On How Lithosphere and Mantle Dynamics affect Shallow Earthquakes

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Presentation objectives

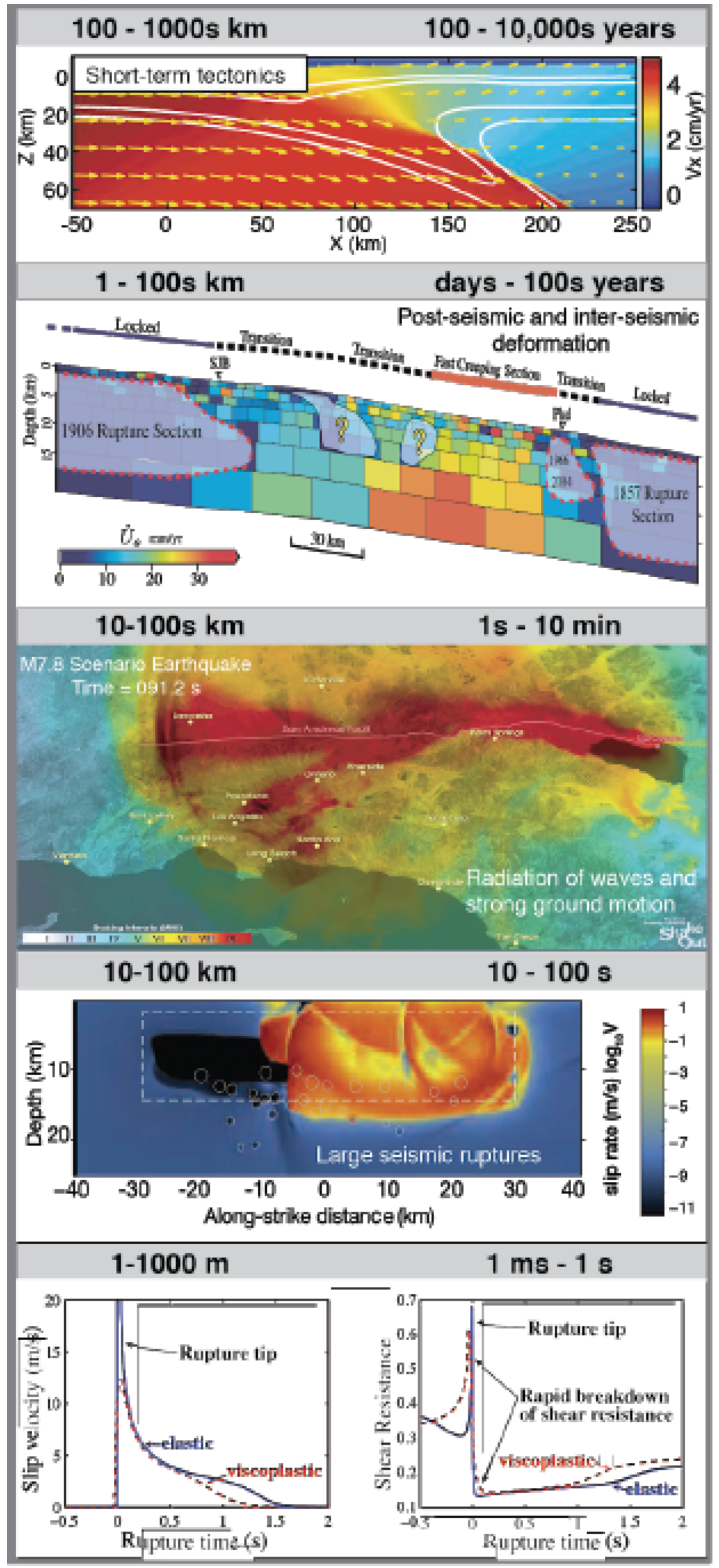
» **Illustrate how lithosphere- and mantle dynamics, structure and rheology can influence shallow tectonics and seismicity**

- Does incoming sediment thickness increase maximum earthquake magnitude?
  - Yes; larger sedimentary wedge → trench moves seaward and slab unbends → slab dip ↓ → seismogenic width ↑ → Mmax ↑
  - Modeling long-term dynamics and sediment presence increases Mmax by an order of magnitude !

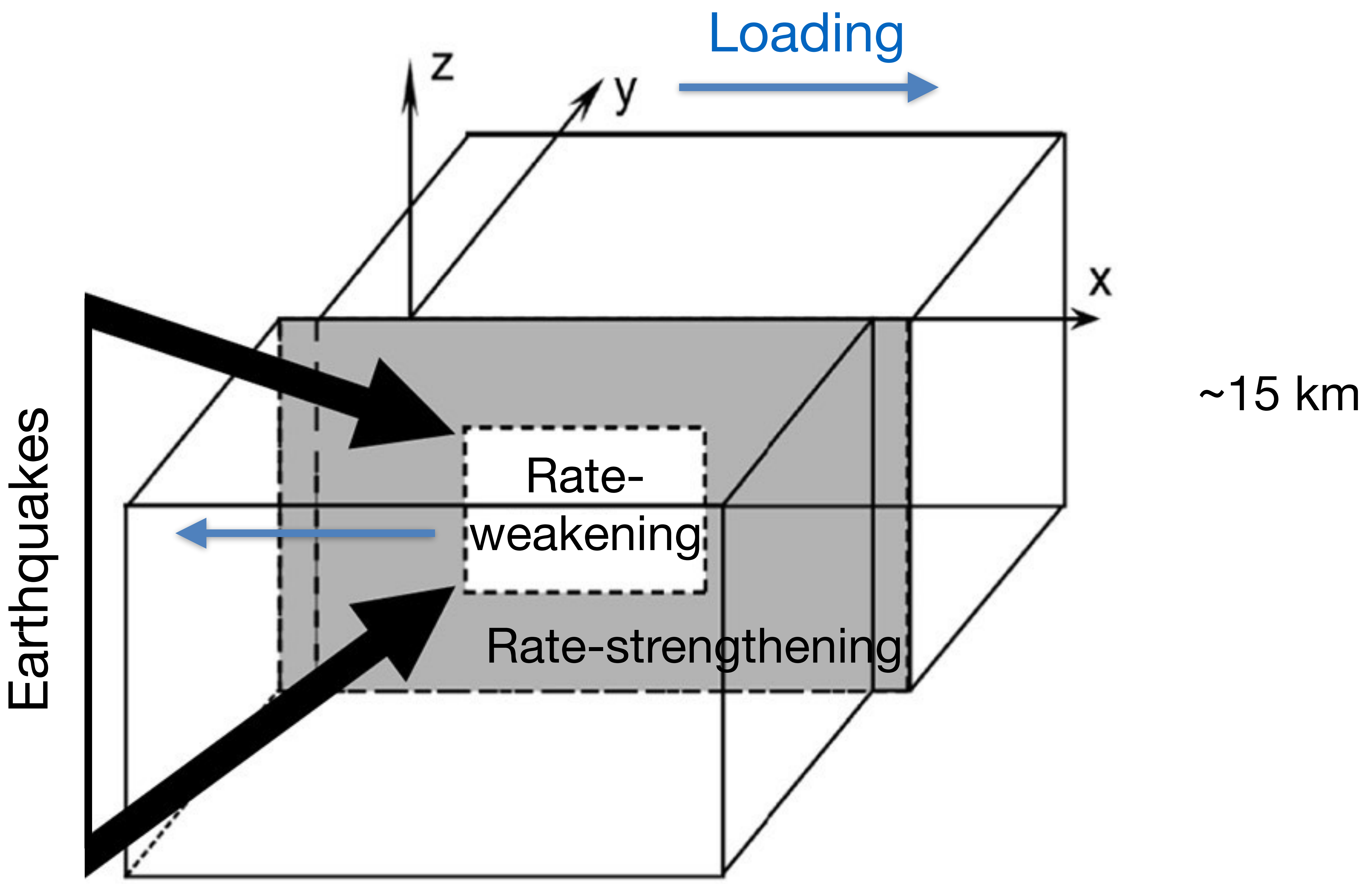
- Do lower crustal and mantle depth temperature and rheology affect seismicity and tectonics?
  - Yes, e.g., in tectonic settings driven by complex loading, such as Northern Apennines

- Does the mantle affect surface displacements at time scales of minutes to days?
  - Yes, STM models predicted a secondary zone of “coseismic” uplift, which was confirmed by observations of 4 out of 4 great megathrust earthquake
  - Accelerated slab penetration causes upward return “flow”

- Most for simplicity ignore what happens below upper crust. For what settings does that hold?



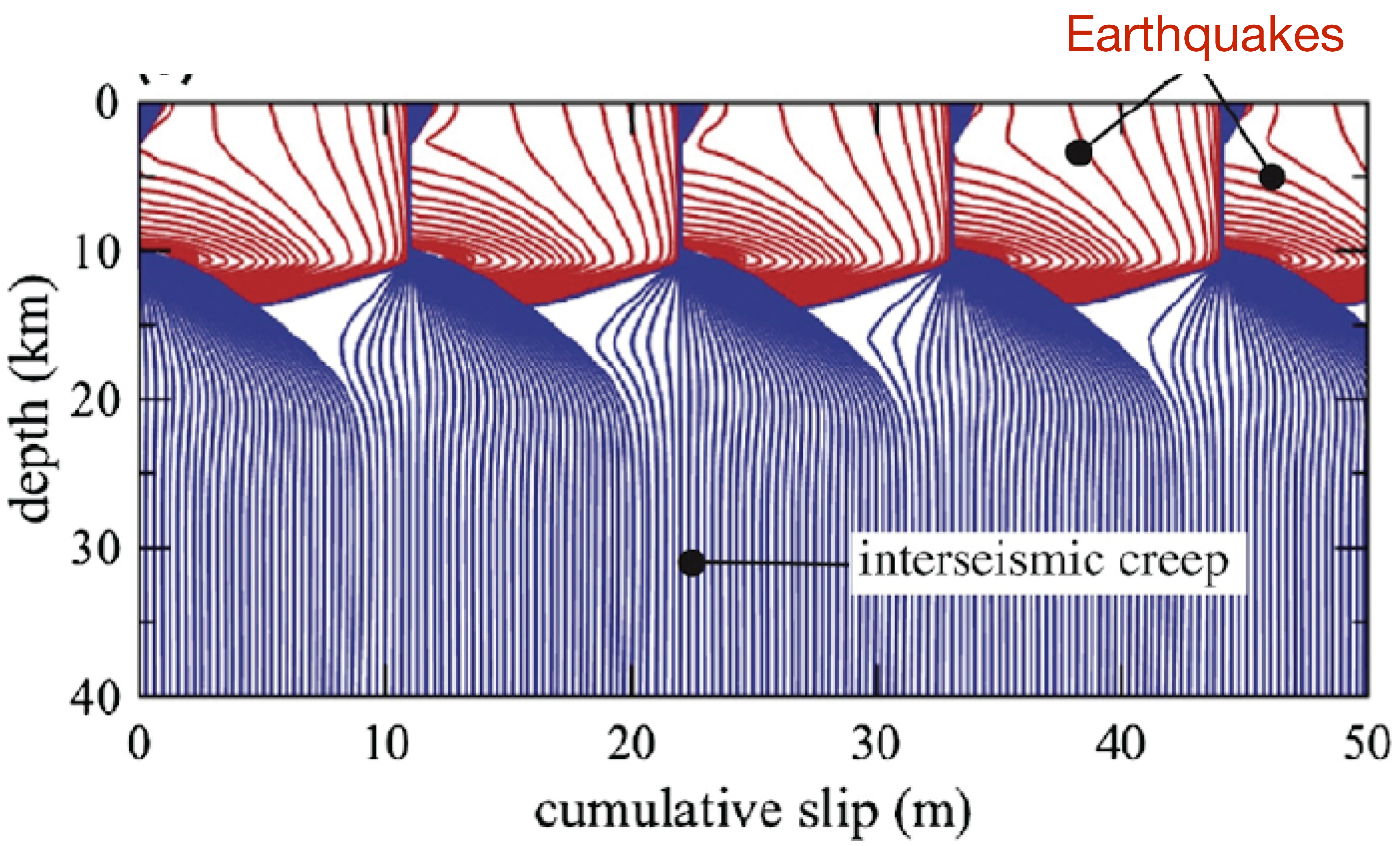
Lapusta et al., NSF, 2019

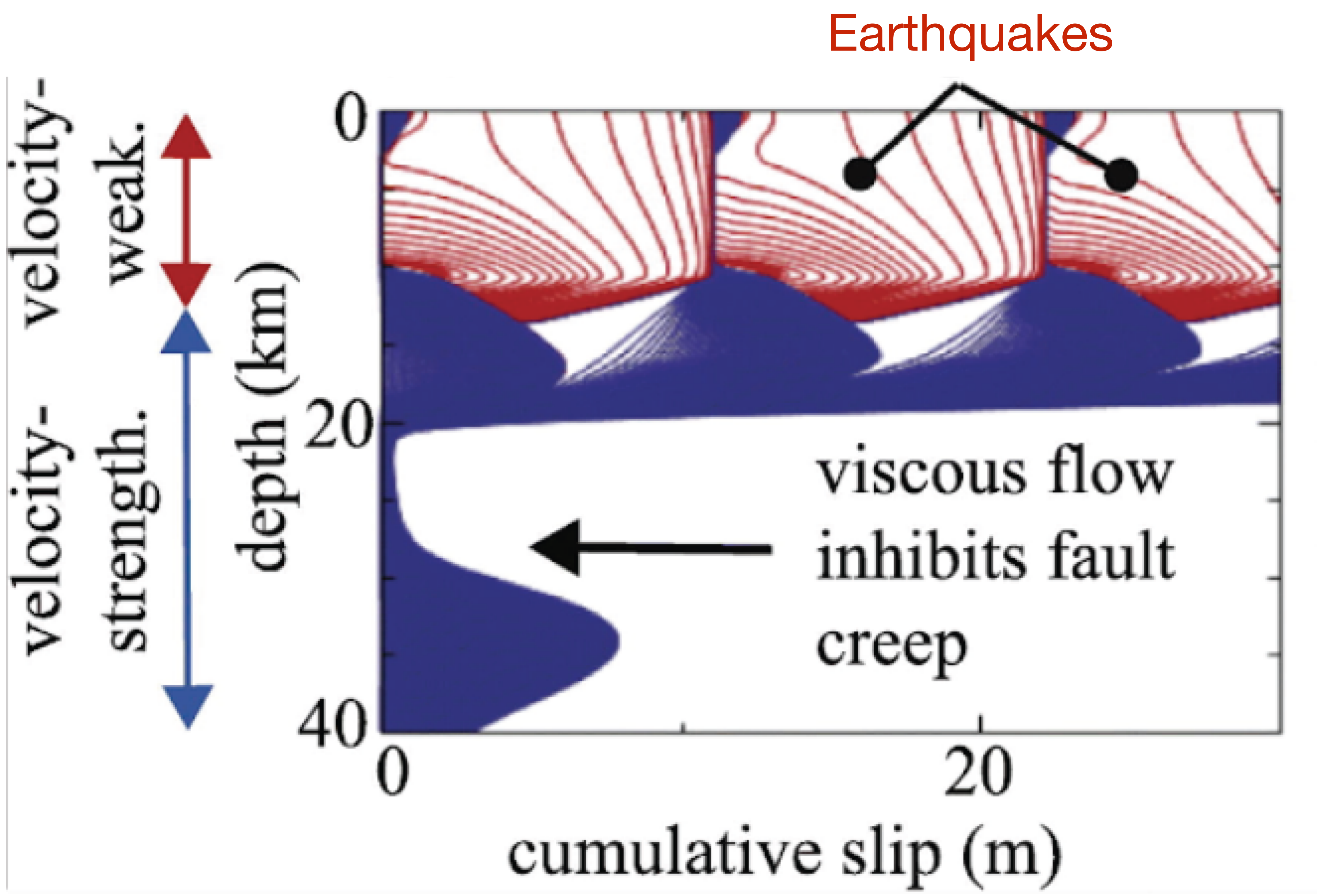


E.g., Schaal & Lapusta, JGR, 2019

» Maybe not for orogens, subduction zones, mid ocean ridges, and likely also not really in strike-slip faults…

- First implementation of a powerlaw viscous rheology *(Allison and Dunham, 2018)*:



