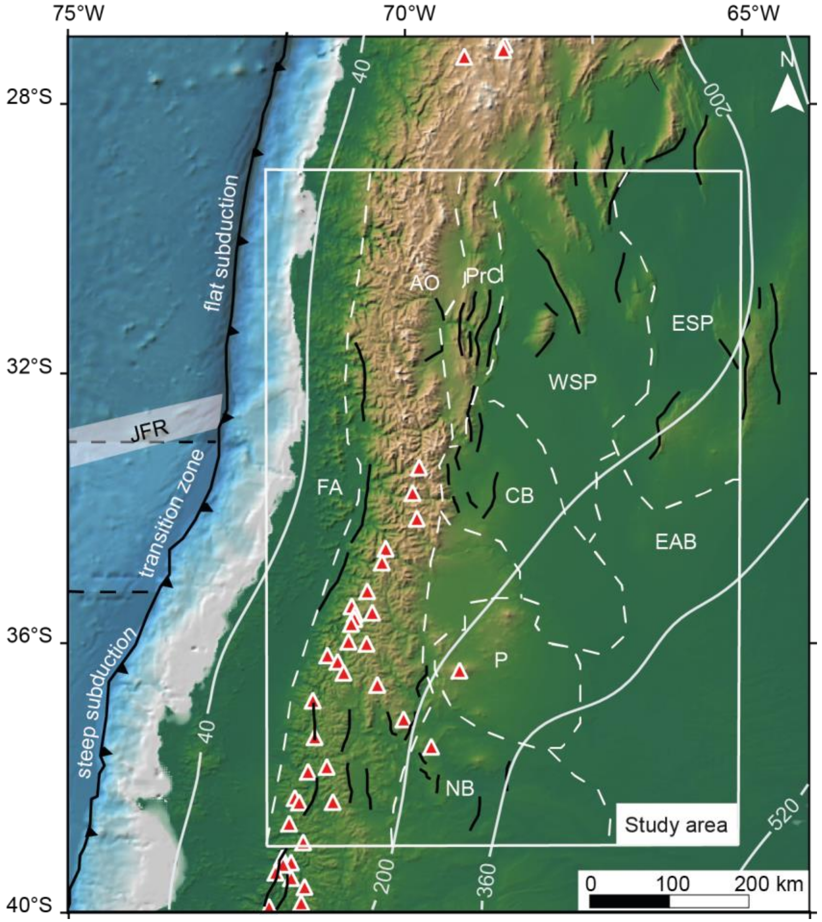
ISC – EHB (2022) seismic catalog

- The Southern Central Andes host one of the most actively seismic areas in South-America
- Oceanic plate changes from flat (< 5°) in the north to steep (~30°) subduction in the south

How do **continental-plate structural inheritance** and **oceanic-plate geometry** affect the localization of seismicity?

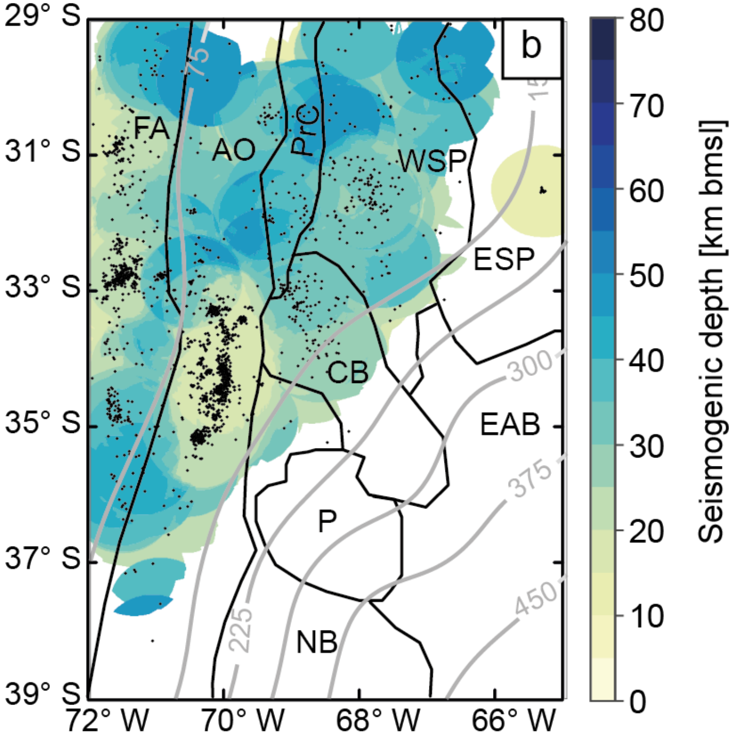
Observations: continental plate seismicity





Abbreviations of main tectonic provinces and features: AO = Andean orogen, CB = Cuyo Basin, ESP = Eastern Sierras Pampeanas, EAB = extra-Andean basins, FA= forearc, NB = Neuquén Basin, P = Payenia volcanic province, Prc = Precordillera, WSP = Western Sierras Pampeanas. JFR= Juan Fernández Ridge

Maximum depth

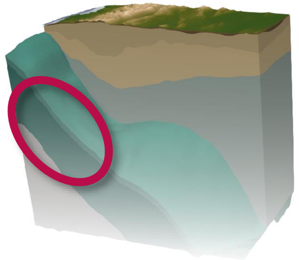


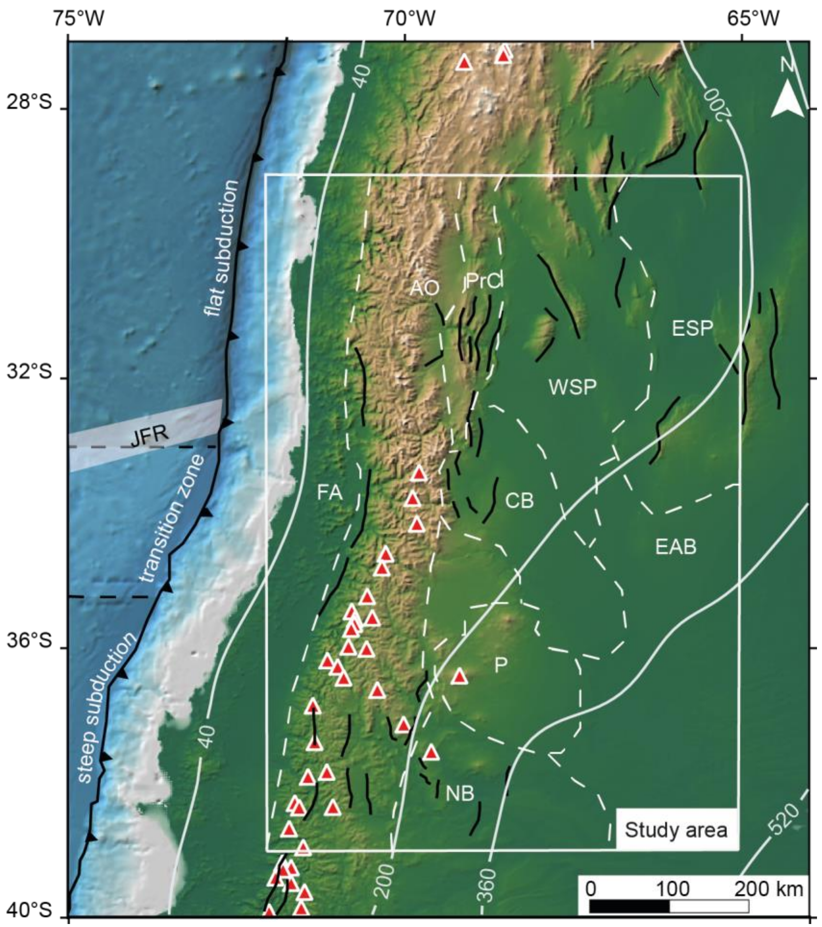
Reviewed bulletin of the International Seismological Centre (2021)

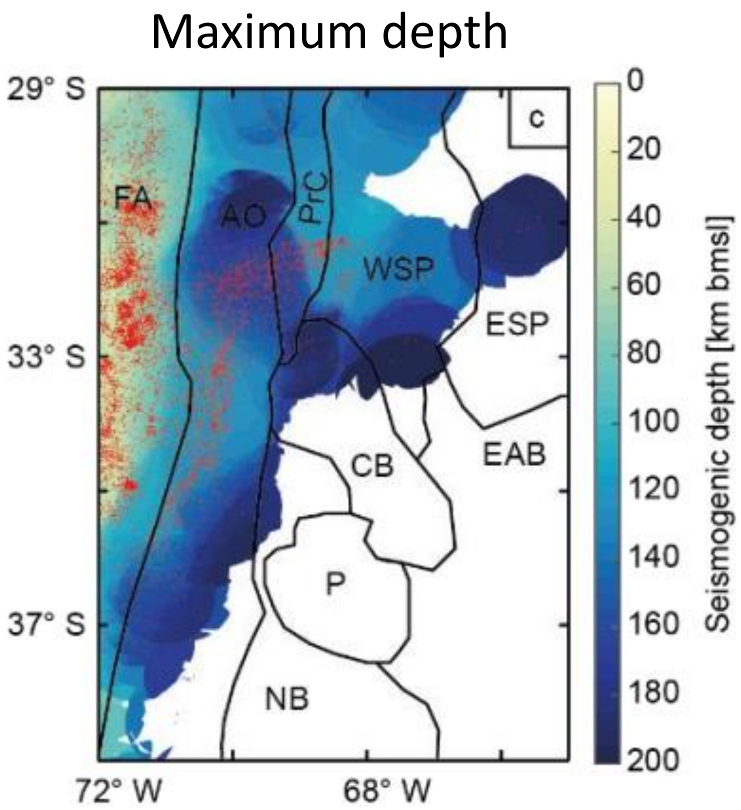
- Shallow seismicity in forearc and central orogen
- Deep seismicity in the Sierras Pampeanas

Rodriguez Piceda et al. (2022, GCubed)