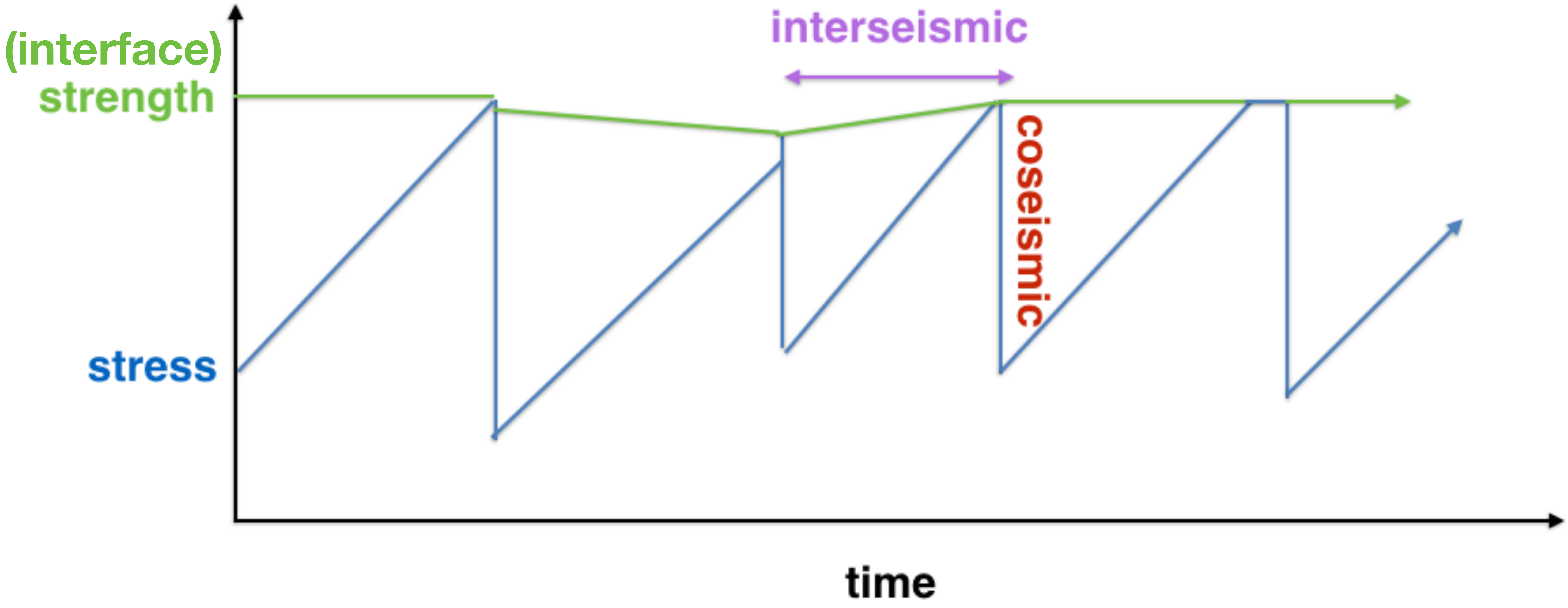


- Challenges next decade (Lapusta, Dunham, Avouac, Denolle, van Dinther, Faulkner Fialko, Katijama et al., NSF, 2019):
  - **Fluids, inelasticity, structural complexity lithosphere, shear heating, chemical reactions, thermomechanical coupling**

» We can join forces!

- Earthquakes occur when fault stress exceed its strength

» **Stress and strength thus regulate earthquake nucleation, propagation and arrest**



What affects (a)seismic slip?

rheology

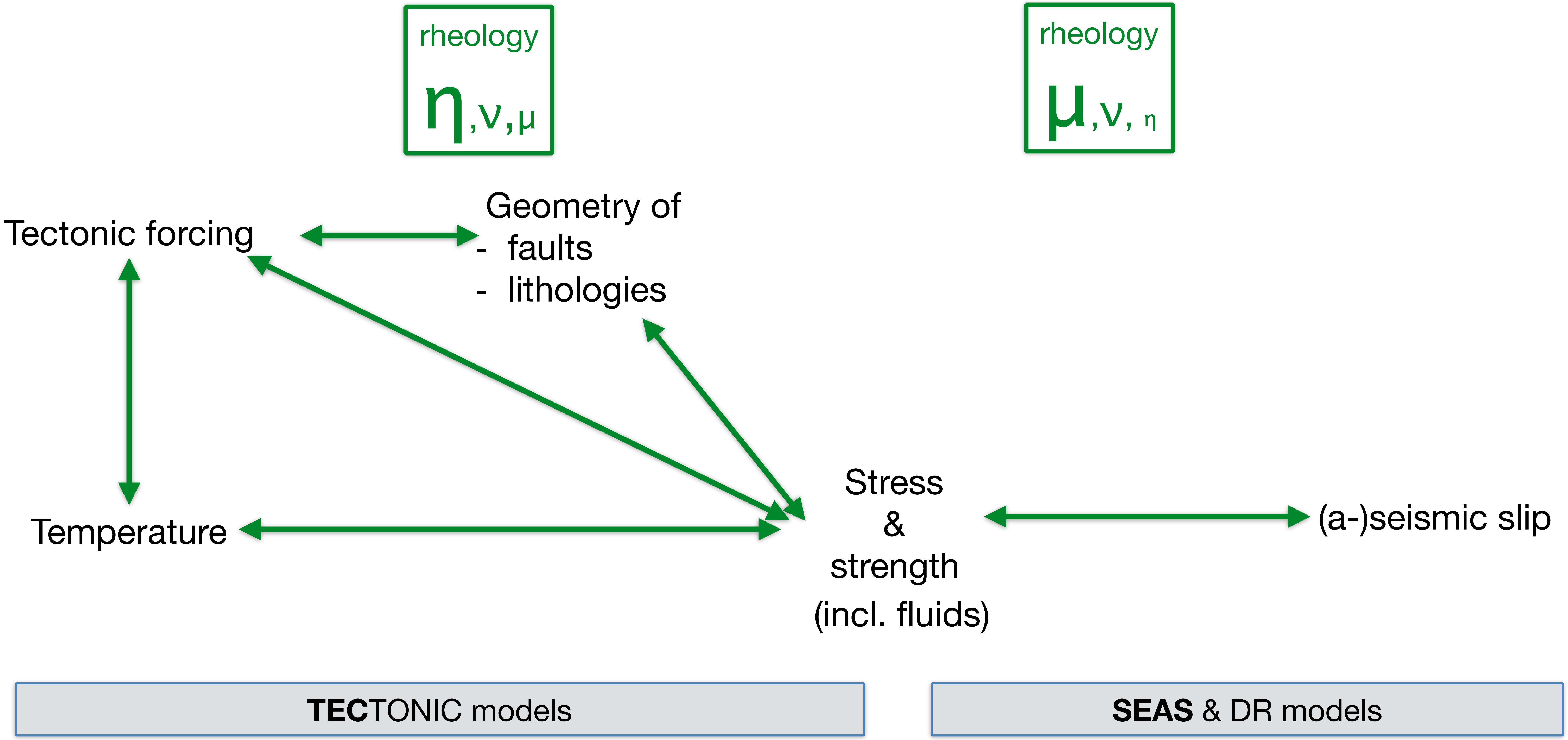
μ, ν, η

Stress & strength ⟷ (a-)seismic slip

SEAS & DR models

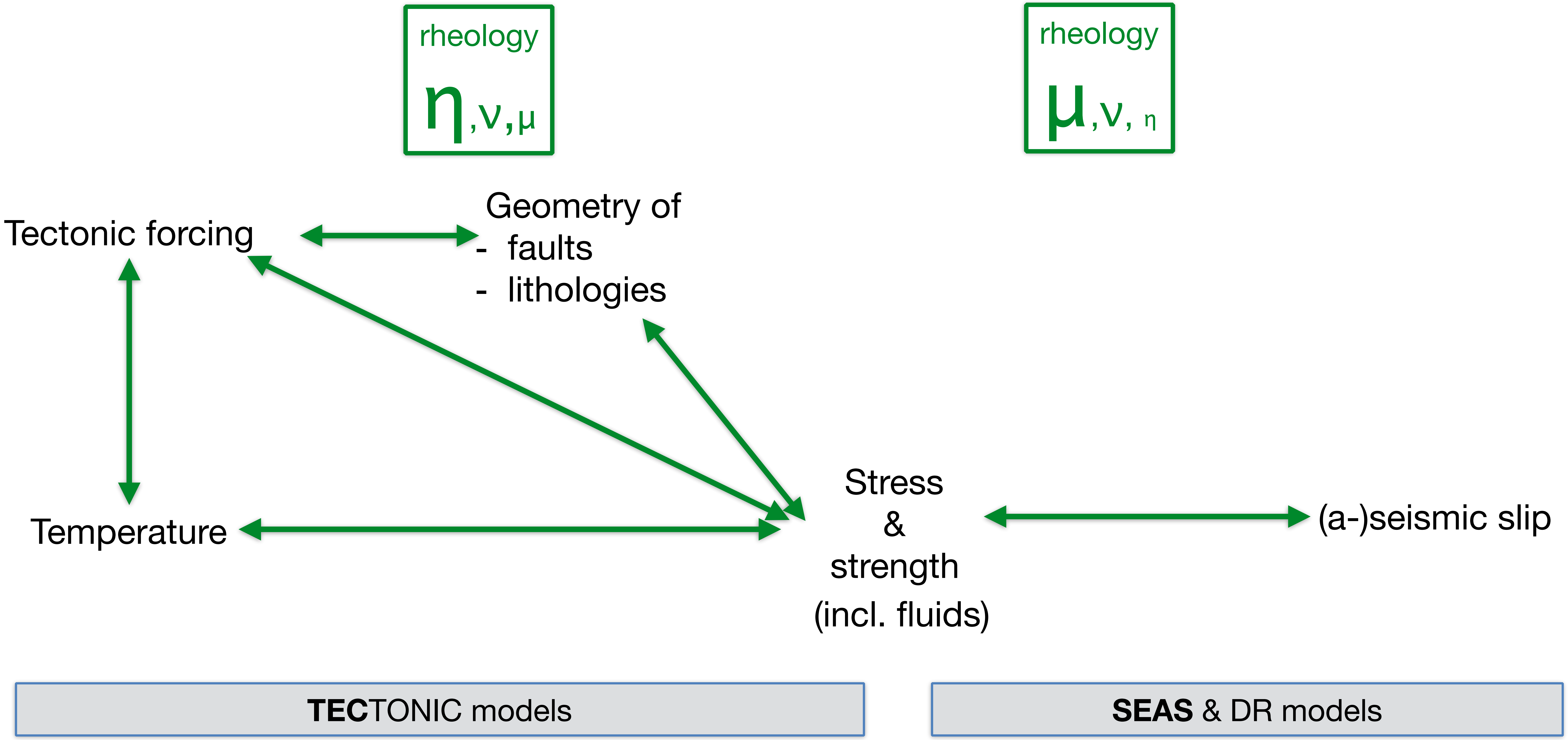
SEAS = sequences of SEismic and Aseismic Slip
aka "seismic cycle"
DR = Dynamic earthquake Rupture

What affects (a)seismic slip?



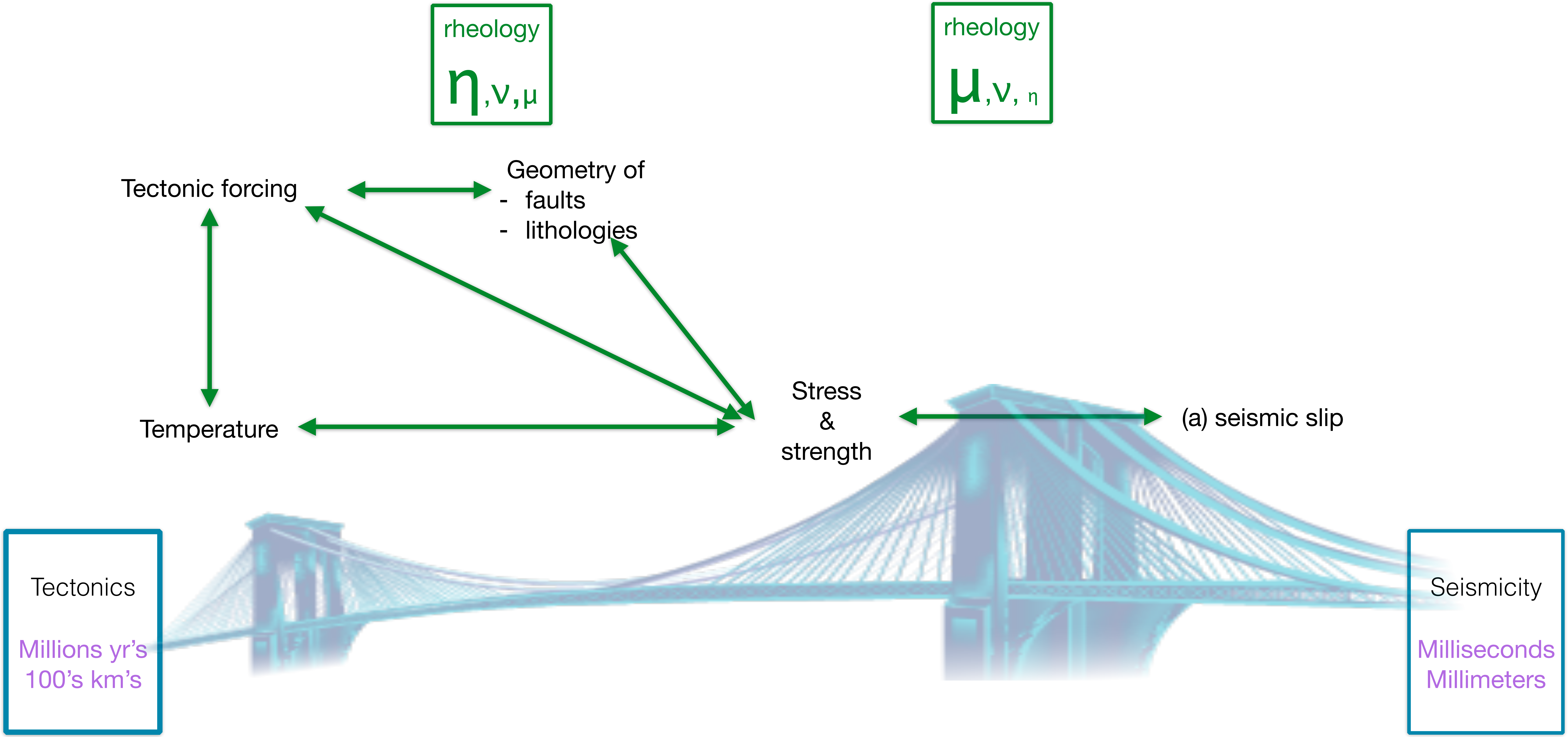
SEAS = sequences of SEismic and Aseismic Slip
aka “seismic cycle”
DR = Dynamic earthquake Rupture

Complex interaction of processes controlling (a)seismic slip

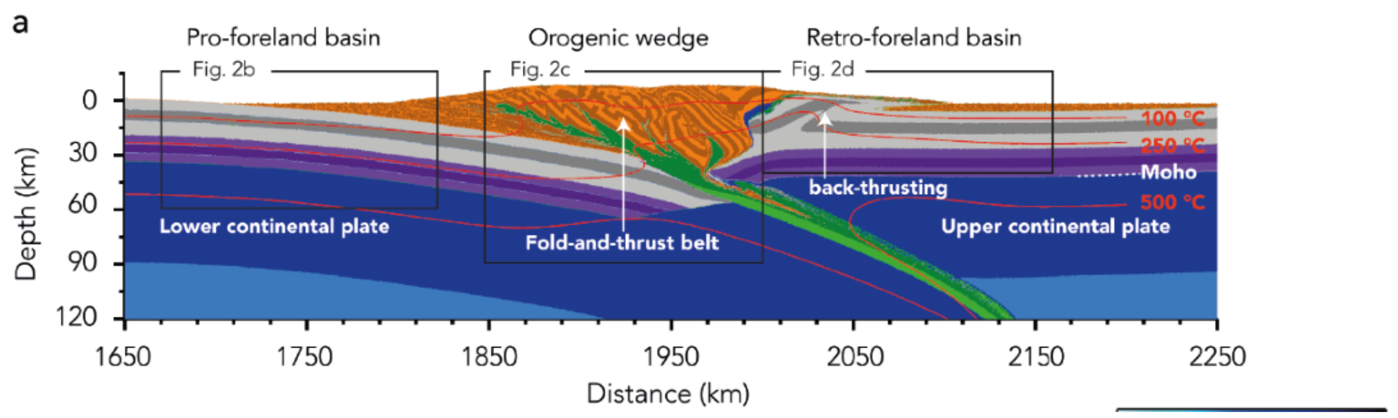


- Both feedback networks have important role for rheology, where material properties are a function of stress, temperature, fluids,…
- Complex, non-linear interactions require spontaneous simulation on both processes on both ranges of time-scales

Bridging time scales from tectonics to dynamic rupture



Bridging time scales from tectonics to dynamic earthquake rupture



Geodynamic evolution

Δt = 1000 years

Tectonics

Millions yr's
100's km's

Seismicity

Milliseconds
Millimeters

van Dinther et al., JGR, 2014b; Dal Zilio et al., EPSL, 2018

Thermo-Mechanical models (TM)