Observations: oceanic plate seismicity





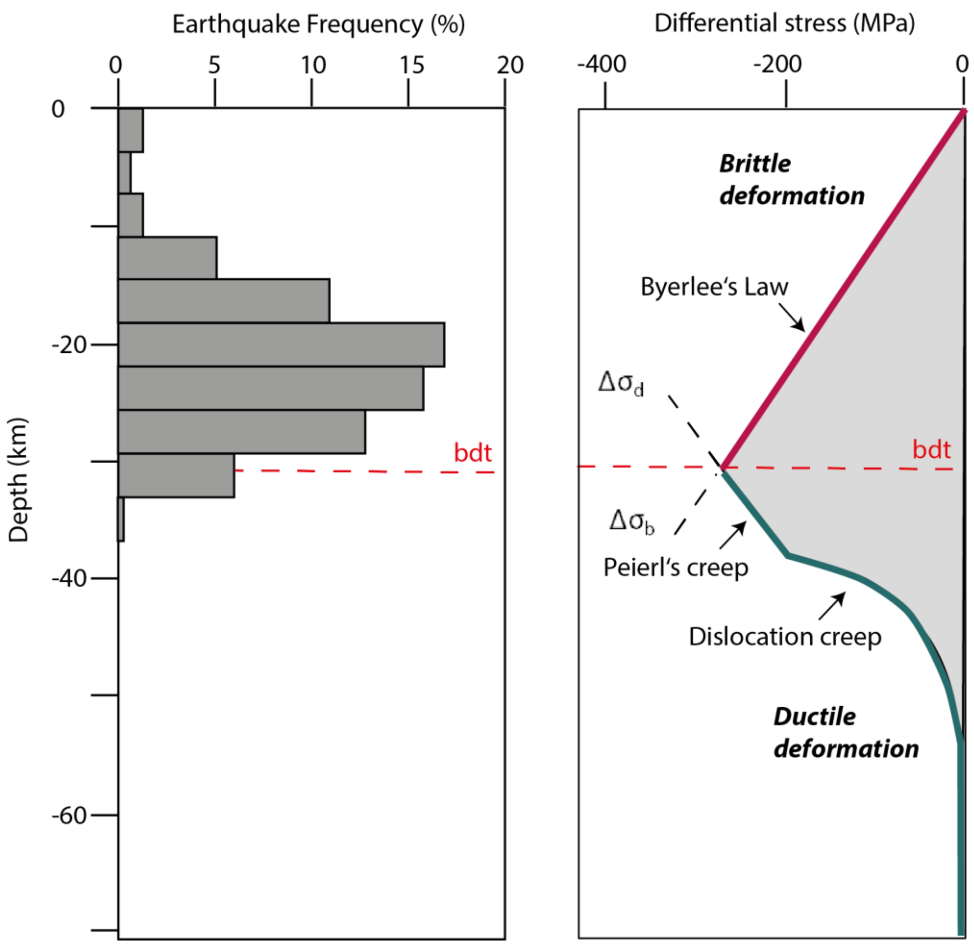


Reviewed bulletin of the International Seismological Centre (2021)

- Shallow seismicity below the forearc
- Deep seismicity within the flat slab segment

Rodriguez Piceda et al. (2022; under review, Nat. Commun. Earth Environ.)

Seismic depth distribution depends on strength



Modified after Sibson (1983), Scholz (1998)

Frictional strength

Byerlee's Law $$\Delta\sigma_b = f_f(1 - f_p)\rho_b g z$$

Frictional parameters (incl. fluids) *density, thickness*

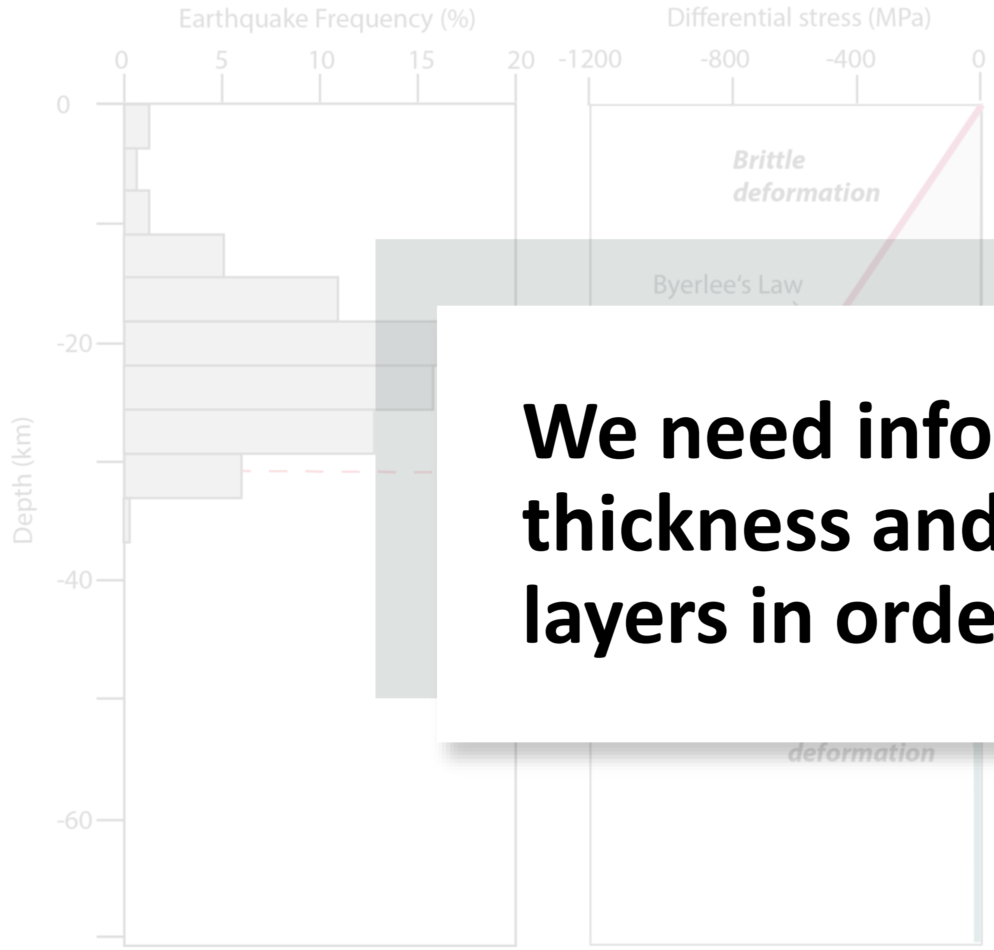
Viscous strength

Dislocation creep (< 200 Mpa) $$\Delta\sigma_d = \left(\frac{\dot{\varepsilon}}{A_p}\right)^{\frac{1}{n}} . \exp\left(\frac{Q_p}{nRT}\right)$$

Peierl's creep (> 200 Mpa) $$\Delta\sigma_D = \sigma_D\left(1 - \left[-\frac{RT}{Q_D} ln \frac{\dot{\varepsilon}}{A_D}\right]^{\frac{1}{2}}\right)$$

Flow law parameters (composition) *Temperature, strain rate*

Seismic depth distribution depends on strength



Modified after Sibson (1983), Scholz (1998)

Frictional strength

Byerlee's Law $\Delta\sigma_b = f_f(1 - f_p)\rho_b g z$

Frictional parameters (incl. fluids) *density, thickness*

We need information on composition, thickness and temperature of the lithospheric layers in order to determine their strength

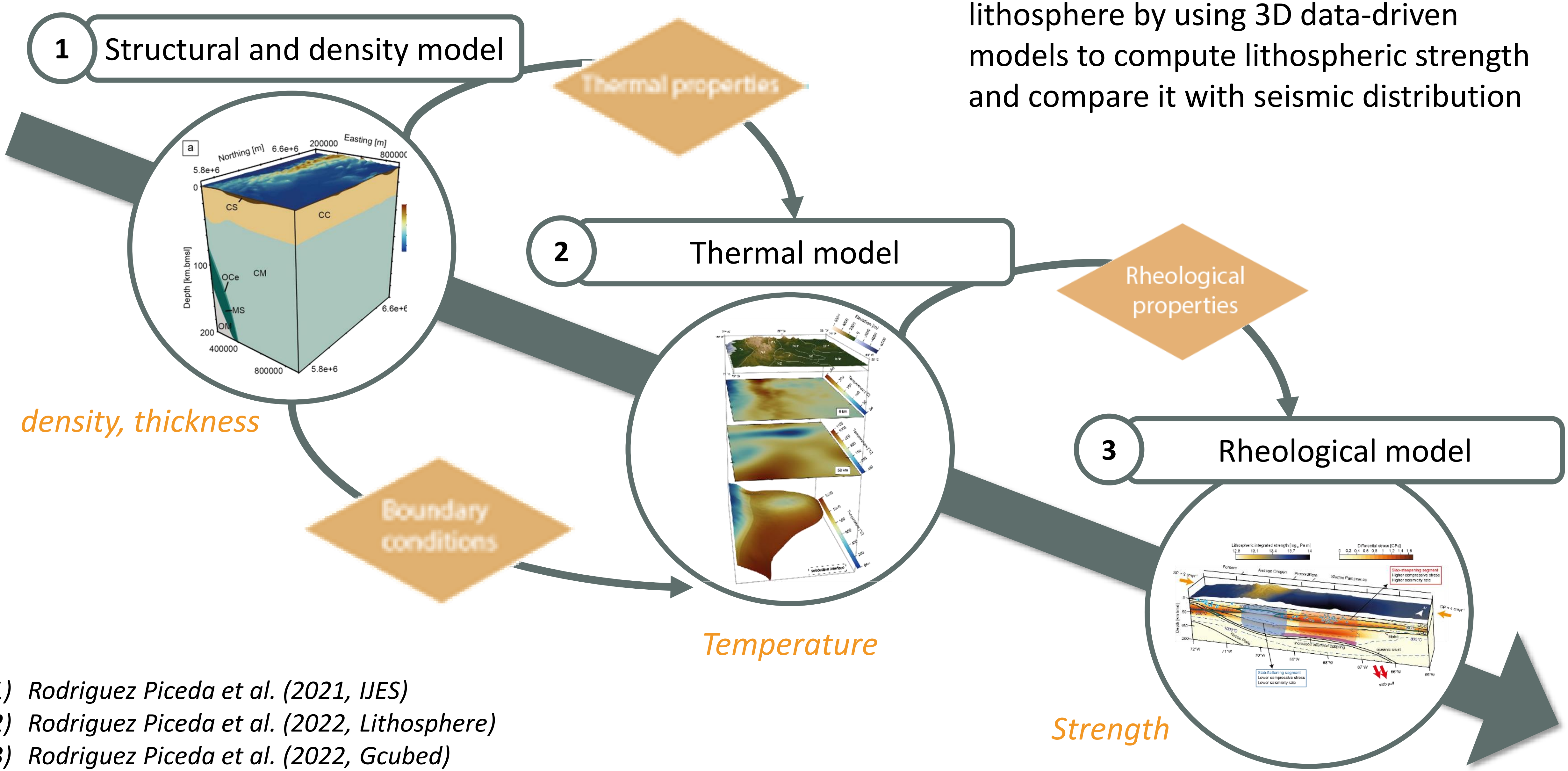
Peierl's creep (> 200 Mpa) $\Delta\sigma_D = \sigma_D\left(1 - \left[-\frac{RT}{Q_D}\ln\frac{\dot{\varepsilon}}{A_D}\right]^{\frac{1}{2}}\right)$