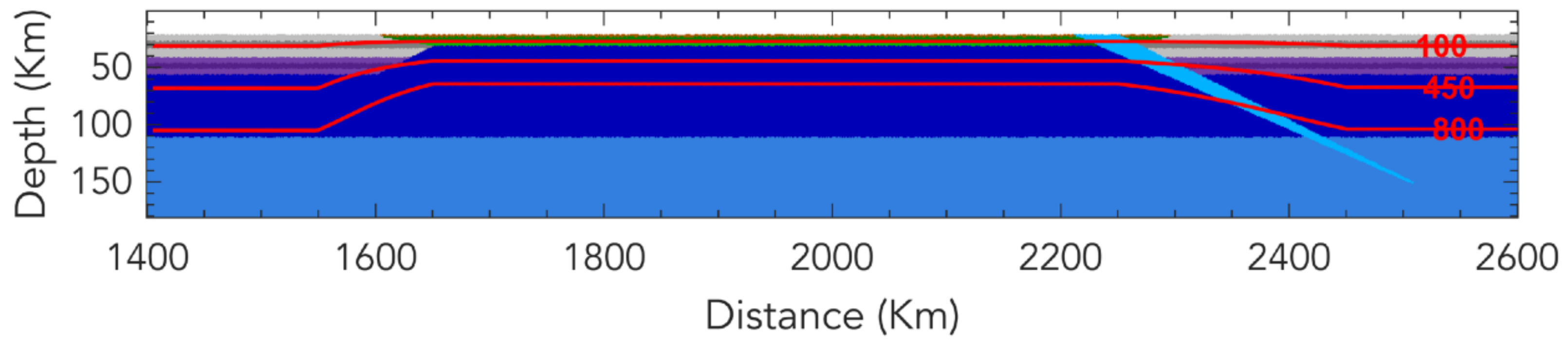
- Based on 2D finite-difference with marker-in-cell code

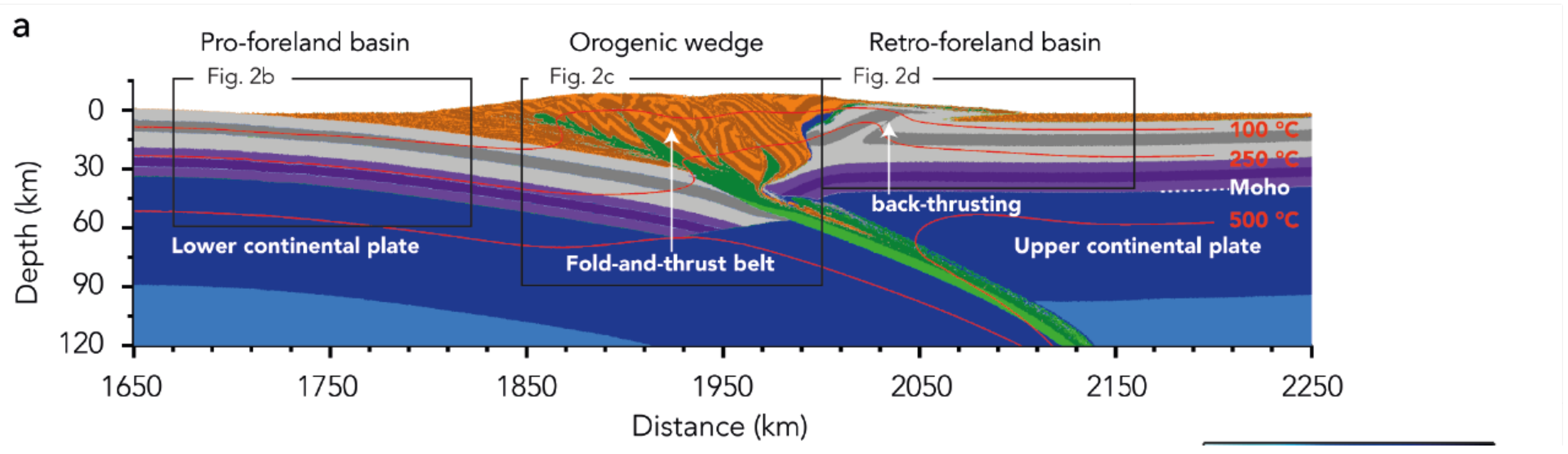
- **Input**
- Initial geometry and temperature
- Tectonic parameters
- Material parameters rock types

- **Tectonic output**
- Geometry
- Distribution physical parameters
  - Viscosity, temperature, stress, fluid pressure

Conservation of mass, momentum and energy

Visco-elasto-plastic rheology





Gerya & Yuen, PEPI, 2007

Seismo-Thermo-Mechanical models (STM)

- Based on 2D finite-difference with marker-in-cell code

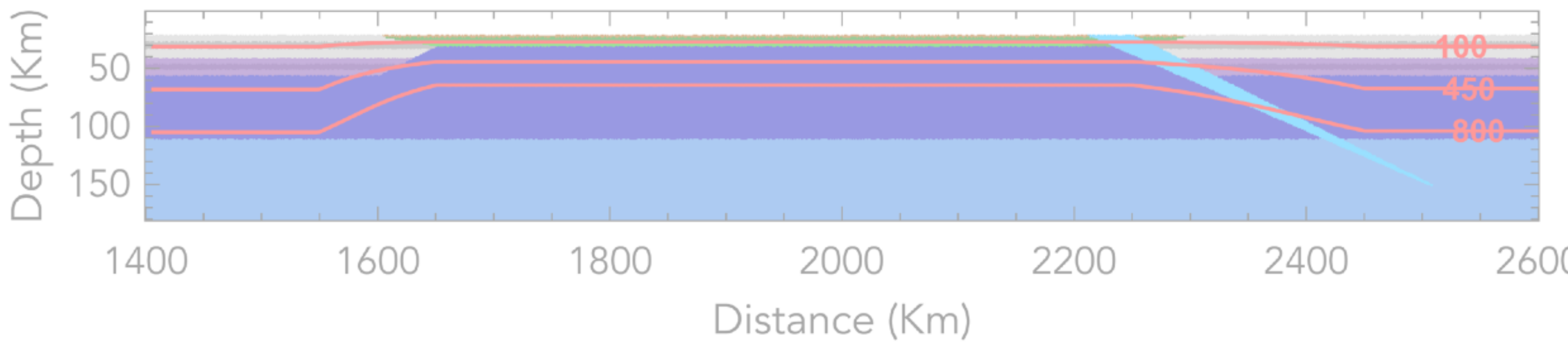
- **Input**
- Initial geometry and temperature
- Tectonic parameters
- Material parameters rock types

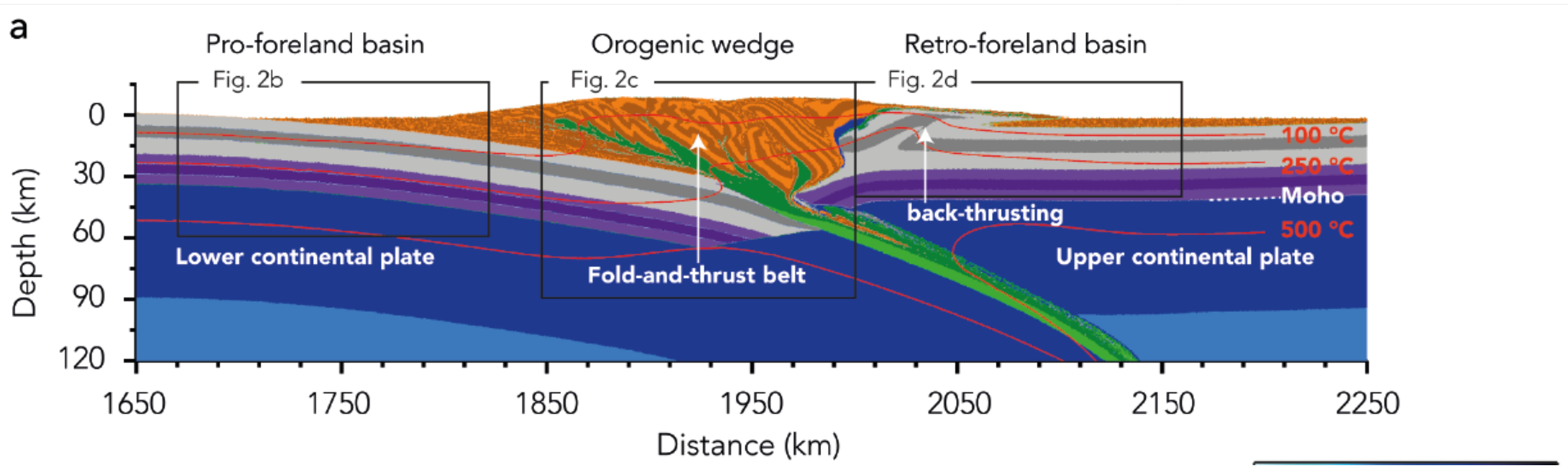
- **Tectonic output**
- Geometry
- Distribution physical parameters
  - Viscosity, temperature, stress, fluid pressure

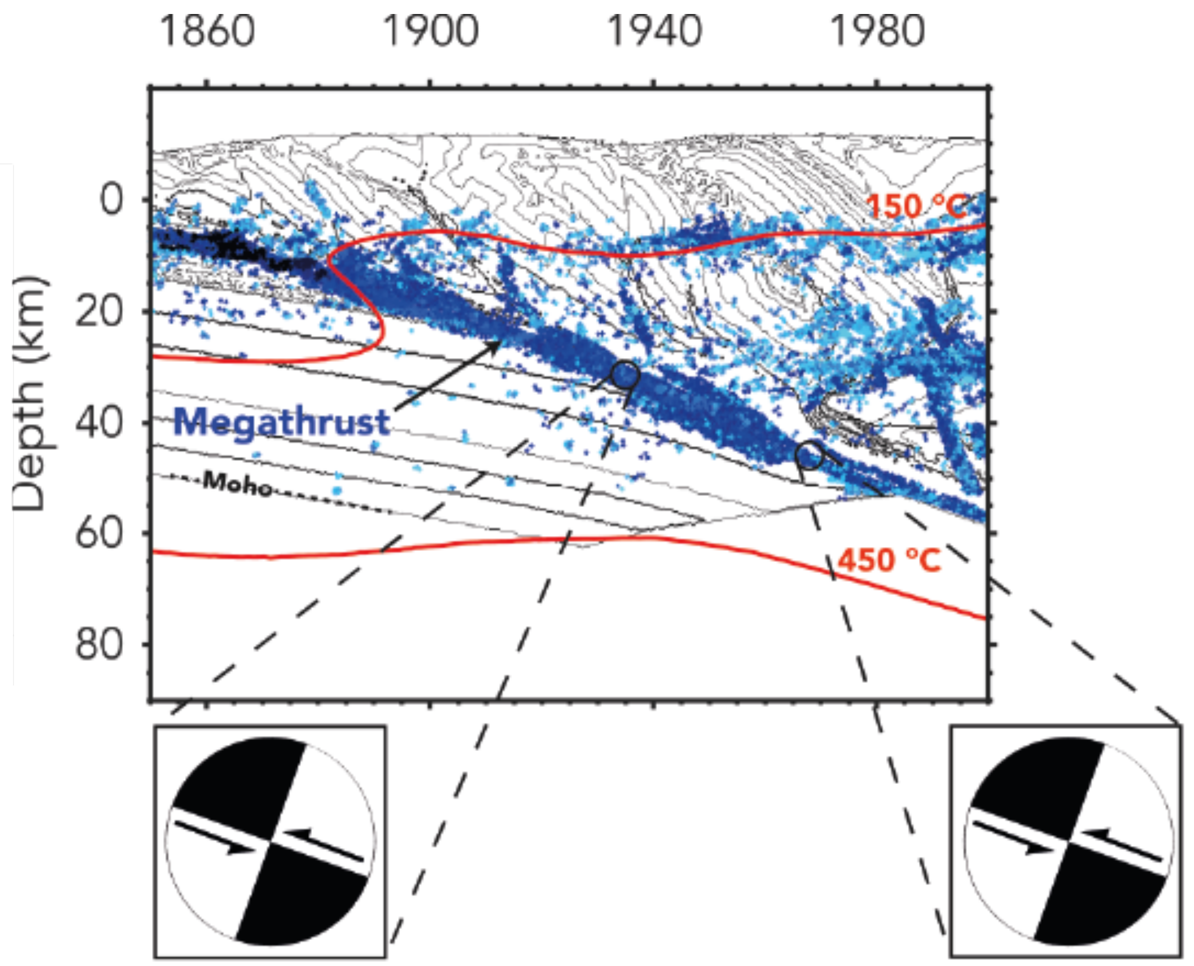
- **Seismicity output**
- Earthquake nucleation, propagation, arrest

Conservation of mass, momentum and energy
Visco-elasto-plastic rheology

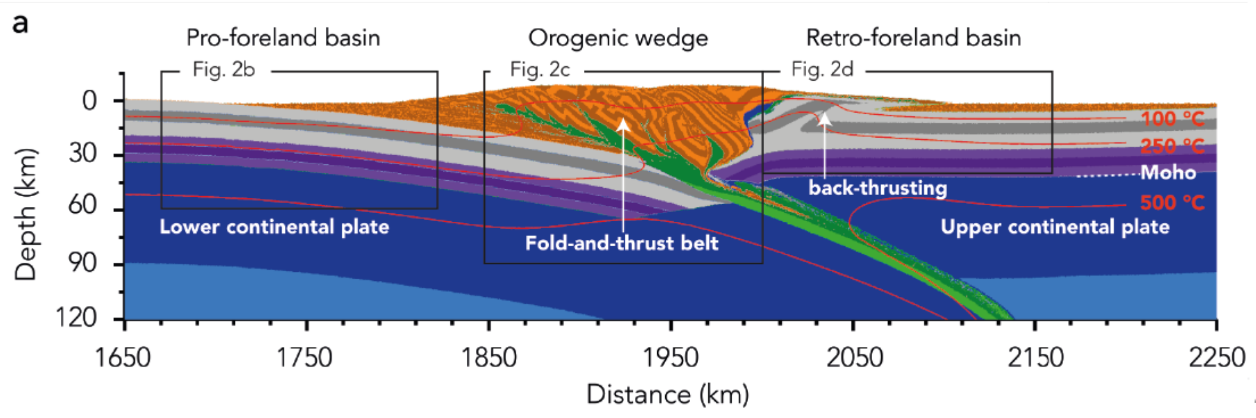
+ inertia
+ rate(-and state) dependent friction

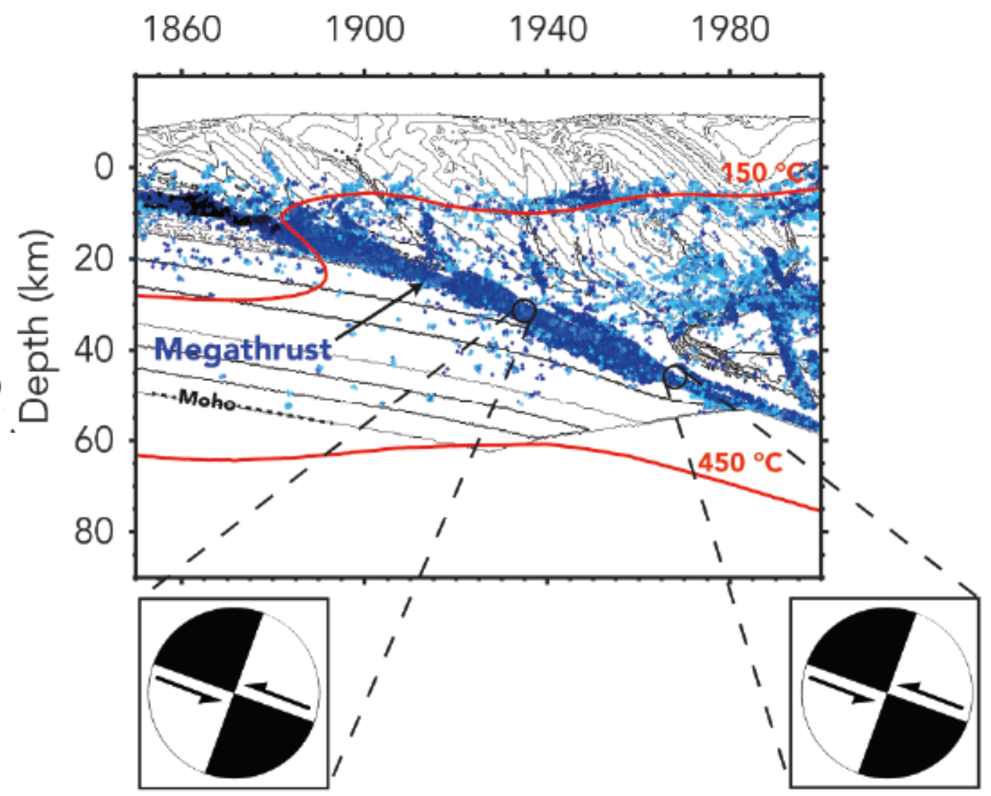






Bridging time scales from tectonics to dynamic earthquake rupture



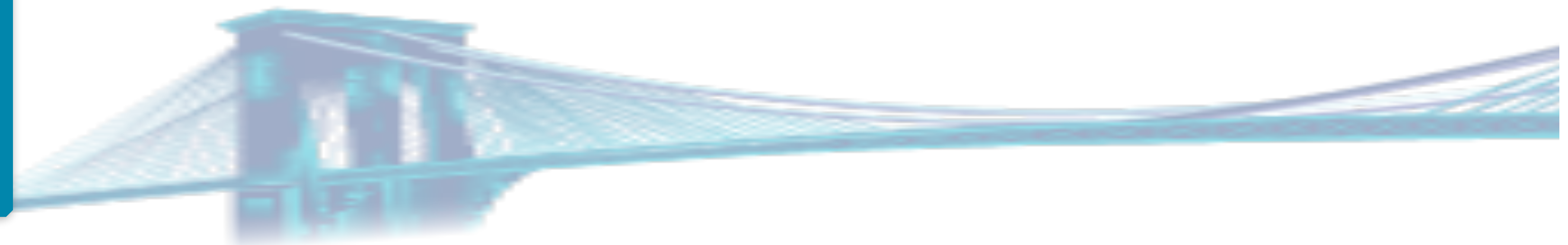


Slip rate-dependent friction

Δt = 1-5 years

Tectonics

Millions yr's
100's km's



Seismicity

Milliseconds
Millimeters

van Dinther et al., JGR, 2014b; Dal Zilio et al., EPSL, 2018

Long-term rheology: constant friction

- Brittle response mimicked by Drucker-Prager plasticity
  - Localizes deformation when σ'_{II} reaches strength $\sigma_{yield} = C + \mu \cdot (1 - \frac{P_{fluid}}{P_{solid}}) \cdot P$

Short-term rheology: strongly slip rate dependent friction

- Brittle response mimicked by Drucker-Prager plasticity
  - Localizes deformation when σ'_{II} reaches strength $\sigma_{yield} = C + \mu \cdot (1 - \frac{P_{fluid}}{P_{solid}}) \cdot P$

Slip rate $V = 2\dot{\varepsilon}'_{II(\mathrm{p})}\Delta x$

Friction $\mu_{eff} = \mu_s(1-\gamma) + \mu_s \frac{\gamma}{1 + \frac{V_{vp}}{V_c}}$

Short-term rheology: regularized rate-and-state dependent friction

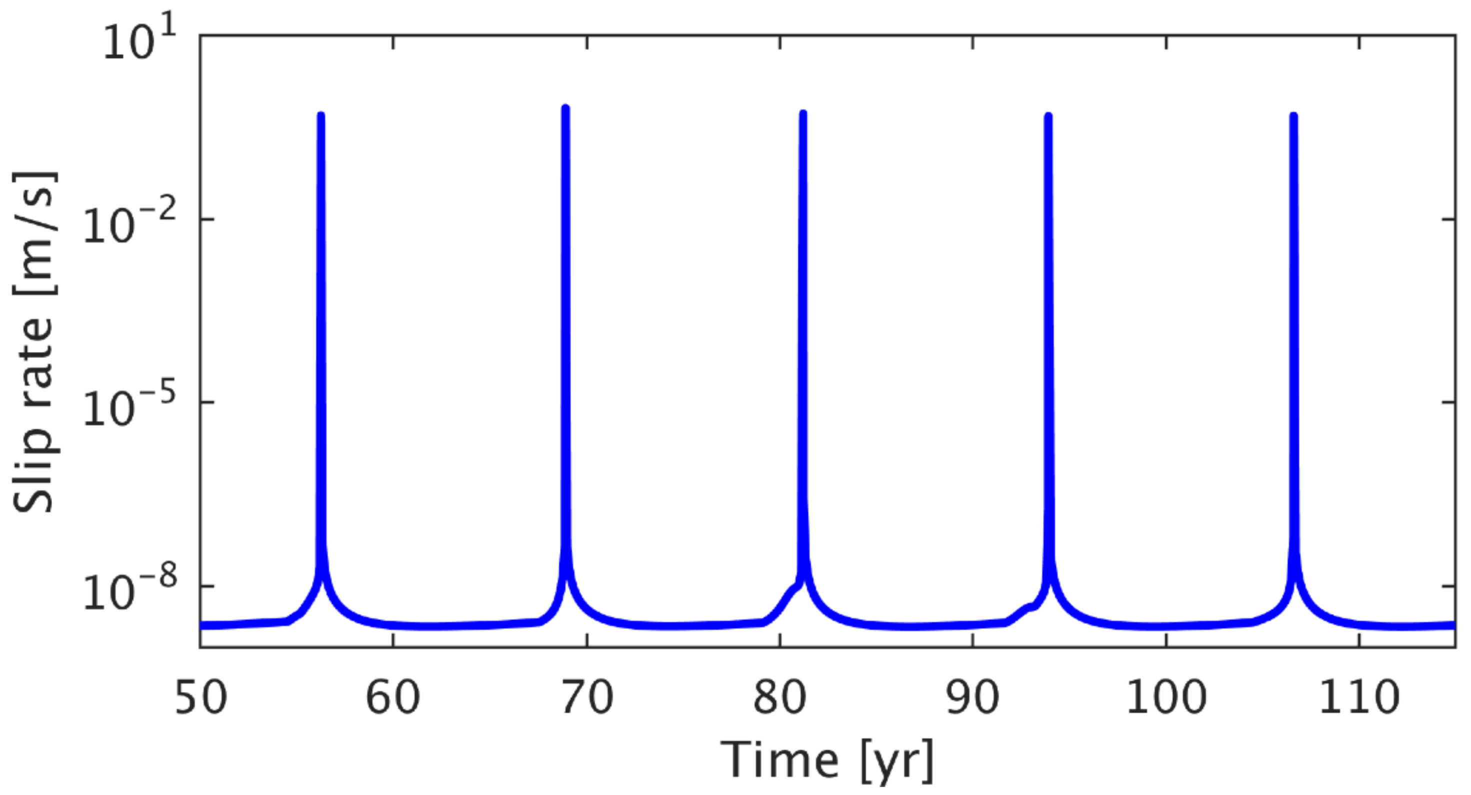
- Brittle response mimicked by Drucker-Prager plasticity
  - Localizes deformation when σ'_{II} reaches strength $\sigma_{yield} = C + \mu \cdot (1 - \frac{P_{fluid}}{P_{solid}}) \cdot P$

Slip rate $V = 2\dot{\varepsilon}'_{II(\mathrm{p})}\Delta x$

Friction $\tau_{II} = \sigma_{\mathrm{yield}} = a\, P \,\mathrm{arcsinh}\left[\frac{V_p}{2V_0}\exp\left(\frac{\mu_0 + b\ln\left(\frac{\theta V_0}{L}\right)}{a}\right)\right]$

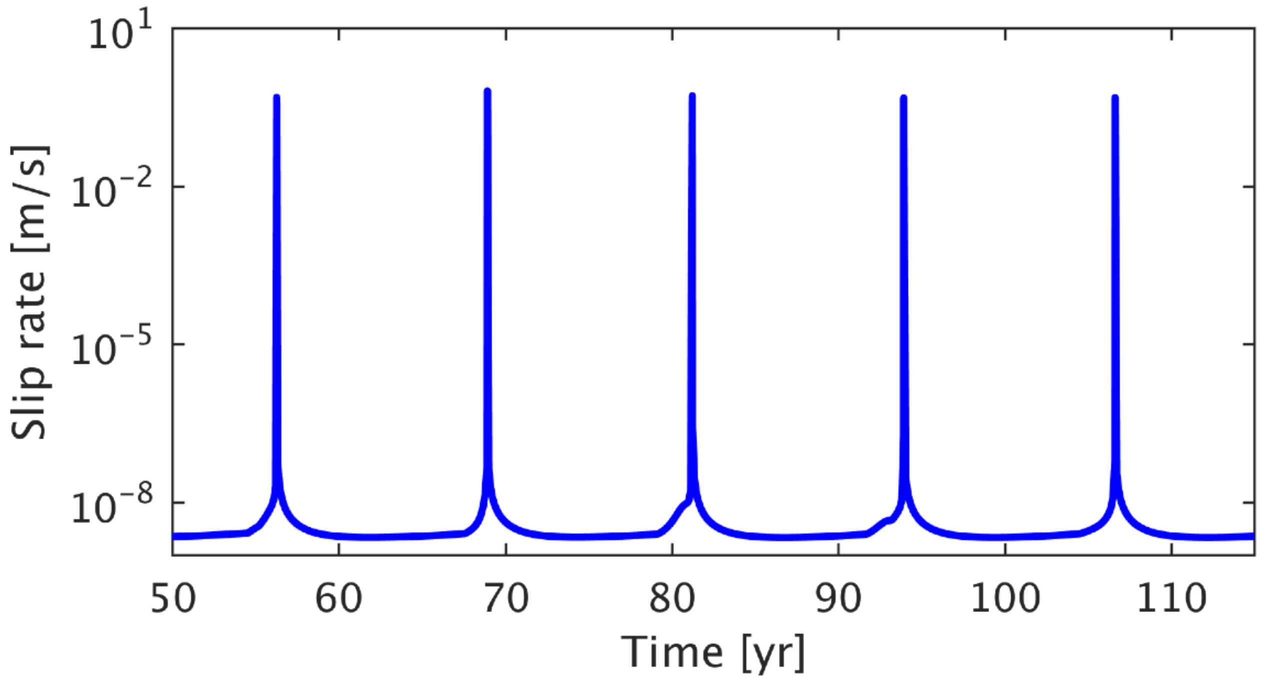
State evolution $\frac{d\theta}{dt} = 1 - \frac{V_p\,\theta}{L}$

with adaptive time stepping and Global picard iterations



Herrendoerfer et al., JGR, 2018

Bridging time scales from tectonics to dynamic earthquake rupture



seismic slip rates!

Rate-and-state dependent friction - invariant reformulation

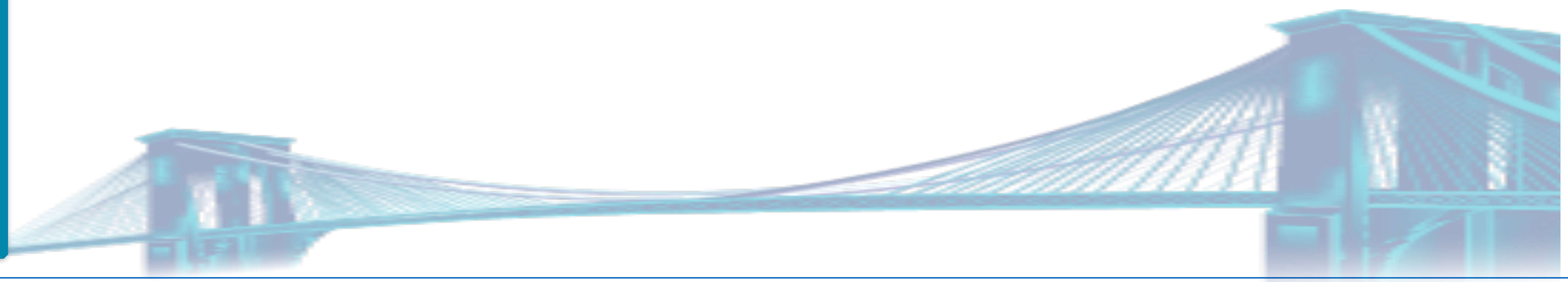
Resolve interseismic, coseismic and postseismic phase