Flow law parameters (composition)

Temperature, strain rate

Our modelling approach

Account for the structural variability of the lithosphere by using 3D data-driven models to compute lithospheric strength and compare it with seismic distribution



(1) Rodriguez Piceda et al. (2021, IJES)
(2) Rodriguez Piceda et al. (2022, Lithosphere)
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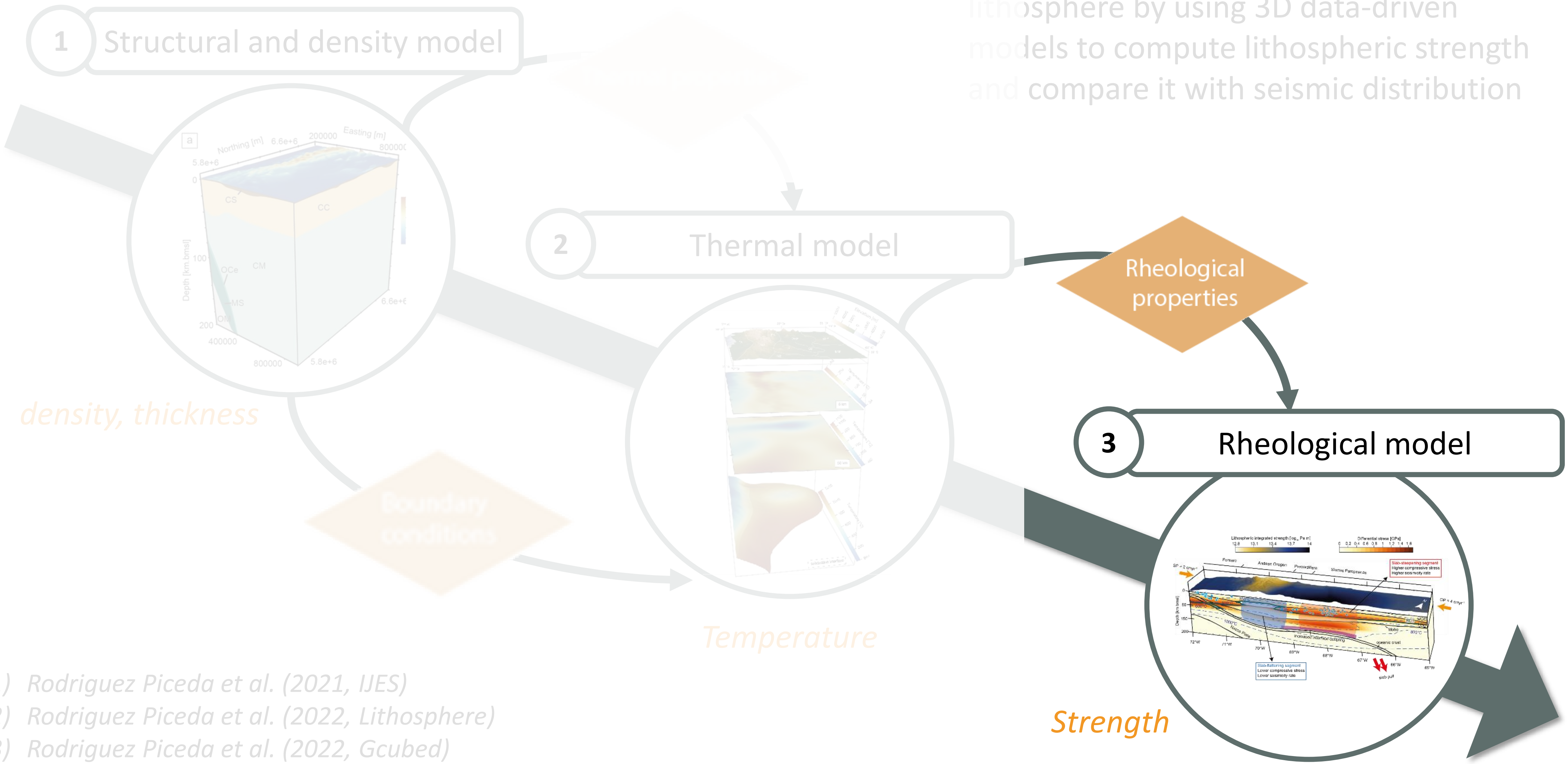

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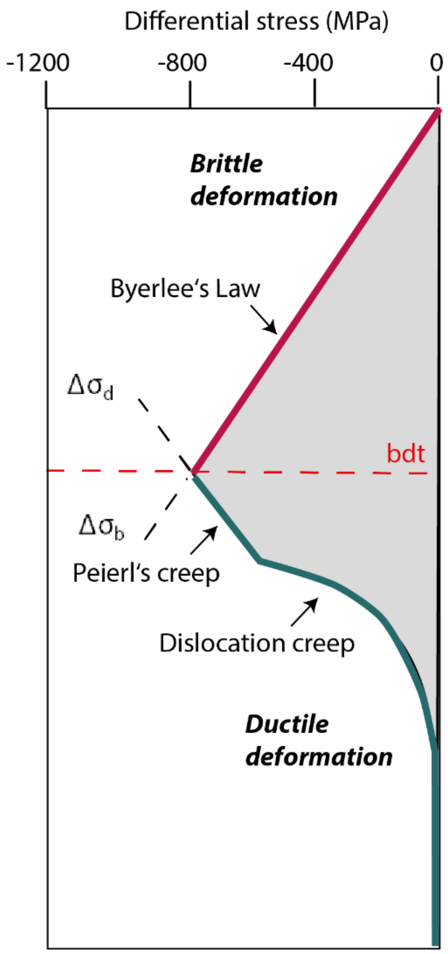
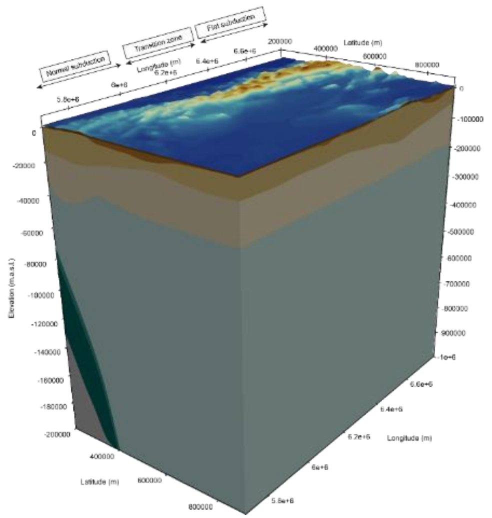
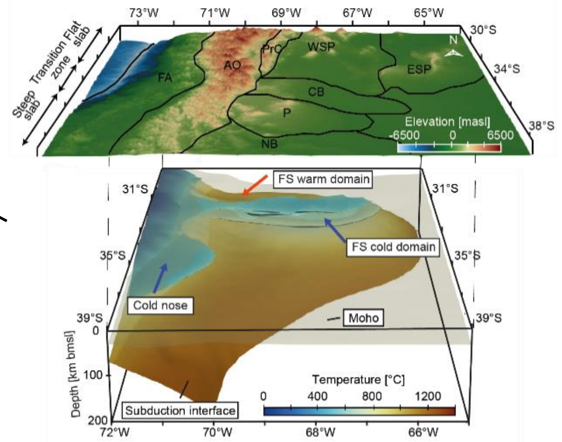
Rheological model







- Computation of yield strength and integrated strength
- Geometries and densities from 3D structural model

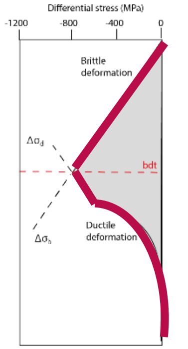
  (Rodriguez Piceda et al., 2021, IJES)
- Temperatures from 3D thermal model

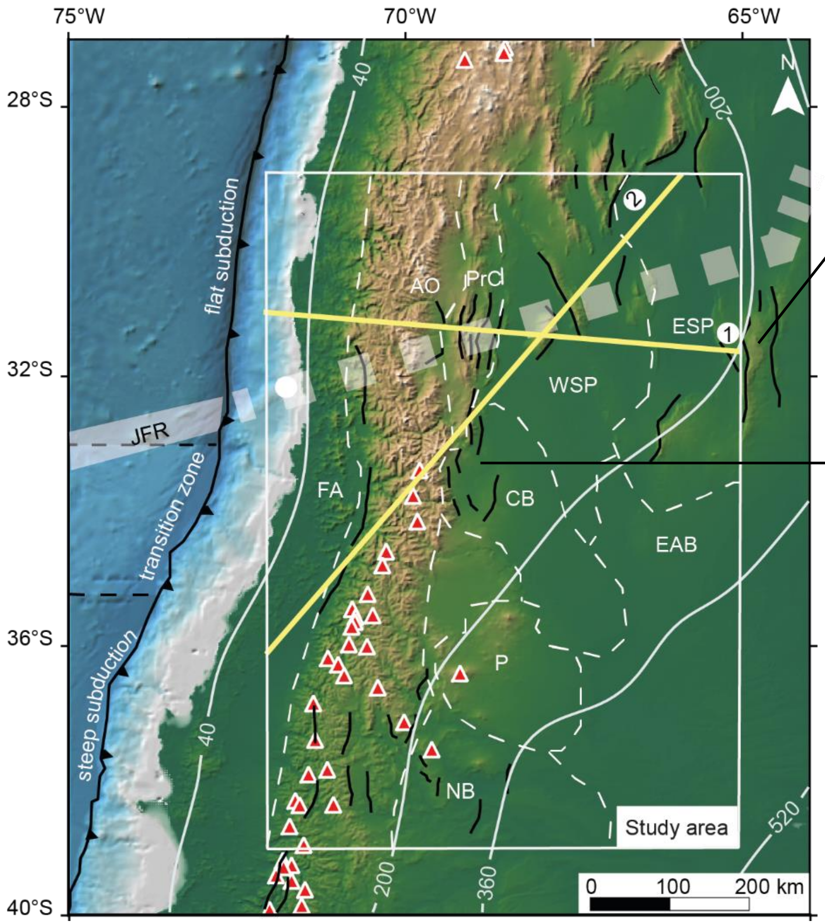
  (Rodriguez Piceda et al., 2022, Lithosphere)
- Assigned frictional and creep parameters – background strain rate