Simulate whole slip spectrum: a-, slow-, seismic slip

Δt = milliseconds - years

Tectonics

Millions yr's
100's km's



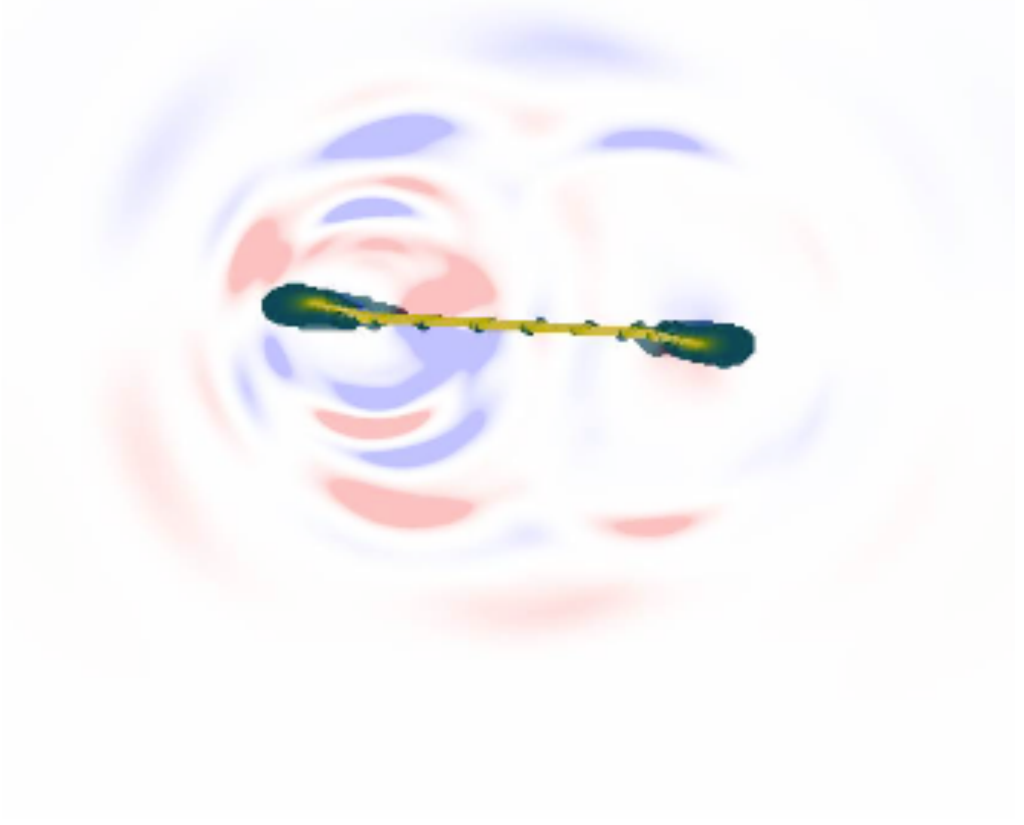
Seismicity

Milliseconds
Millimeters

Herrendörfer et al., JGR, 2018

Bridging time scales from tectonics to dynamic earthquake rupture

seismic waves



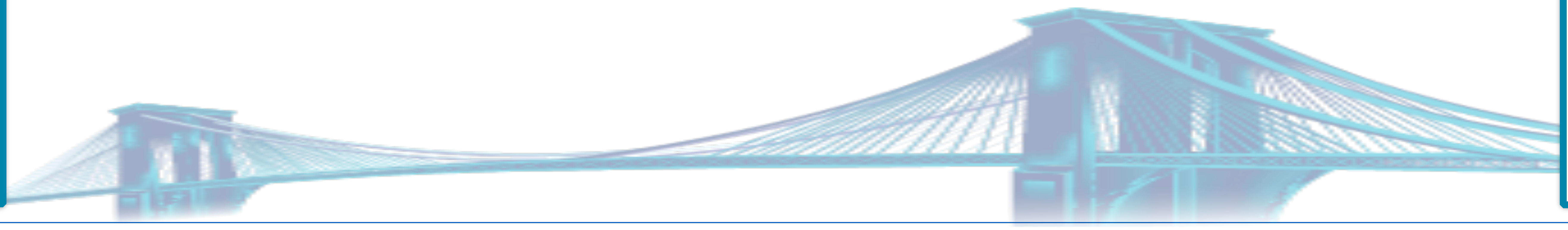
Dynamic earthquake rupture

Fault evolution

Δt = milliseconds

Tectonics

Millions yr's
100's km's

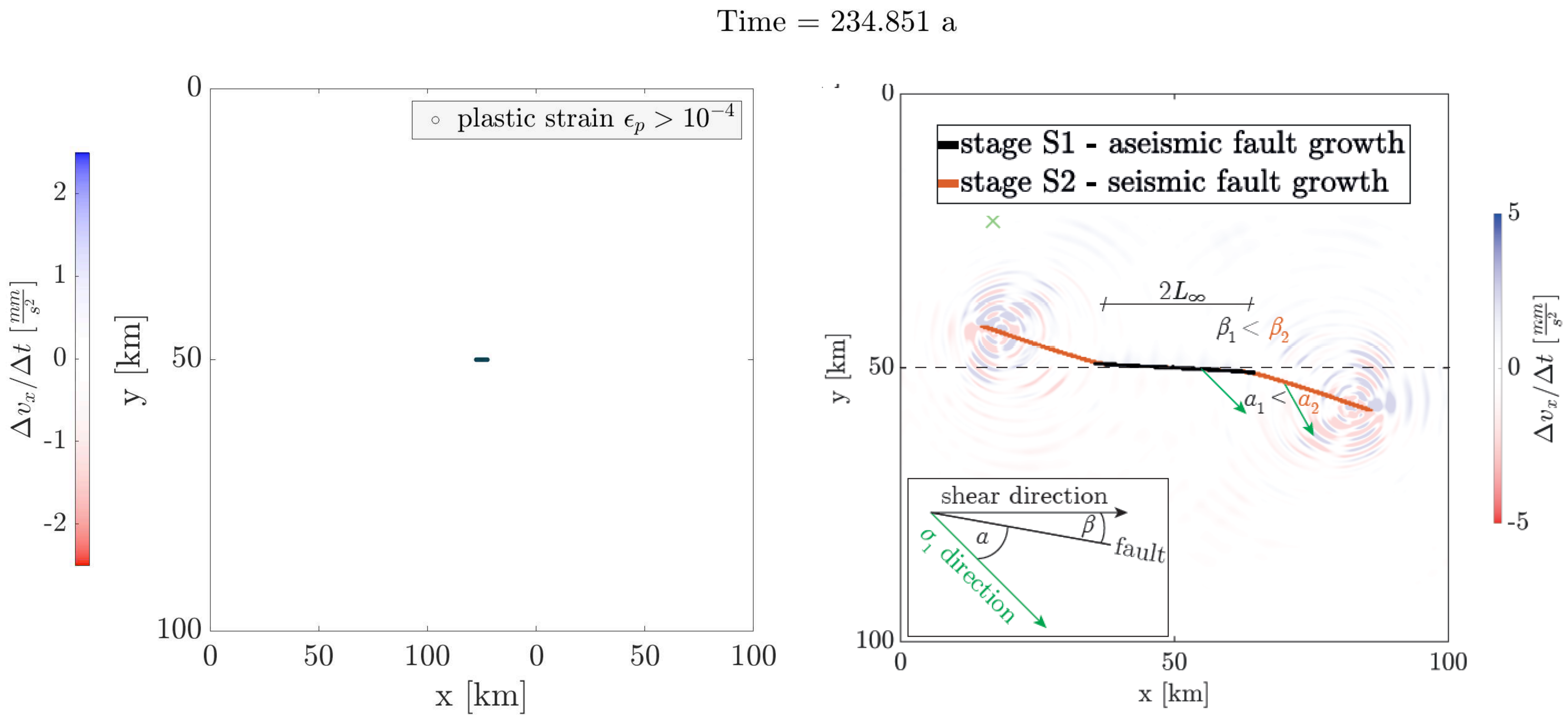


Seismicity

Milliseconds
Millimeters

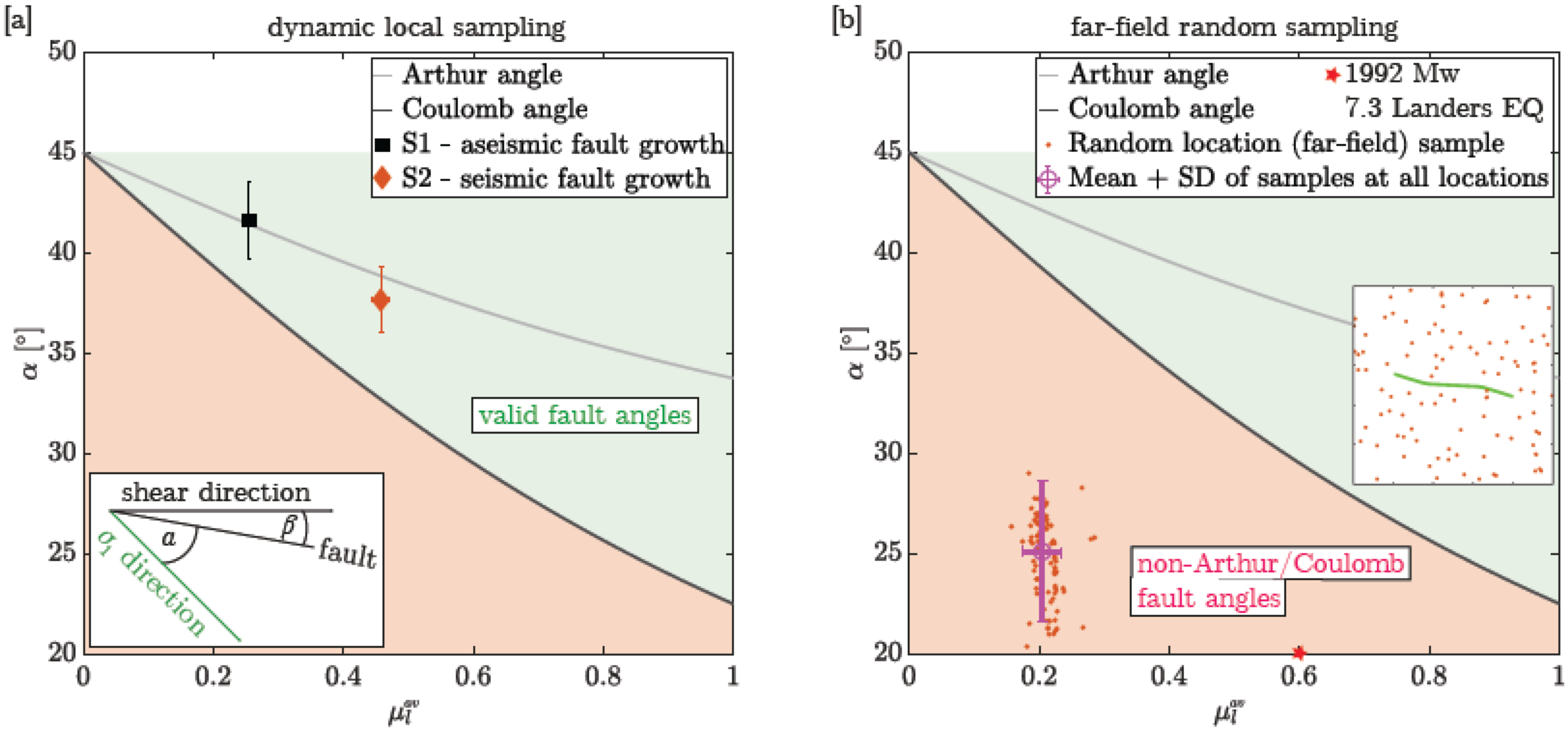
Preuss et al., JGR, 2019

Two fault growth modes exist: seismic and aseismic



Classical faulting theory retained if near-tip, time dependent friction and stress

» **Mis-orientation may indicate seismic fault growth**

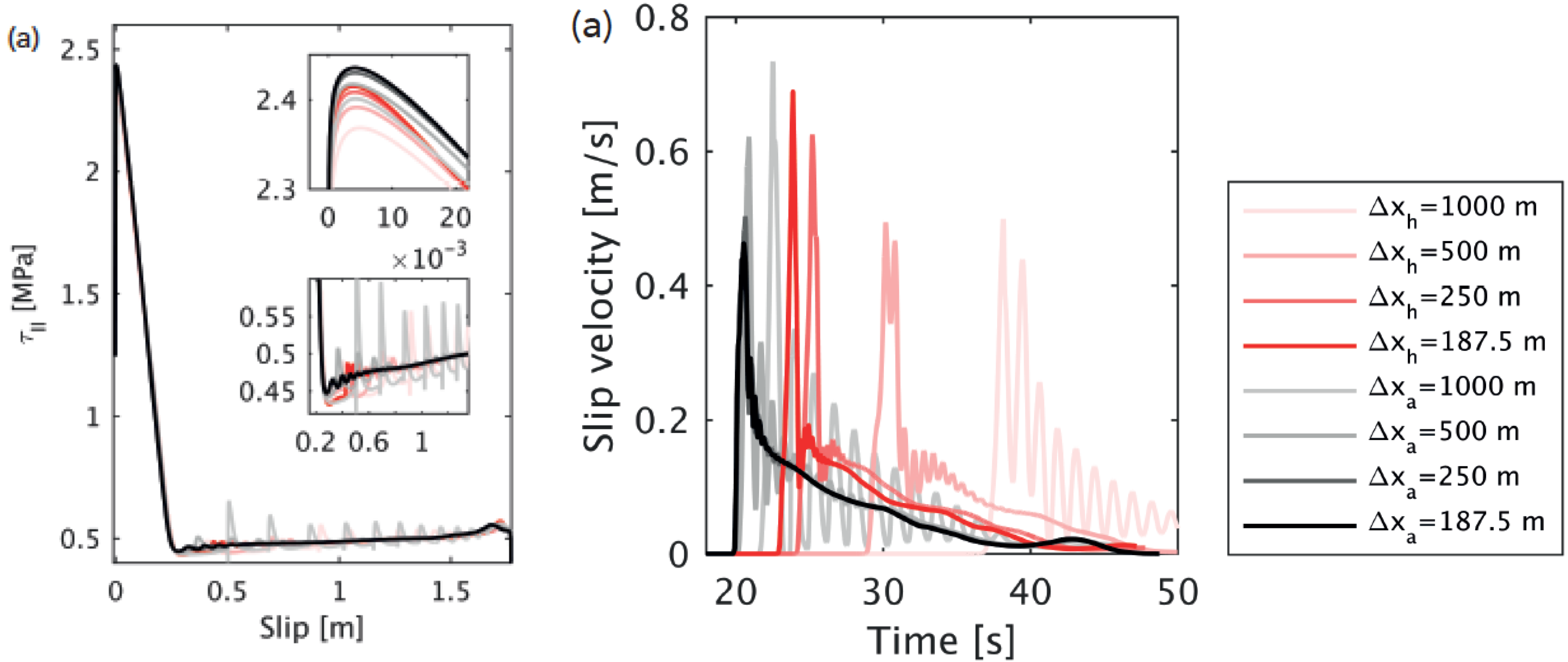


Do these angles and characteristics depend on grid size?

- Plasticity is grid size dependent (e.g., Vermeer and de Borst, 1984)
- Length-scale in slip rate formulation helps with grid convergence (e.g., Needleman, 1988)

$$V = 2\dot{\varepsilon}'_{II(\mathrm{p})}\Delta x$$

fault width



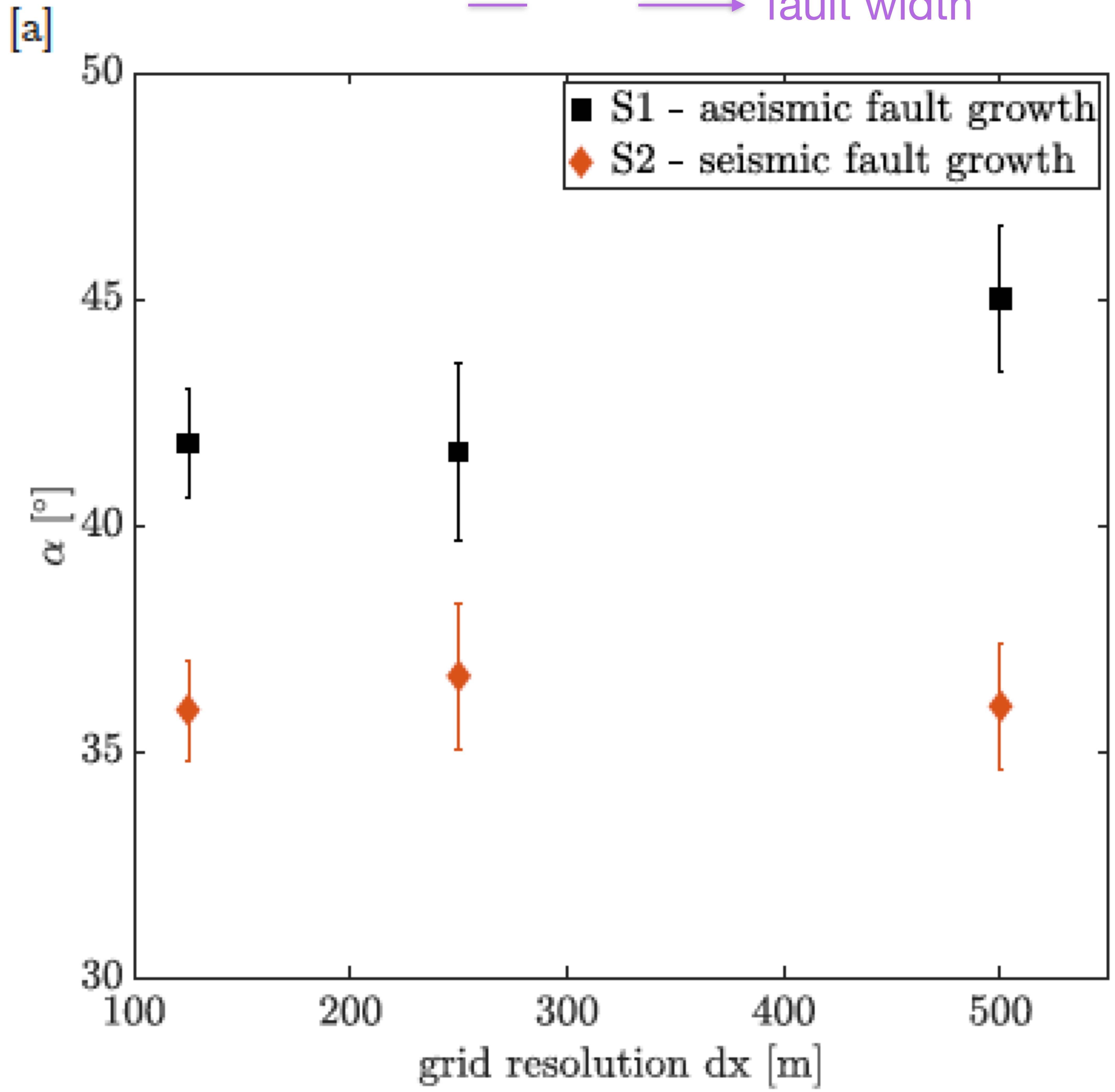
Herrendoerfer et al., JGR, 2018

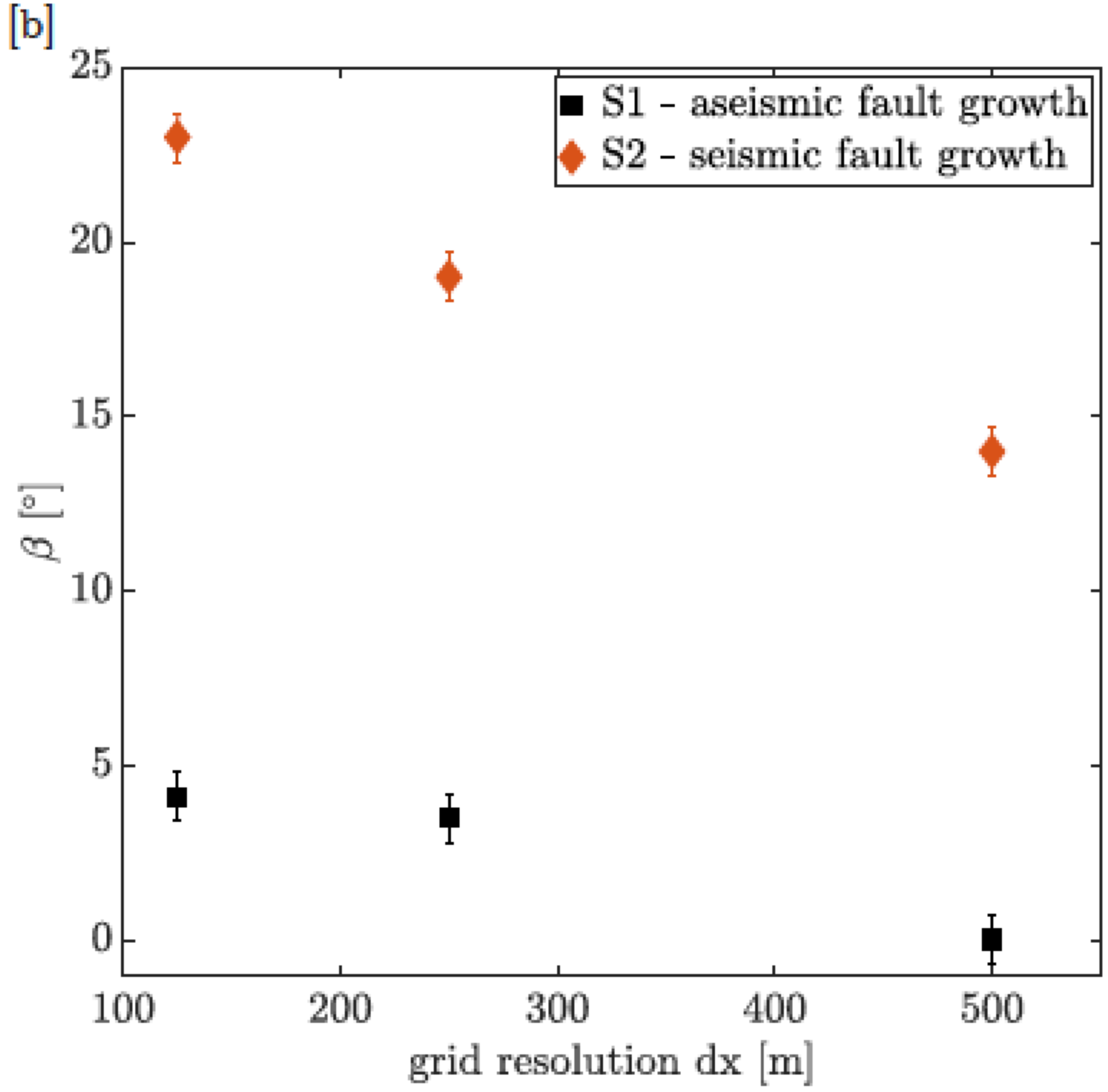
Do these angles depend on grid size?