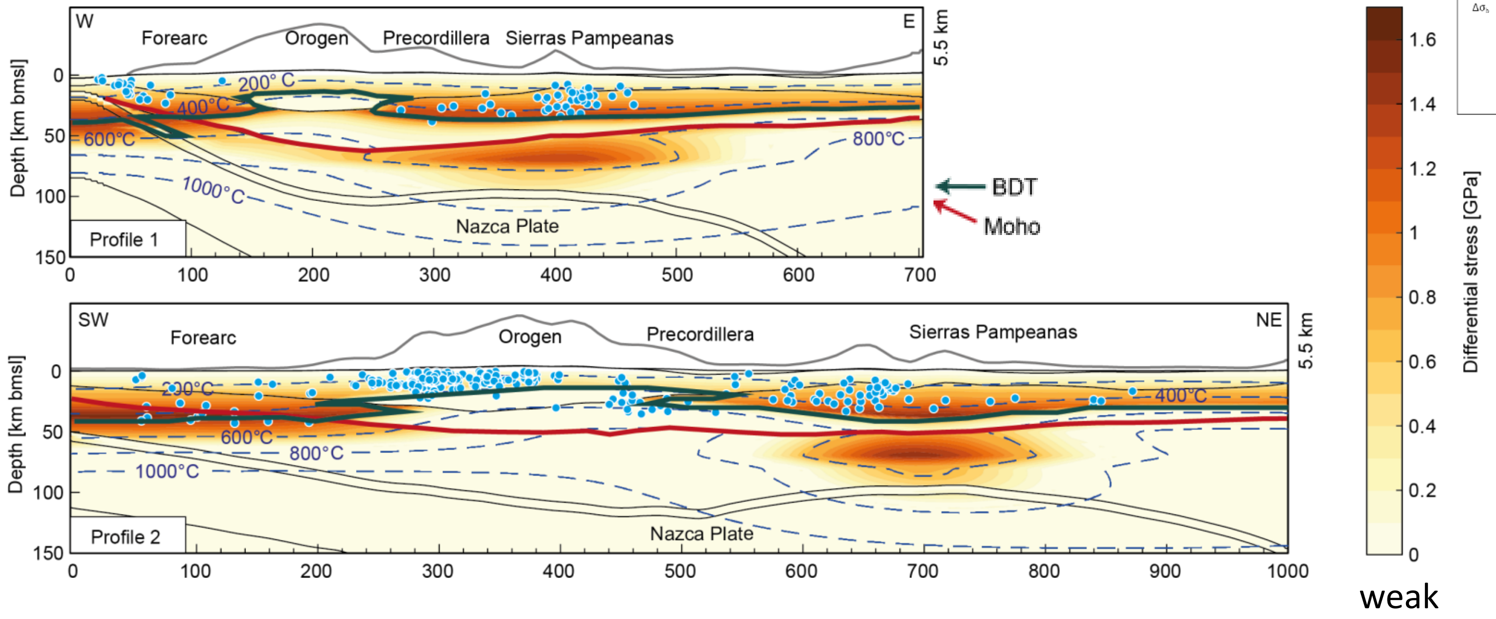
Rodriguez Piceda et al. (2022, Gcubed)

Continental plate seismicity

Lithospheric strength & continental plate seismicity



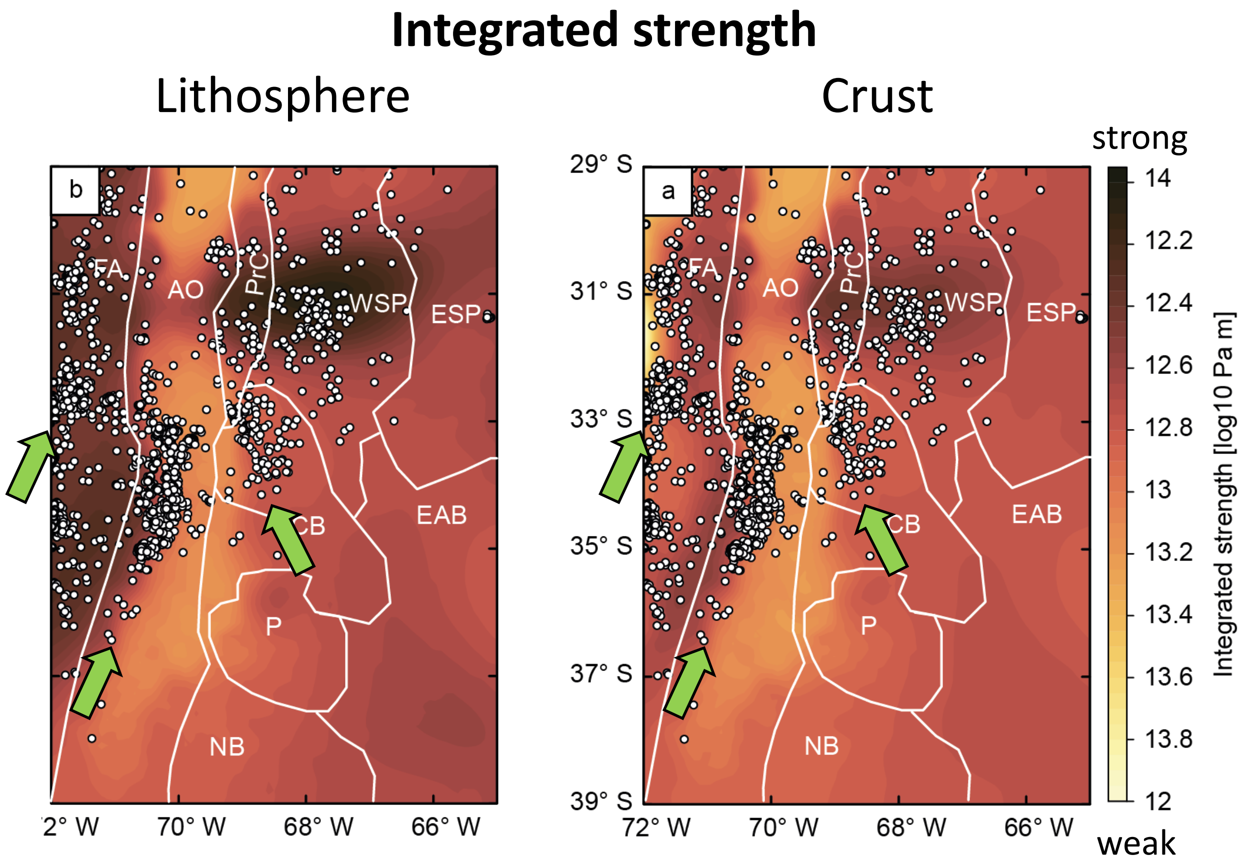




- Strength of the continental plate largely controlled by the thermal field which in turn mainly depends on the thickness of the upper radiogenic crust (thicker upper crust = warm and weak; thinner upper crust = cold and strong)
- Brittle-ductile transition bounds the depth extent of the seismogenic zone
- Deeper earthquakes in cold and strong domains
- Shallower earthquakes in warm and weak domains

Rodriguez Piceda et al. (2022, Gcubed)

Strength & continental plate seismicity



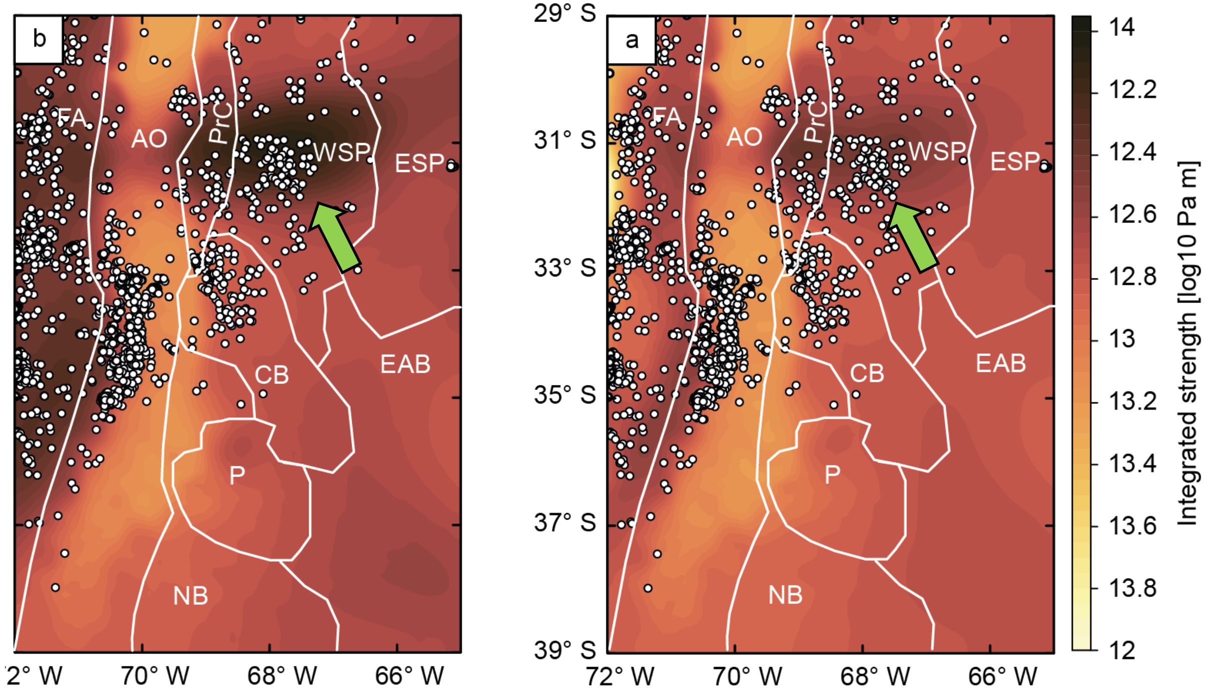
Rodriguez Piceda et al. (2022, Gcubed)

- Lateral strength contrast needed to localize seismicity
- Seismicity at the boundaries between strong and weak crustal domains
- **Sierras Pampeanas:** Seismicity within strong flat slab domain (yield strength > horizontal tectonic stresses)

Strength & continental plate seismicity

Integrated strength

Lithosphere   Crust

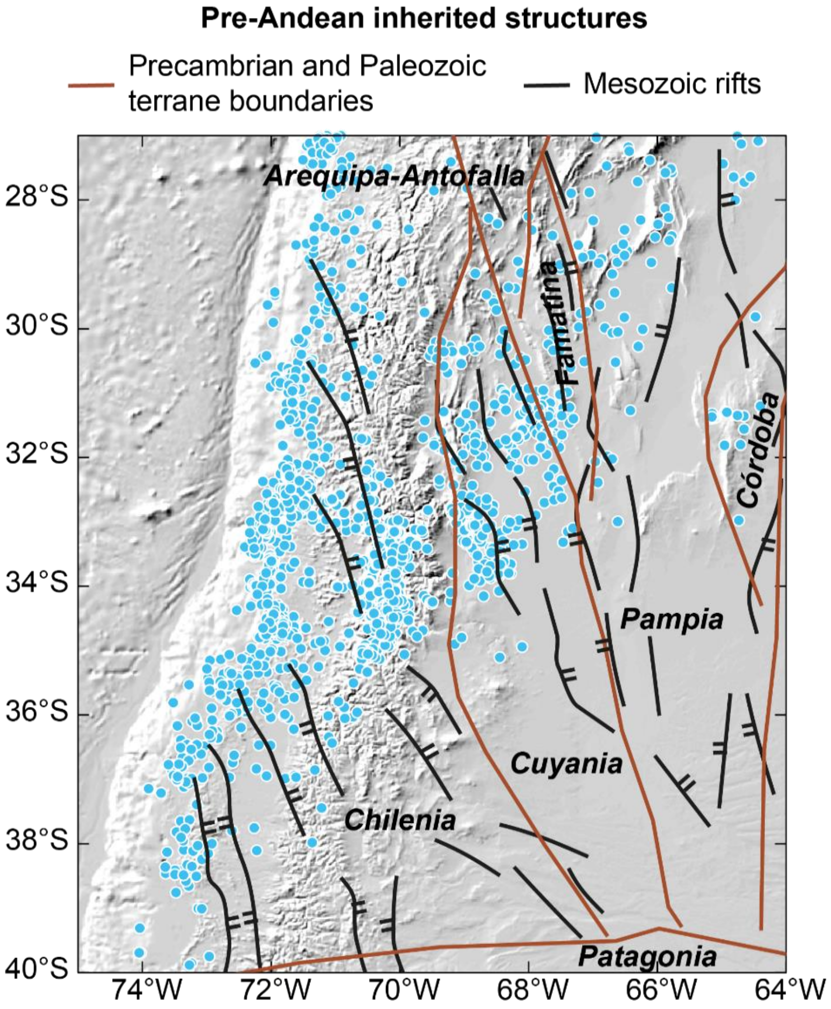


- Lateral strength contrast needed to localize seismicity
- Seismicity at the boundaries between strong and weak crustal domains
- **Sierras Pampeanas:** Seismicity within strong flat slab domain (yield strength > horizontal tectonic stresses)

Additional mechanisms to weaken the lithosphere in the Sierras Pampeanas ?

Rodriguez Piceda et al. (2022, Gcubed)

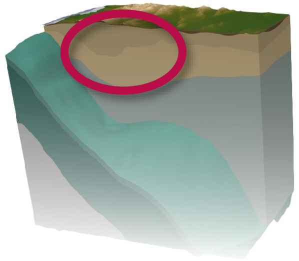
Continental plate seismicity

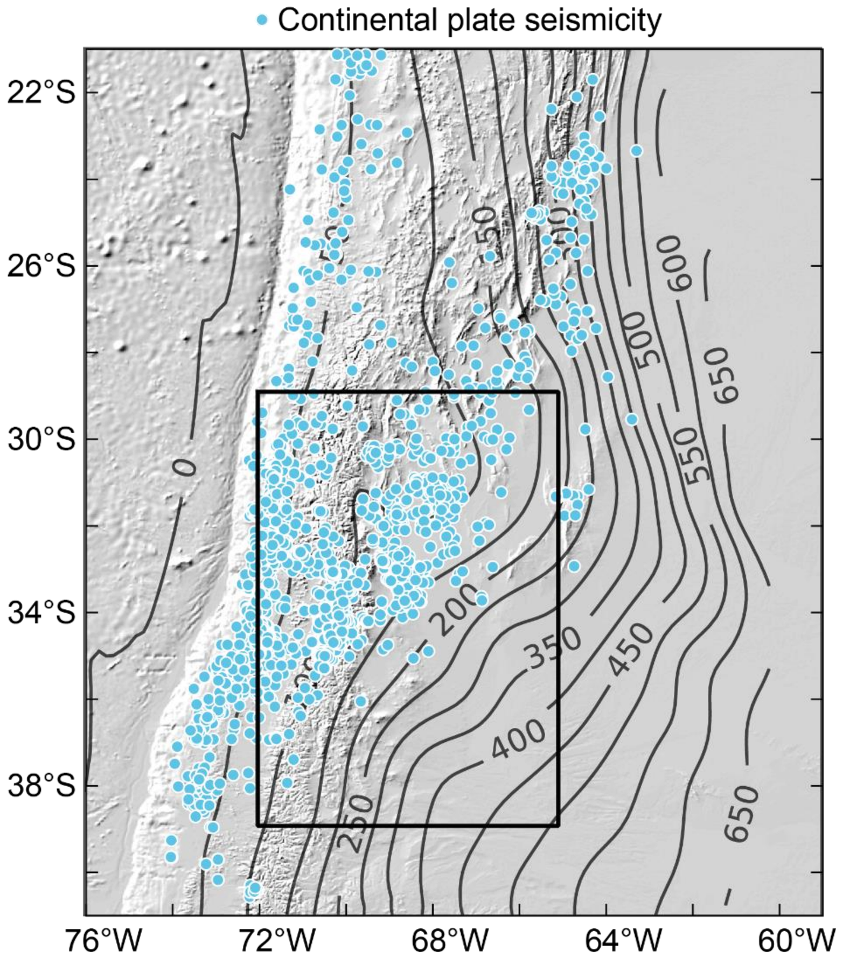


Modified Ramos (2009), Ramos et al. (2010), Wimpenny (2022)

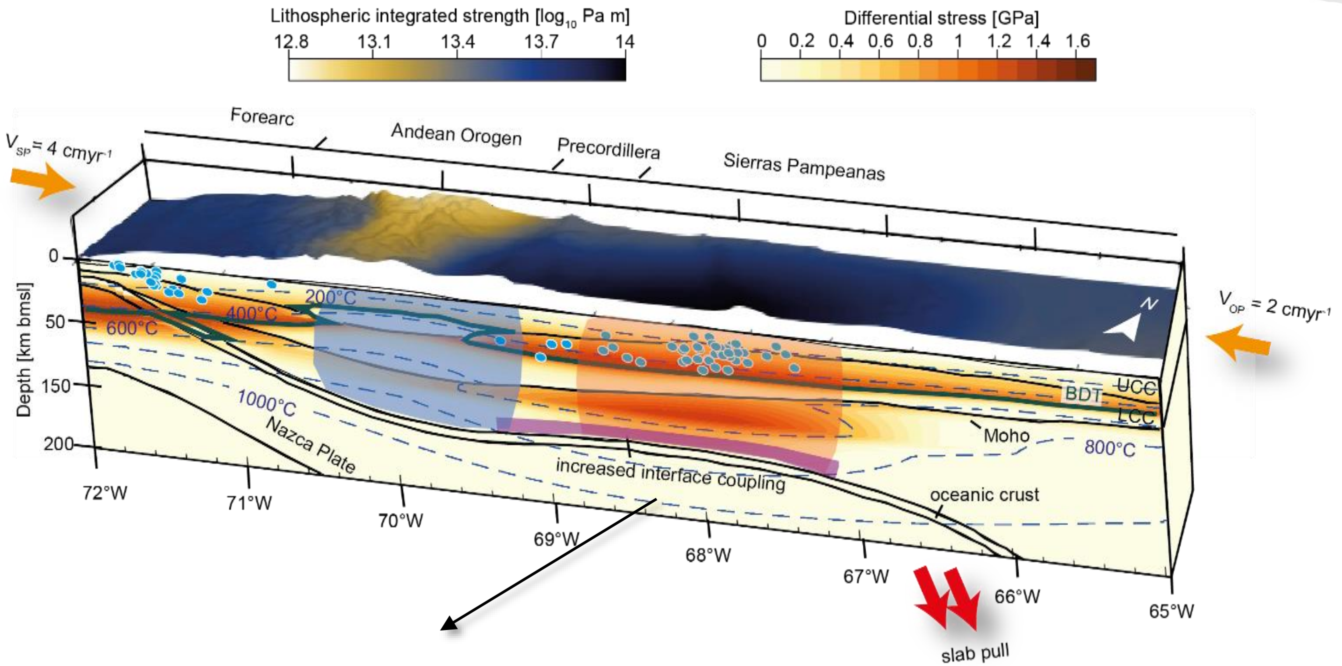
- 1st weakening mechanism: crustal-scale discontinuities (terrane sutures, Mesozoic rifts)
- However, not all inherited structures are seismically active