- Length-scale in slip rate formulation helps with grid convergence (e.g., Needleman, 1988), **but not enough for evolving fault**

$$V = 2\dot{\varepsilon}'_{II(\mathrm{p})}\Delta x$$

fault width

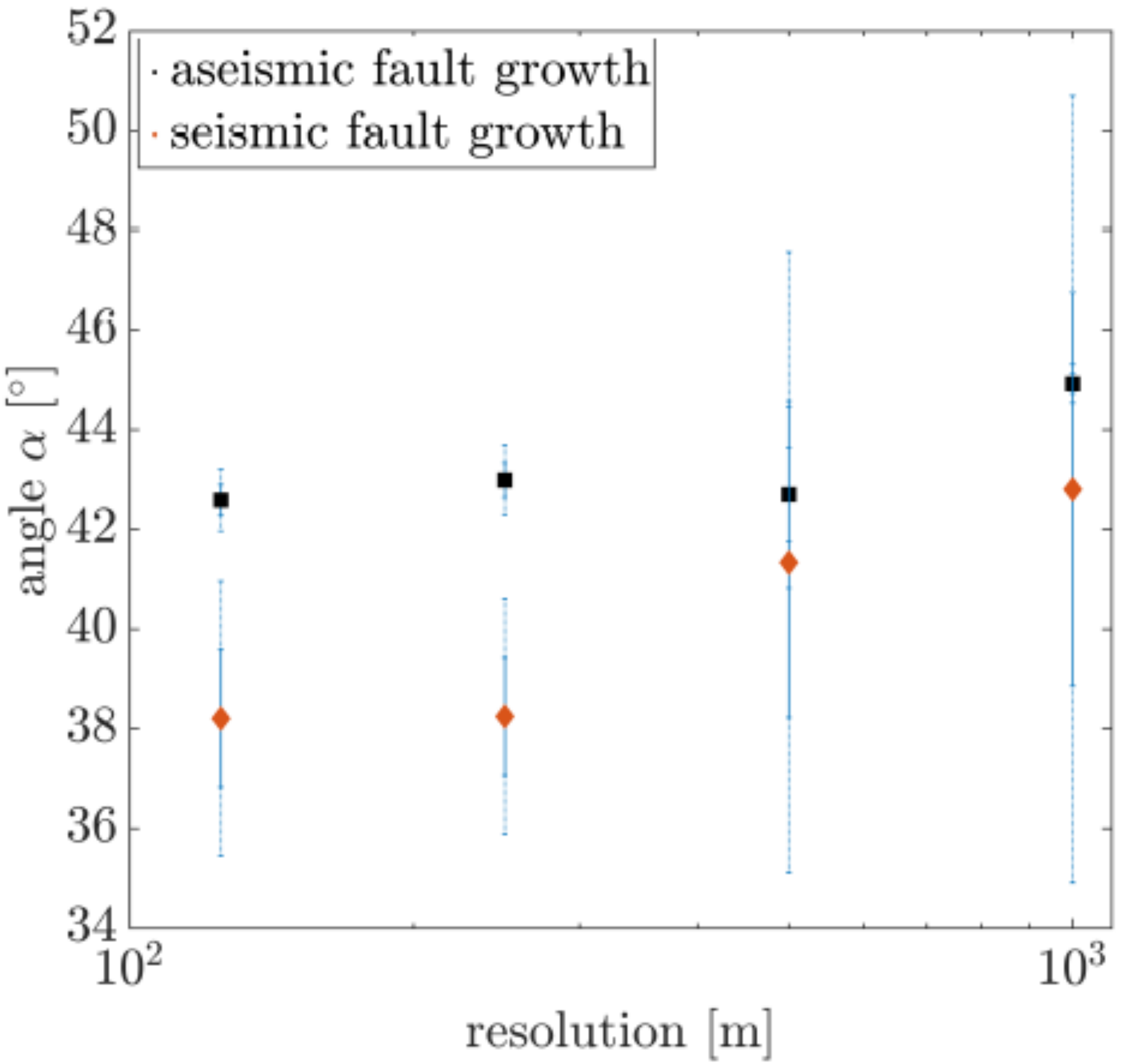


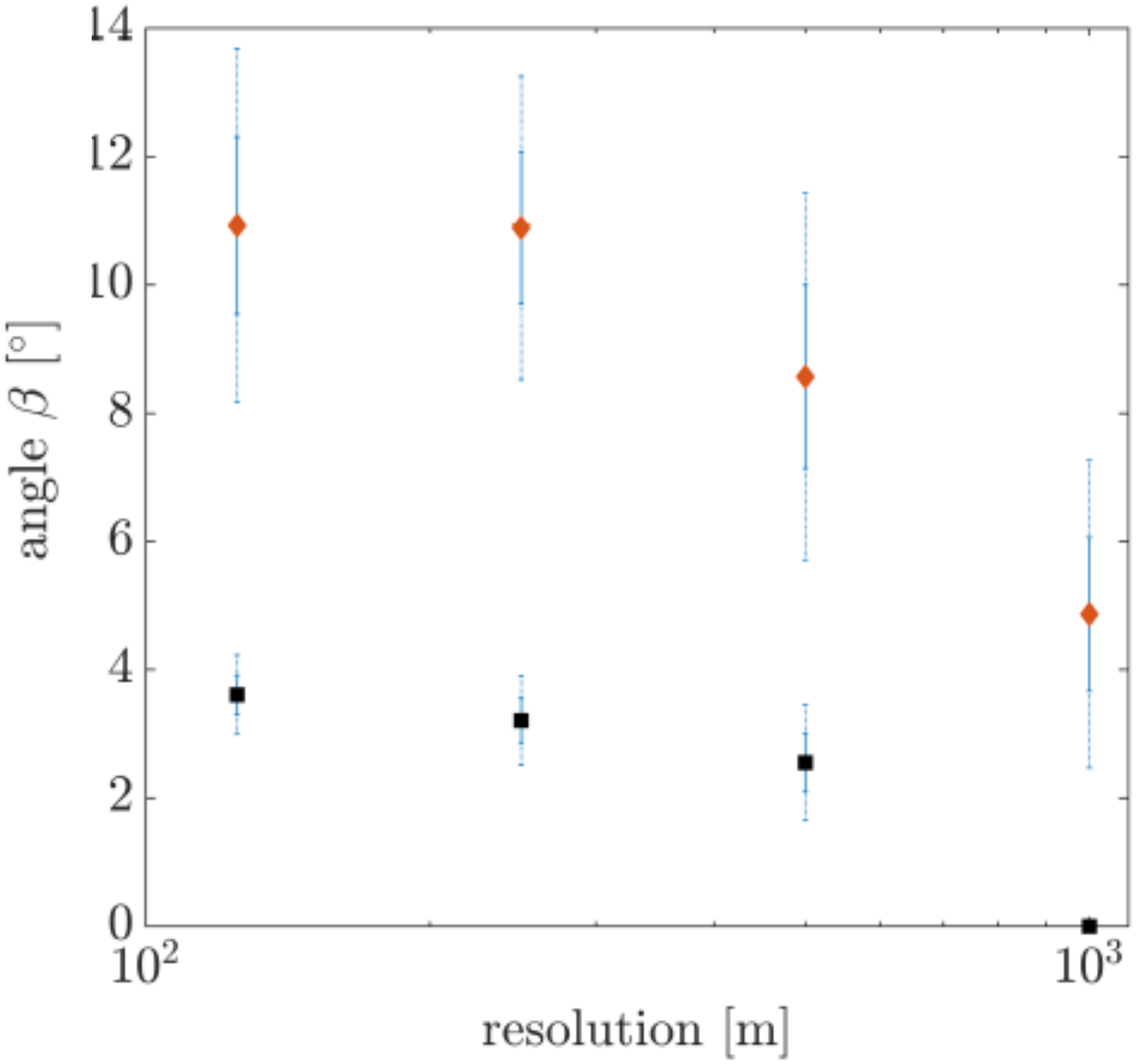


Preuss et al., JGR, 2019; van Dinther et al., JGR, 2013a; Herrendoerfer et al., JGR, 2018

- What is fault width W if a fault has no yet localized?

$$W_V^2 = W_{max} \log(1 + K \frac{V_0}{V_p})$$





Preuss et al., in pre.

» Illustrate how lithosphere- and mantle dynamics, structure and rheology can influence shallow tectonics and seismicity

- **Does incoming sediment thickness increase maximum earthquake magnitude?**

How sediment thickness influences subduction dynamics and seismicity

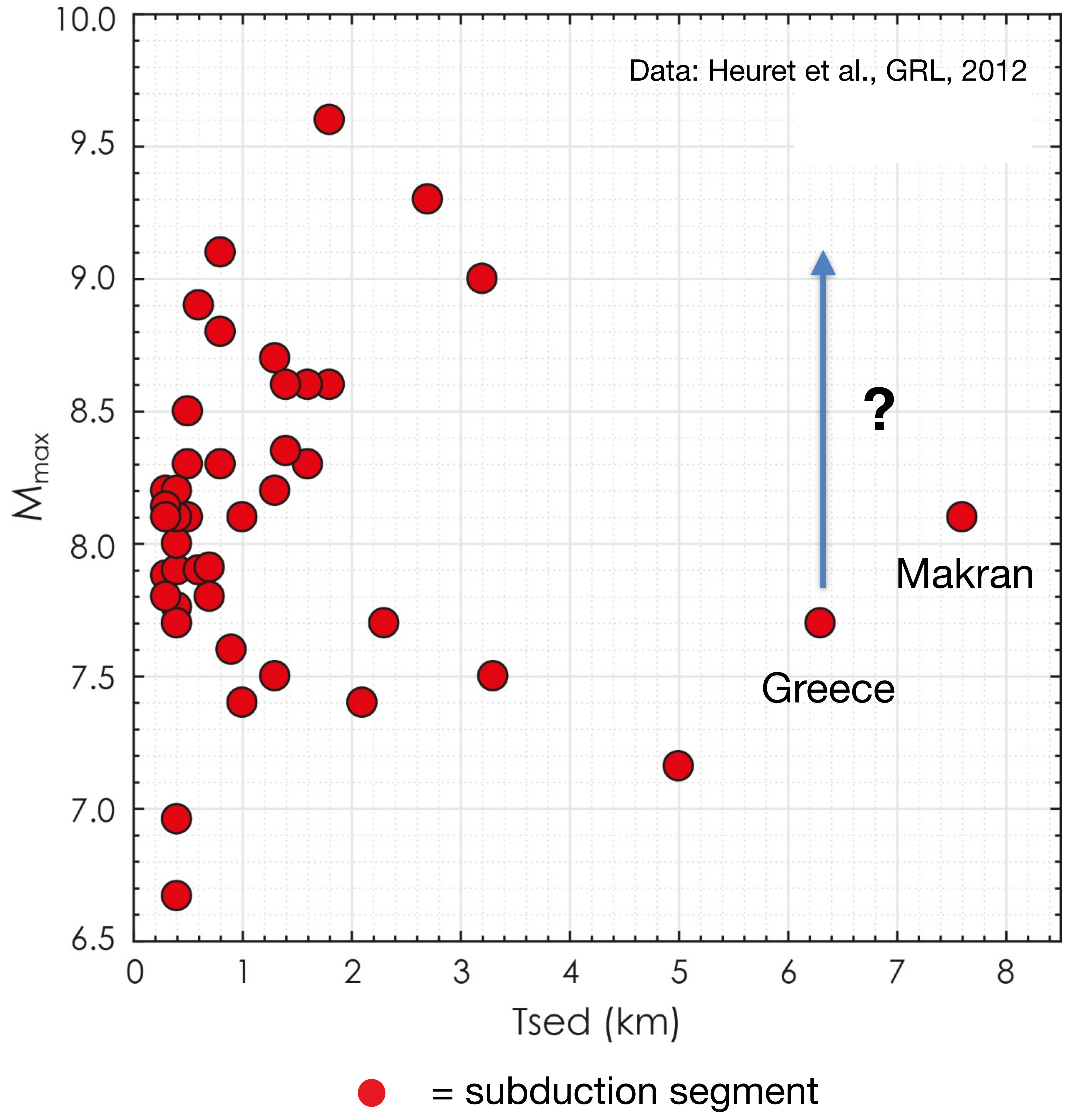
S. Brizzi[1,2*], I. van Zelst[3], F. Funiciello[1], F. Corbi[1], Y. van Dinther[3,4]

[1]*Laboratory of Experimental Tectonics, University of Roma Tre, Italy;* [2]*Natural and Experimental Tectonics research group, University of Parma, Italy;* [3]*Seismology and Wave Physics, ETH Zürich, Switzerland;* [4]*Department of Earth Sciences, Utrecht University, Utrecht, the Netherlands*

Under review at Earth Planetary Science Letters

Does incoming sediment thickness increase maximum earthquake magnitude?

- Various observations suggest Tsed increases Mmax (e.g., Ruff, 1989; Heuret et al., 2012; Scholl et al., 2015; Seno, 2017; Brizzi et al., 2018)
- But does it? And how?

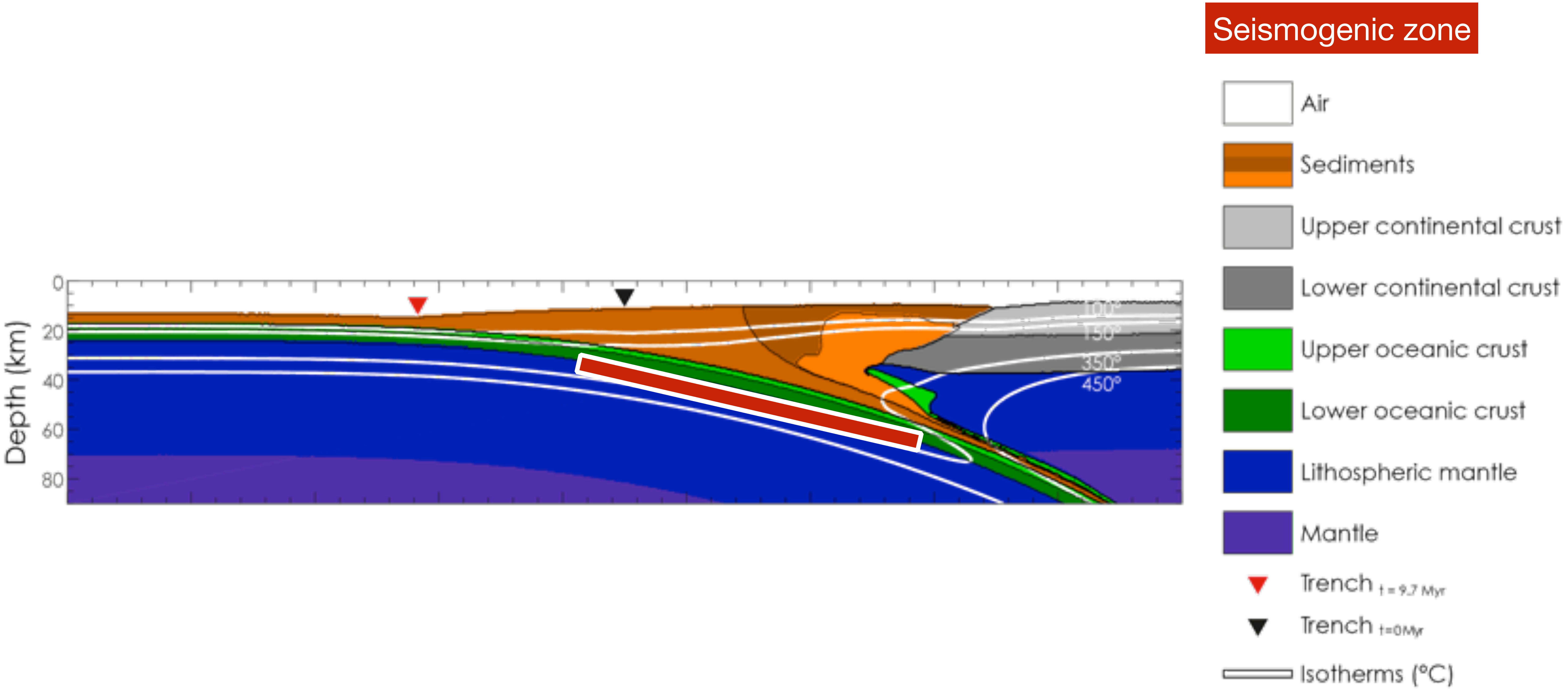


- Cross-scale modeling is needed because
  - Observation window <(<) recurrence interval
  - Concurrent influence of multi-parameters

Sediment thickness controls geometry of convergent margin

Sediment thickness:

4 km



Sediment thickness controls geometry of convergent margin

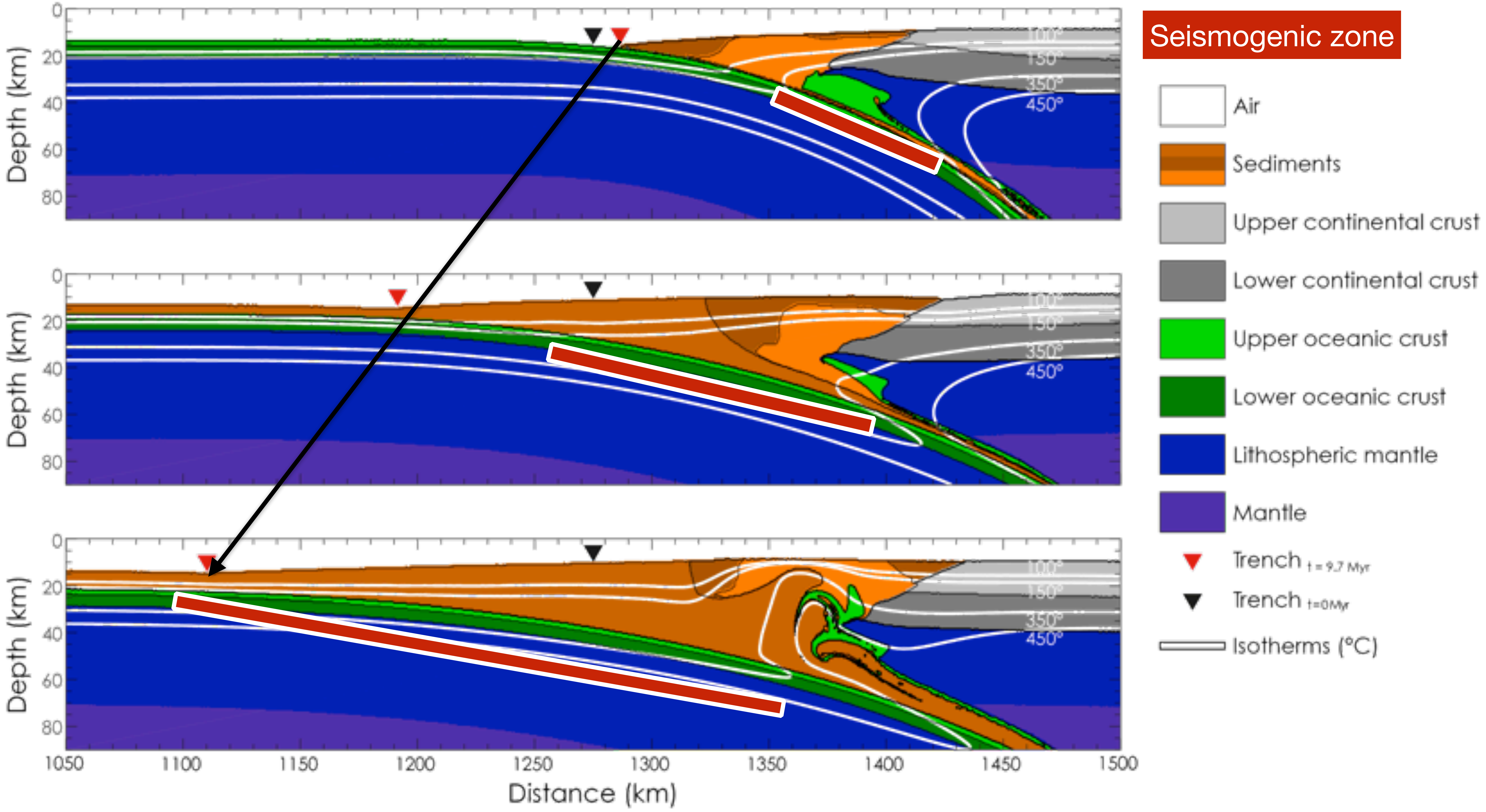
- More sediments → seaward growth wedge → trench retreat and unbending → shallower dip → wider seismogenic zone

Sediment thickness:

0 km

4 km

8 km



Brizzi et al., EPSL, in rev.

Sediment thickness controls Mmax and type of seismicity

- More sediments → less mechanical coupling → more slab retreat → shallower dip → wider seismogenic zone → Mmax up

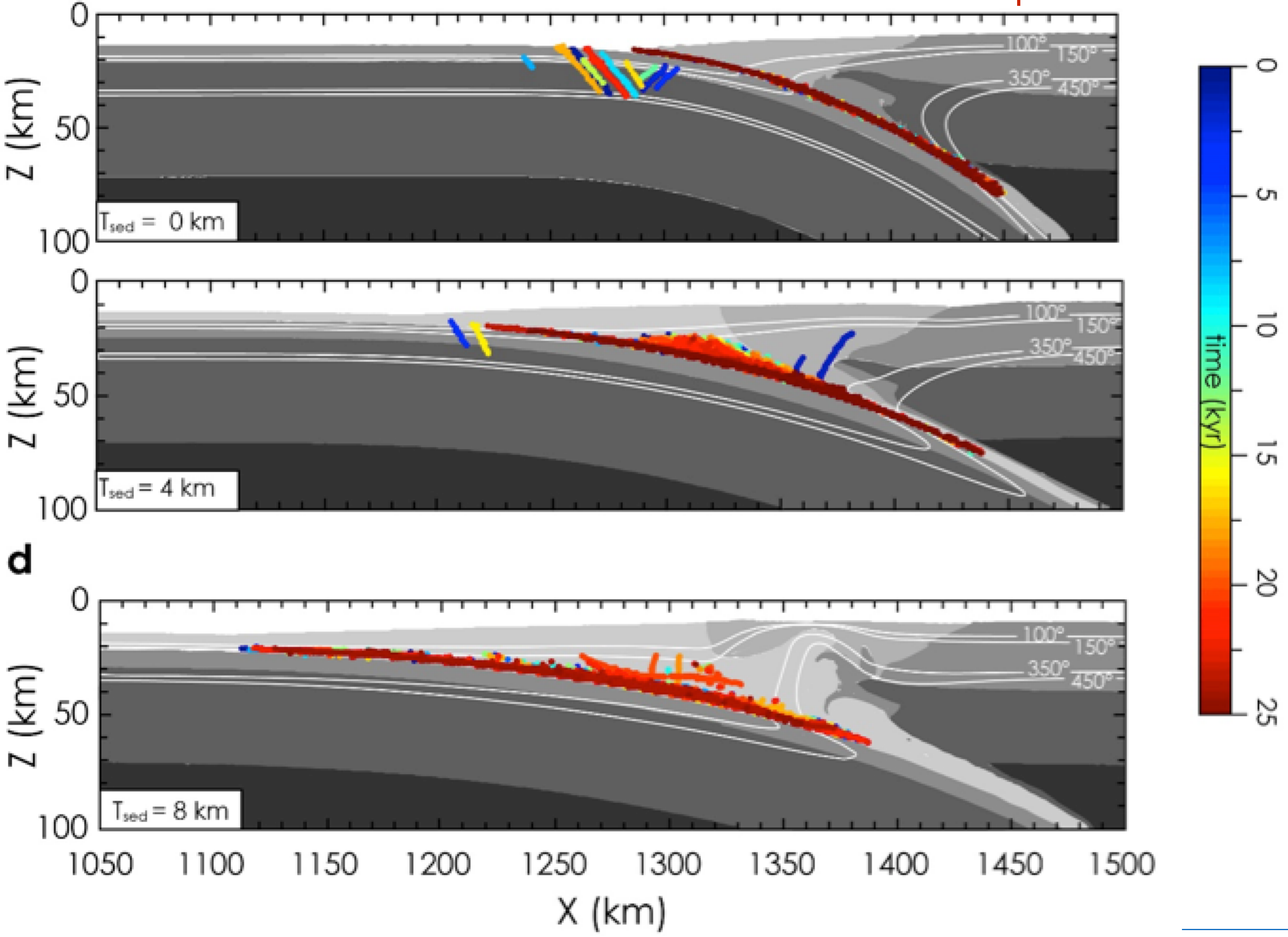
Transfers dissipation from outer-rise to wedge

Sediment thickness:

0 km

4 km

8 km

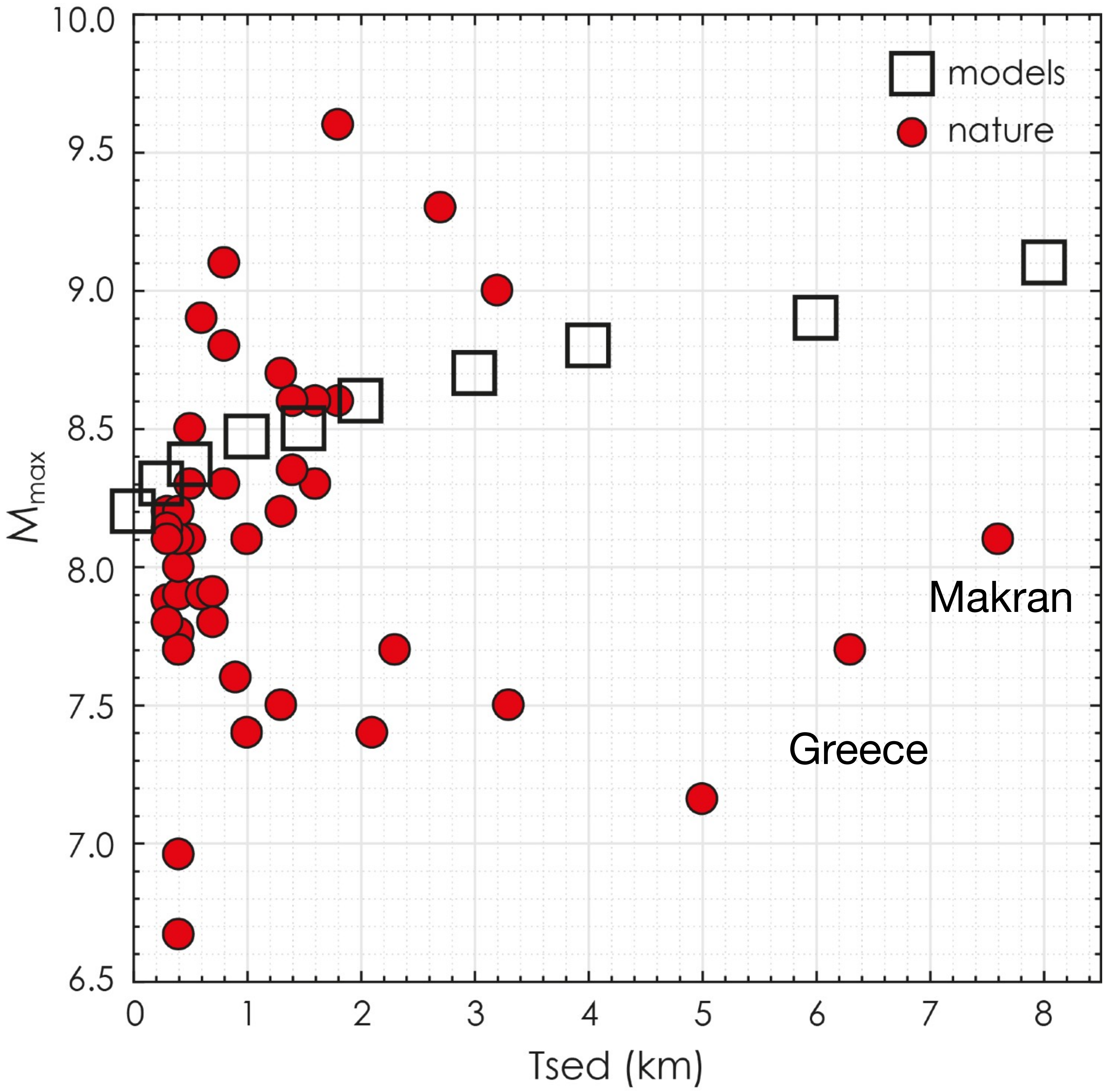


$Mw = a + b \log(W)$

(Blaser et al., 2010)

Sediment thickness controls maximum magnitude

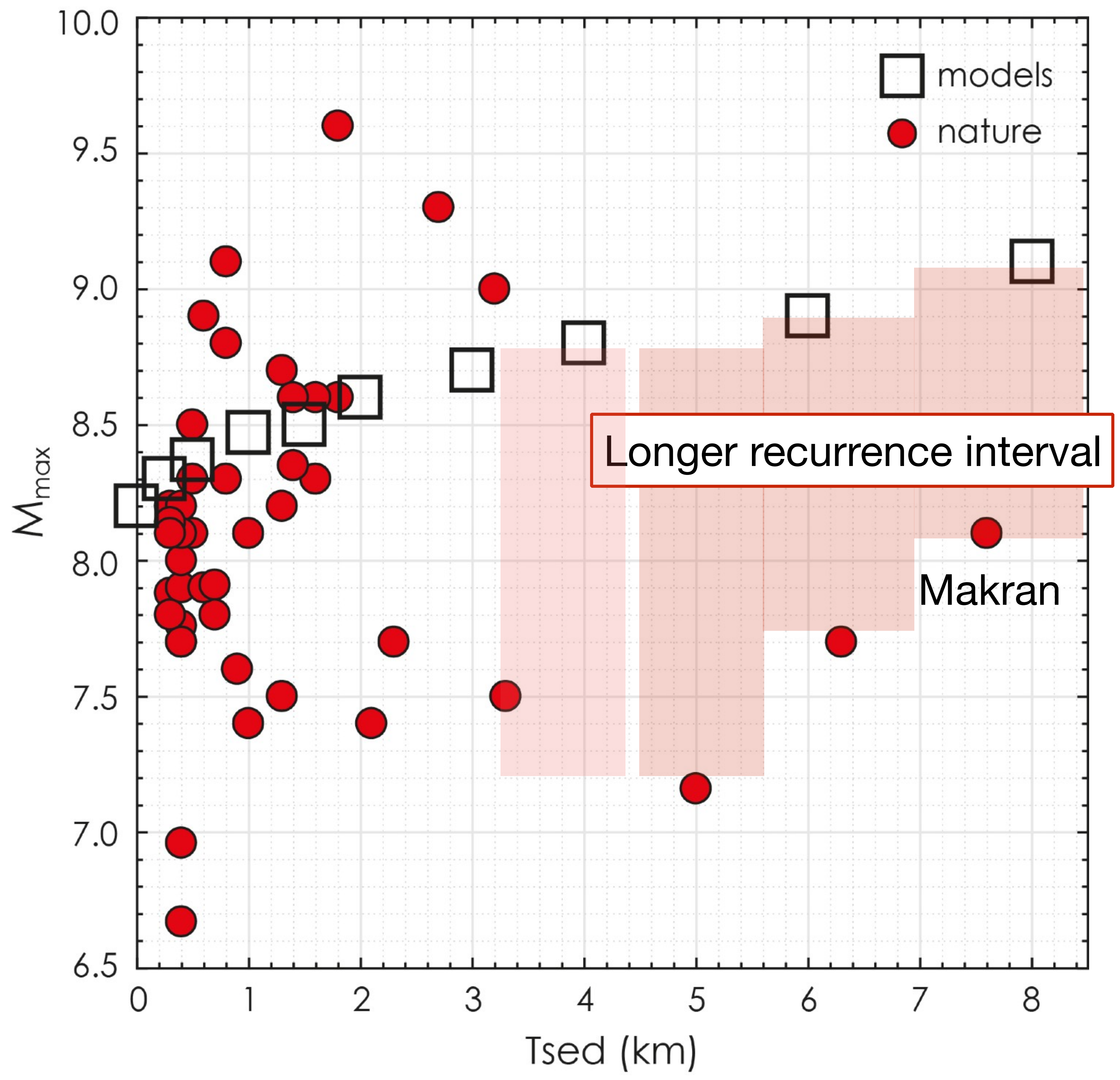
- Models - clarify and quantify suspected trend in nature