Continental plate seismicity in the Sierras Pampeanas





2nd weakening mechanism: oceanic slab



Slab steepening segment

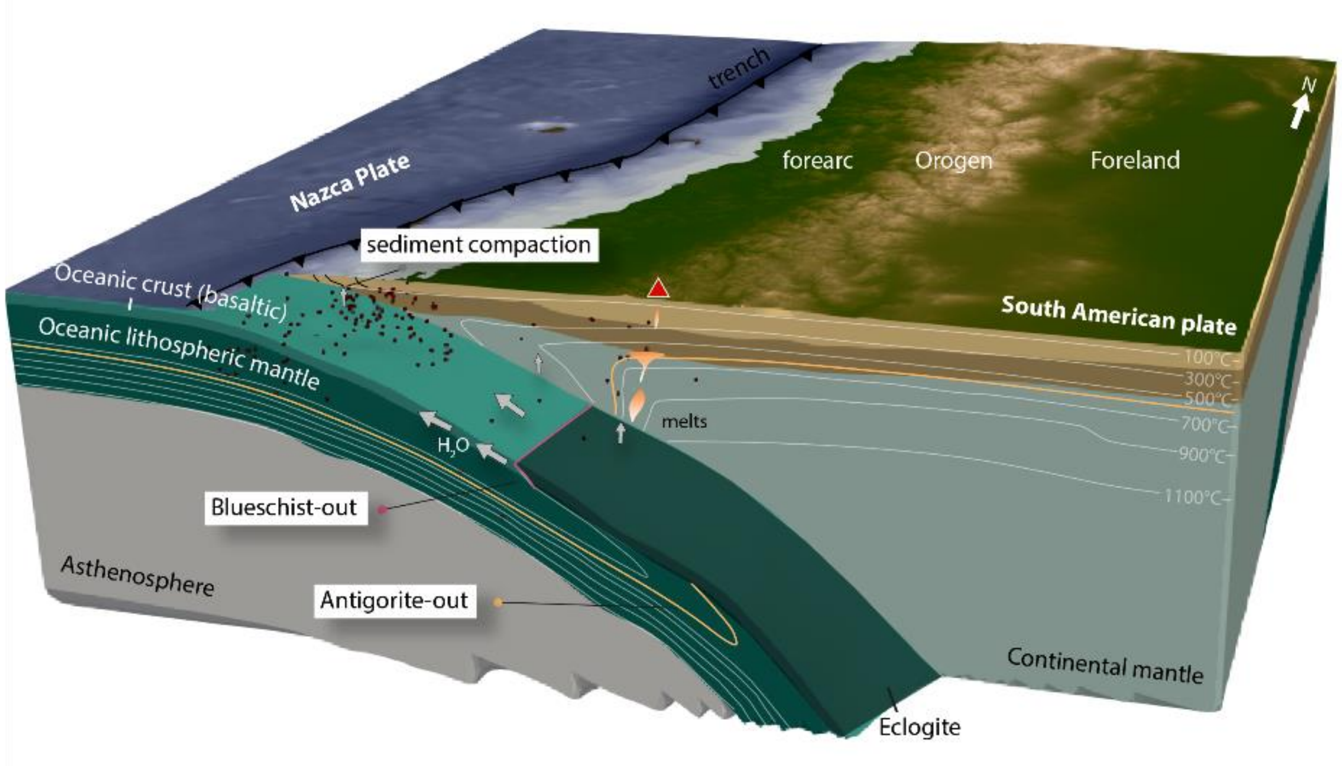
- Increased interplate coupling allows inland transmission of stresses
- Increased negative buoyancy when slab returns to steep subduction weakens continental plate

Higher seismicity rate

Rodriguez Piceda et al. (2022, Gcubed)

Oceanic plate seismicity

Oceanic plate seismicity and dehydration



Frictional weakening from release of fluids related to:

- Sediment consolidation (**interface**)

  Saffer & Marone (2003), Han et al. (2017), etc.

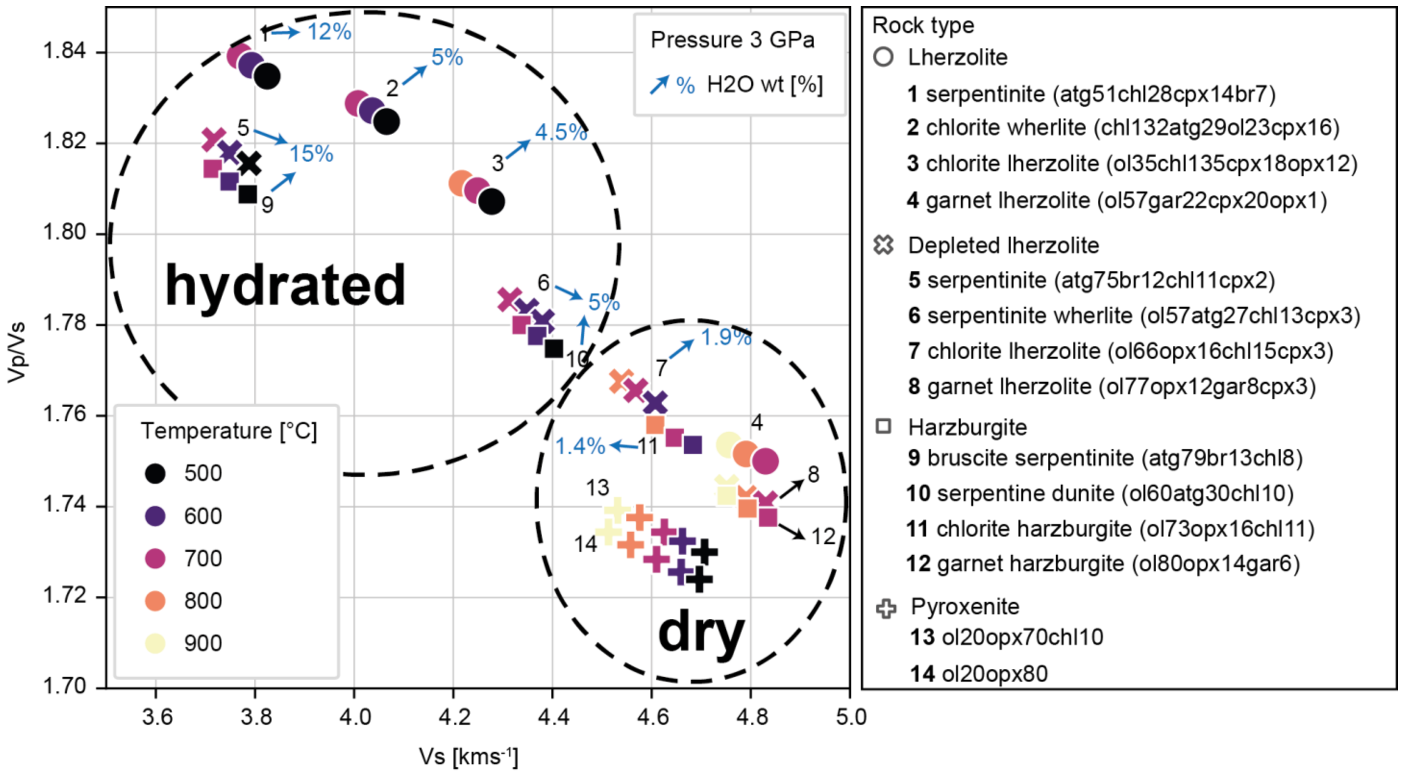
- Metamorphic reactions (**oceanic crust and mantle**)

  Kirby (1995), Peacock (2001), Ferrand et al. (2017), etc.

Affect state of hydration of slab and overriding plate mantle

Hydrated regions more seismically active than dry regions

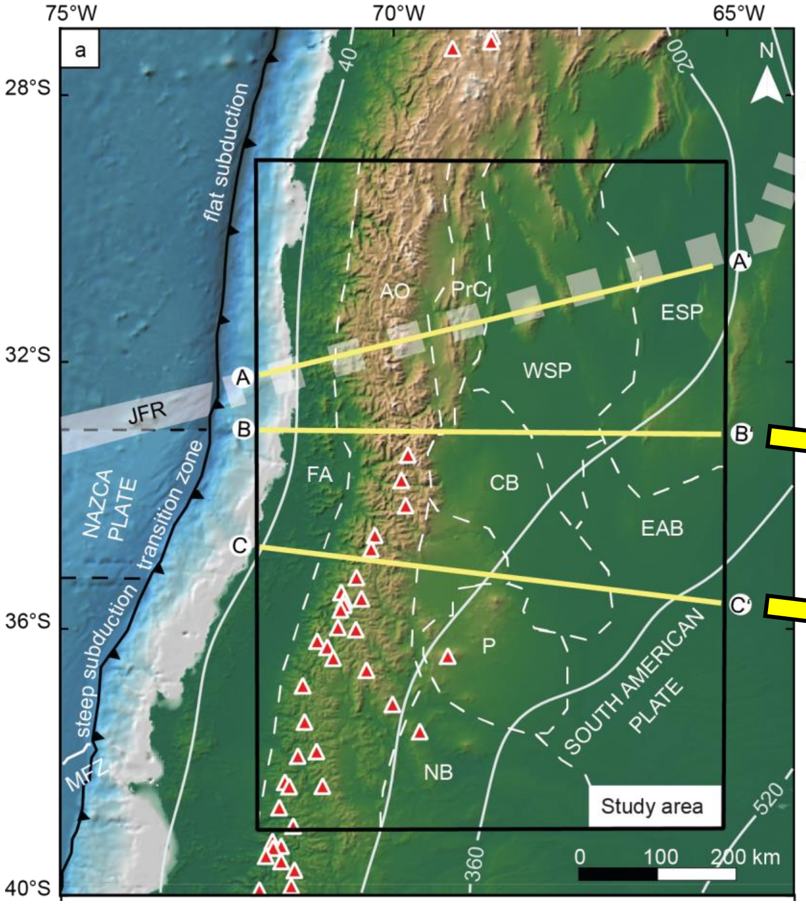
Oceanic plate seismicity and dehydration



Modified after Linkimer et al. (2020)

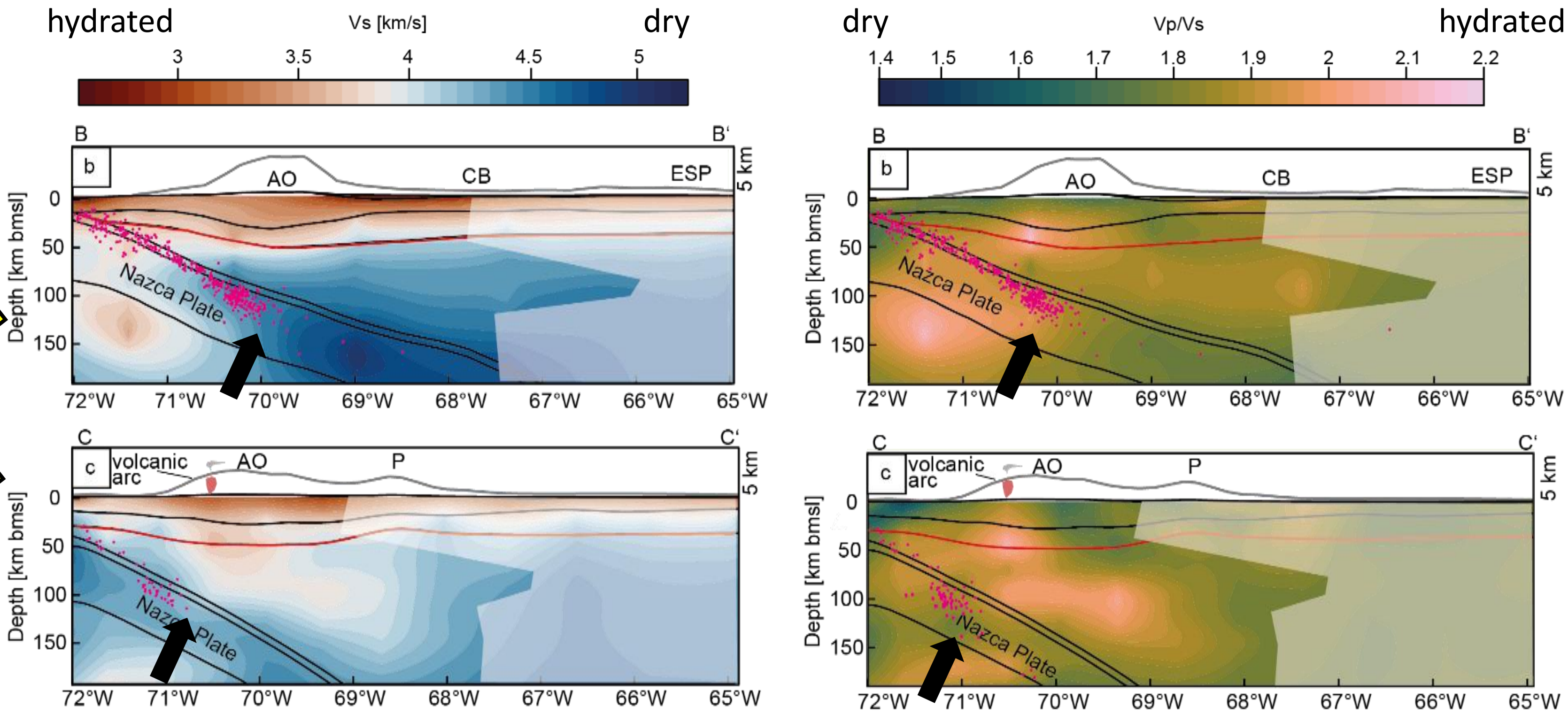
- Vp/Vs ratio and Vs as proxy for the state of hydration of the mantle
- Dry regions characterized by high Vs and low Vp/Vs
- Hydrated regions characterized by low Vs and high Vp/Vs

Oceanic plate seismicity and deshydration



Seismic tomography from Gao et al. (2021)

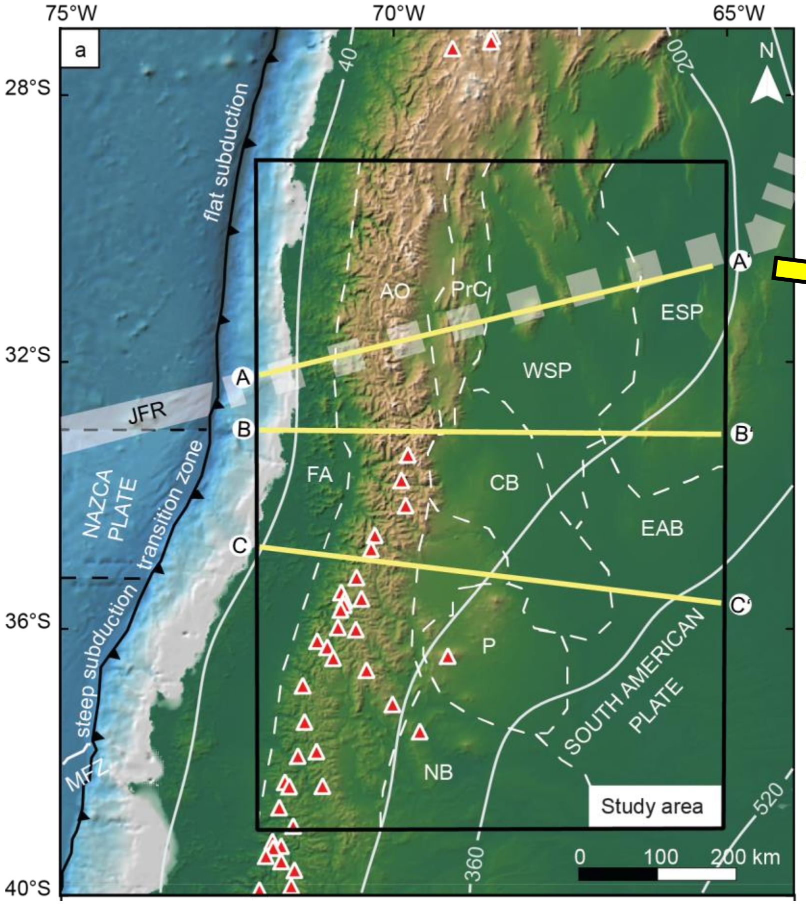
Transition zone and steep slab segments



Rodriguez Piceda et al. (under review, Nat. Commun. Earth Environ.)

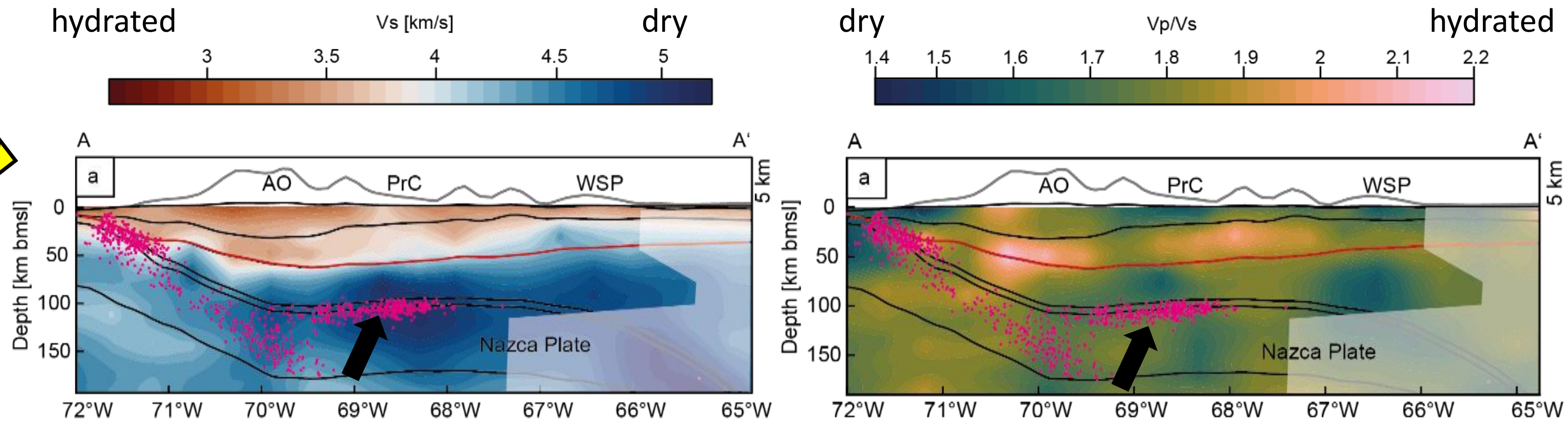
Seismicity within hydrated mantle (low Vs; high Vp/Vs) → **fluid mediated**

Oceanic plate seismicity and deshydration



Seismic tomography from Gao et al. (2021)

Flat slab segment

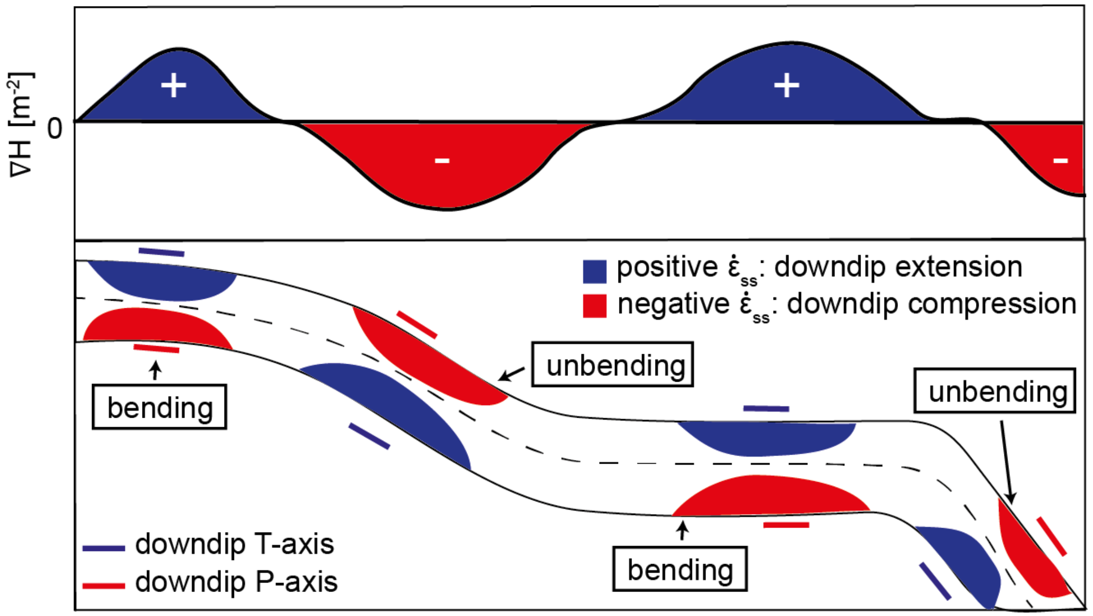


Rodriguez Piceda et al. (under review, Nat. Commun. Earth Environ.)

Seismicity within dry mantle (high Vs; low Vp/Vs) → **not fluid mediated**

Hypothesis: seismicity in the flat slab driven by flexural stresses

Oceanic plate seismicity and flexure



Modified after Sandiford et al. (2020)

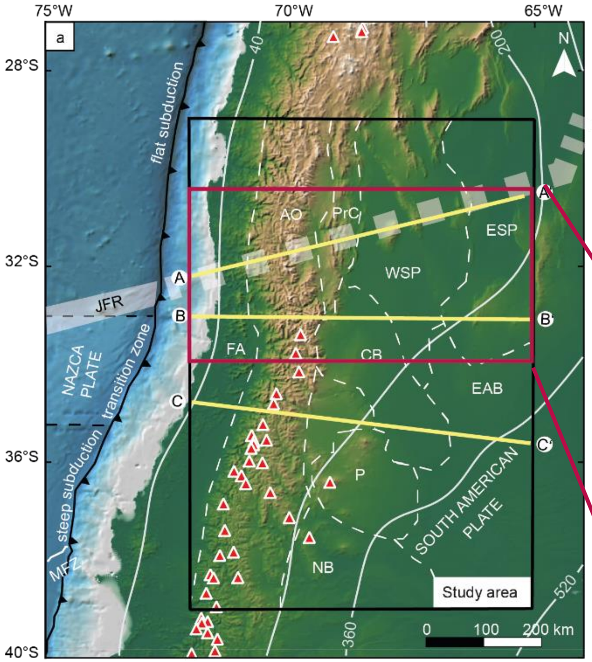
- Relationship between curvature gradient (∇H) and axis orientation of focal mechanisms

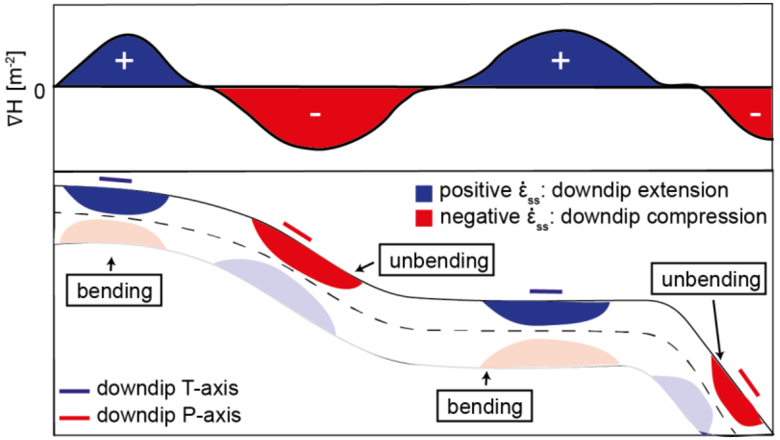
Engdahl and Scholz (1977), Isacks and Molnar (1971)

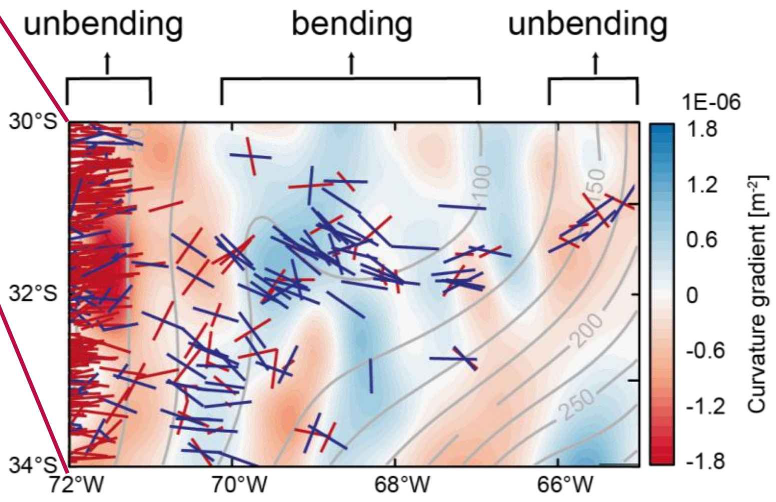
Top slab

- **Positive** curvature gradient: downdip **T-**axis
- **Negative** curvature gradient: downdip **P**-axis

Oceanic plate seismicity and flexure







GCMT catalog (Ekström et al., 2012)

- Correlation between orientation of principal axes of focal mechanisms and curvature gradient of the slab
- Slab seismicity in the flat slab segment driven by flexural stresses due to variations in dip angle

Rodriguez Piceda et al. (under review, Nat. Commun. Earth Environ.)

Conclusions

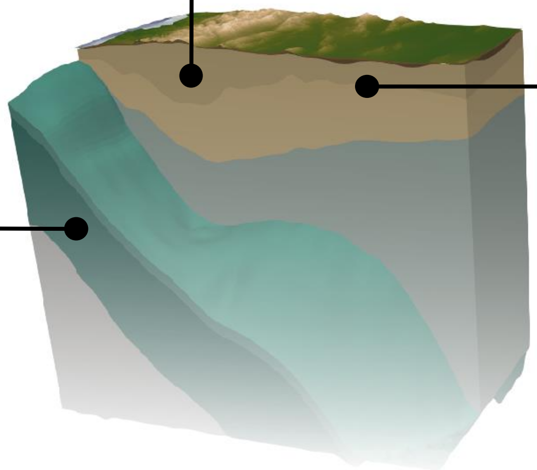
How do **continental-plate structural inheritance** and **oceanic-plate geometry** affect the localization of seismicity?

Continental plate seismicity

- By long-term strength variations related to the layer thickness (upper radiogenic crust)

Oceanic plate seismicity

- By deshydration of oceanic slab
- Flat slab: by internal flexural stresses



Sierras Pampeanas seismicity

- By shallow inherited faulting
- By propagating the deformation to the east and exherting additional forces related to steepening

References

Gao, Y., Yuan, X., Heit, B., Tilmann, F., van Herwaarden, D.-P., Thrastarson, S., et al. (2021). Impact of the Juan Fernandez Ridge on the Pampean Flat Subduction Inferred From Full Waveform Inversion. Geophysical Research Letters, 48(21), e2021GL095509. https://doi.org/10.1029/2021GL095509

Han, S., Bangs, N. L., Carbotte, S. M., Saffer, D. M., & Gibson, J. C. (2017). Links between sediment consolidation and Cascadia megathrust slip behaviour. Nature Geoscience, 10(12), 954–959. https://doi.org/10.1038/s41561-017-0007-2

International Seismological Centre. (2021). On-line Bulletin. Retrieved from https://doi.org/10.31905/D808B830

International Seismological Centre. (2022). ISC-EHB dataset. Retrieved from https://doi.org/10.31905/PY08W6S3

Kirby, S. (1995). Interslab earthquakes and phase changes in subducting lithosphere. Reviews of Geophysics, 33(S1), 287–297. https://doi.org/10.1029/95RG00353

Linkimer, L., Beck, S., Zandt, G., Alvarado, P., Anderson, M., Gilbert, H., & Zhang, H. (2020). Lithospheric structure of the Pampean flat slab region from double-difference tomography. Journal of South American Earth Sciences, 97, 102417. https://doi.org/10.1016/j.jsames.2019.102417

Peacock, S. M. (2001). Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle? Geology, 29(4), 299–302. https://doi.org/10.1130/0091-7613(2001)029<0299:ATLPOD>2.0.CO;2

Ramos, Víctor A. (2009). Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. In S. M. Kay, V. A. Ramos, & W. R. Dickinson (Eds.), Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision (Vol. 204, p. 0). Geological Society of America. https://doi.org/10.1130/2009.1204(02)

Ramos, Victor A. (2010). The tectonic regime along the Andes: Present-day and Mesozoic regimes. Geological Journal, 45(1), 2–25. https://doi.org/10.1002/GJ.1193

Rodriguez Piceda, C., Scheck-Wenderoth, M., Bott, J., Gomez Dacal, M. L., Cacace, M., Pons, M., et al. (2022). Controls of the Lithospheric Thermal Field of an Ocean-Continent Subduction Zone: The Southern Central Andes. Lithosphere, 2022(1), 2237272. https://doi.org/10.2113/2022/2237272

Rodriguez Piceda, C., Scheck-Wenderoth, M., Cacace, M., Bott, J., & Strecker, M. R. (2022). Long-Term Lithospheric Strength and Upper-Plate Seismicity in the Southern Central Andes, 29°–39°S. Geochemistry, Geophysics, Geosystems, 23(3), 22. https://doi.org/10.1029/2021GC010171

Rodriguez Piceda, Constanza, Scheck Wenderoth, M., Gomez Dacal, M. L., Bott, J., Prezzi, C. B., & Strecker, M. R. (2021). Lithospheric density structure of the southern Central Andes constrained by 3D data-integrative gravity modelling. International Journal of Earth Sciences, 110(7), 2333–2359. https://doi.org/10.1007/s00531-020-01962-1

Saffer, D. M., & Marone, C. (2003). Comparison of smectite- and illite-rich gouge frictional properties: application to the updip limit of the seismogenic zone along subduction megathrusts. Earth and Planetary Science Letters, 215(1), 219–235. https://doi.org/10.1016/S0012-821X(03)00424-2

Sandiford, D., Moresi, L. M., Sandiford, M., Farrington, R., & Yang, T. (2020). The Fingerprints of Flexure in Slab Seismicity. Tectonics, 39(8). https://doi.org/10.1029/2019TC005894

Scholz, C. H. (2002). The Mechanics of Earthquakes and Faulting. The Mechanics of Earthquakes and Faulting. https://doi.org/10.1017/CBO9780511818516

Sibson, R. H. (1982). Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States. Bulletin of the Seismological Society of America, 72(1), 151–163. https://doi.org/10.1785/BSSA0720010151

Wimpenny, S. (2022). Weak, Seismogenic Faults Inherited From Mesozoic Rifts Control Mountain Building in the Andean Foreland. Geochemistry, Geophysics, Geosystems, 23(3), e2021GC010270. https://doi.org/10.1029/2021GC010270