● = subduction segment

Sediment thickness controls maximum magnitude

- Models - clarify and quantify suspected trend in nature
  - provide an explanation for why we might not have yet seen such large magnitudes



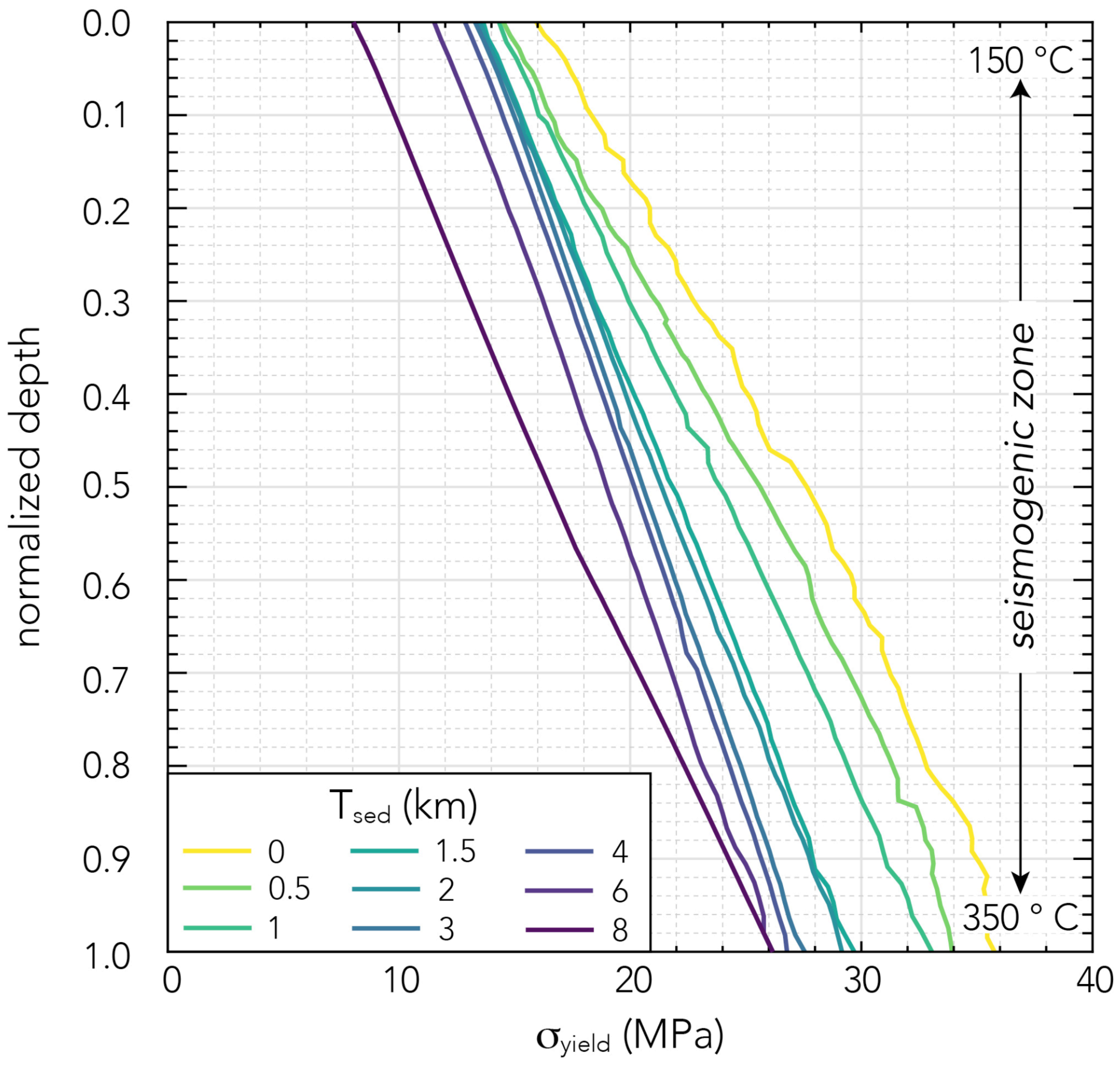
● = subduction segment

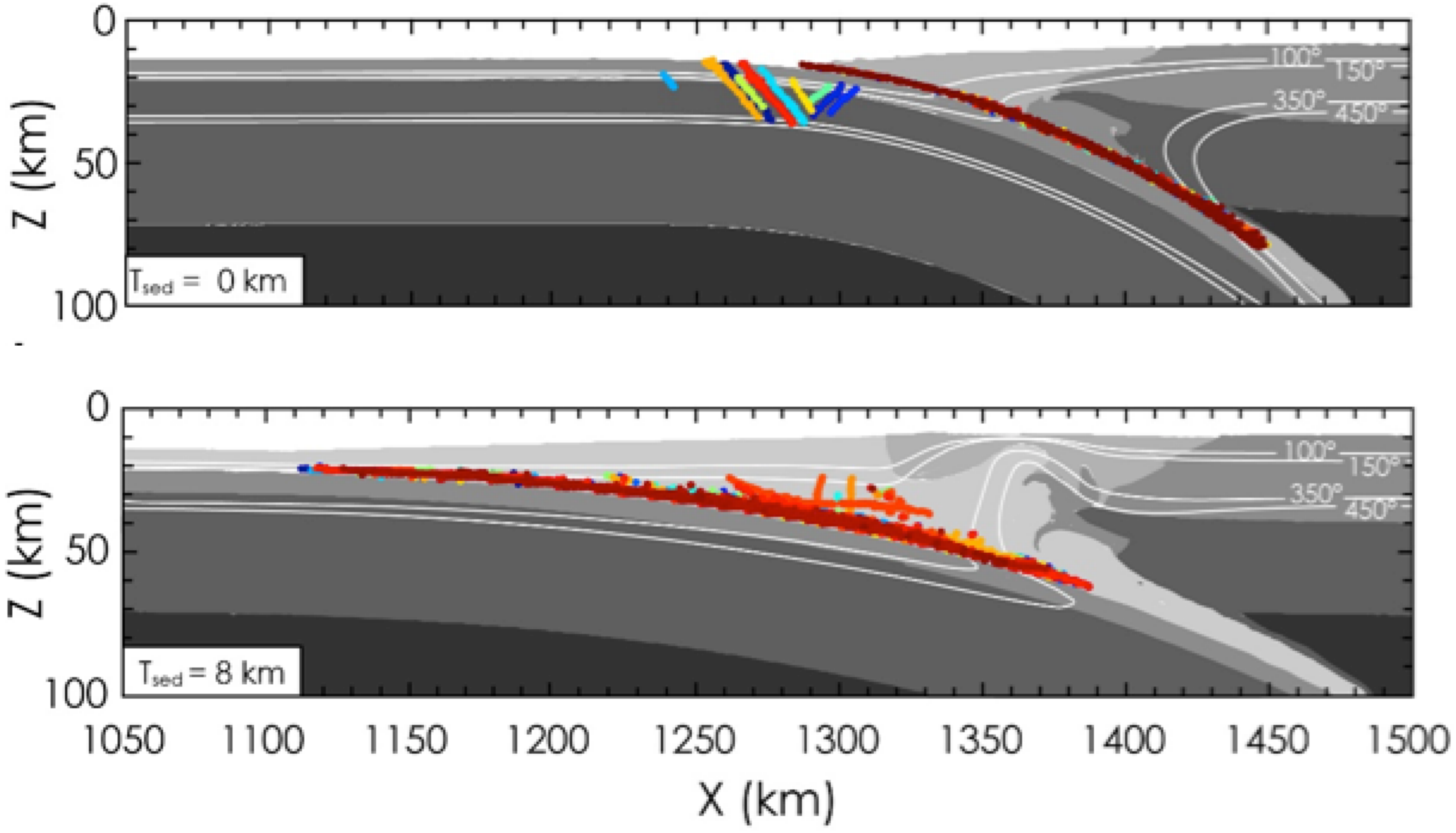
Brizzi et al., EPSL, in rev.

Why does megathrust interface strength decrease with Tsed?

- Intuitive explanation for slab dip decrease through slab retreat as interface is increasingly weaker is not cause

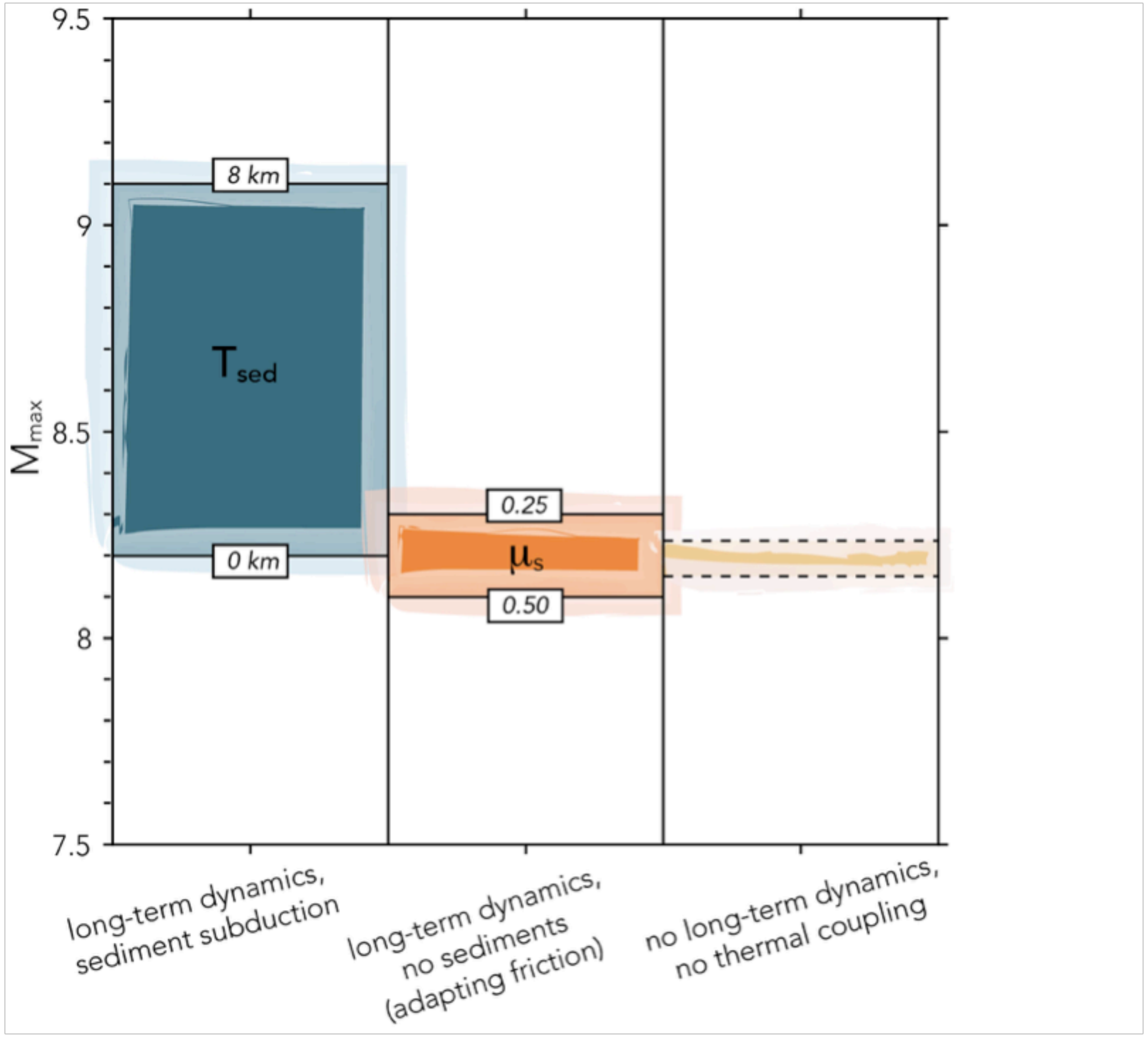
- What makes interface weaker, if “all” models have weak sediments?
  - Warmer incoming sediments → seismogenic zone depth ↓ & a lighter forearc structure → pressure in seismogenic zone ↓





Why model long-term dynamics?

- **Simulating long-term dynamics and sediment presence significantly changes quantification**



Brizzi et al., EPSL, in rev.

» Illustrate how lithosphere- and mantle dynamics, structure and rheology can influence shallow tectonics and seismicity

- Does incoming sediment thickness increase maximum earthquake magnitude?

- **Do lower crustal and mantle depth temperature and rheology affect seismicity and tectonics?**

Tectonics and seismicity in the Northern Apennines driven by slab retreat and crustal delamination

Mario D'Acquisto[1,2], Luca Dal Zilio[1,3], Irene Molinari[1,4], Edi Kissling[1], Taras Gerya[1], Ylona van Dinther[1,2]

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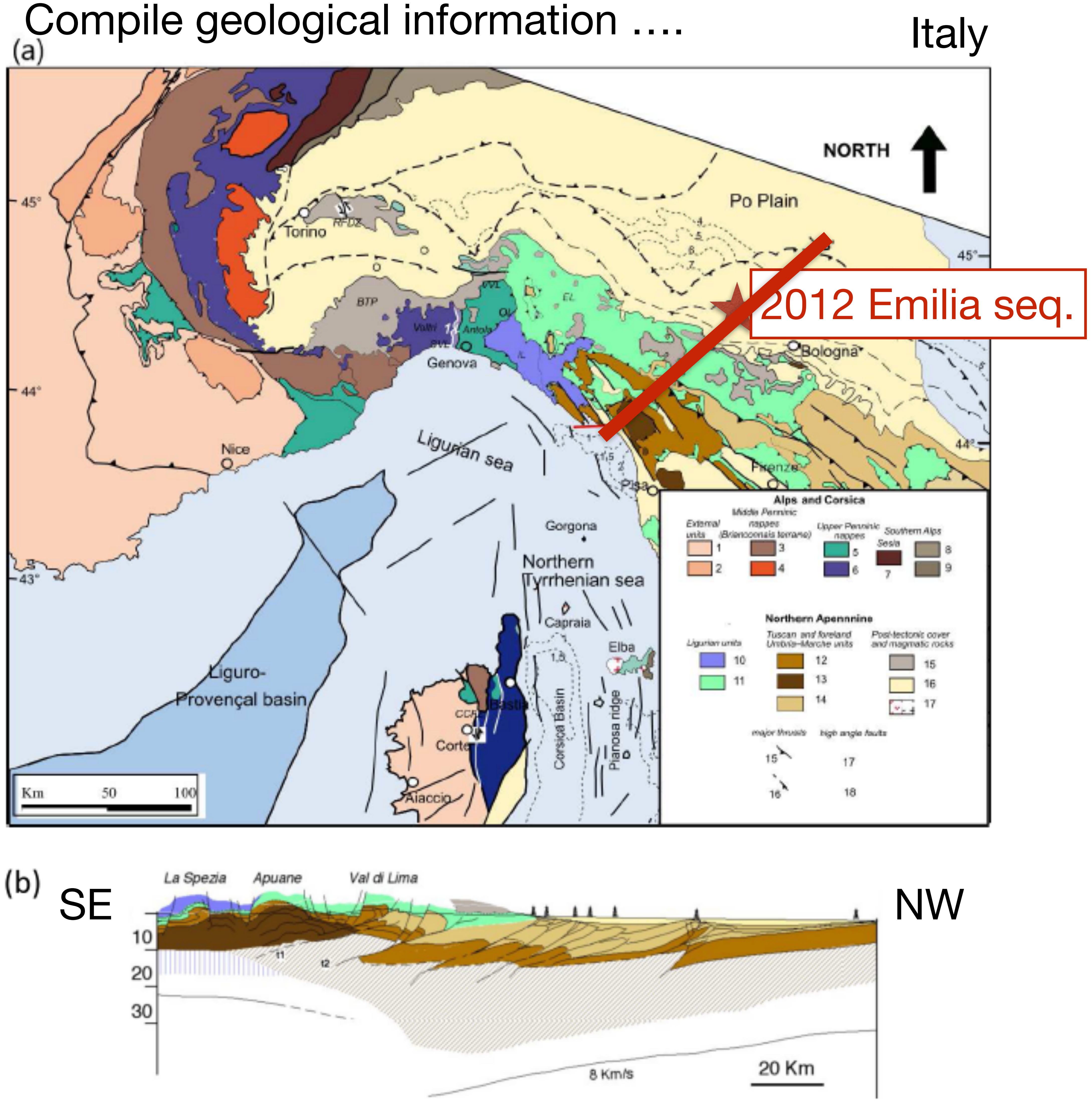
Submitted to Journal of Geophysical Research - Solid Earth

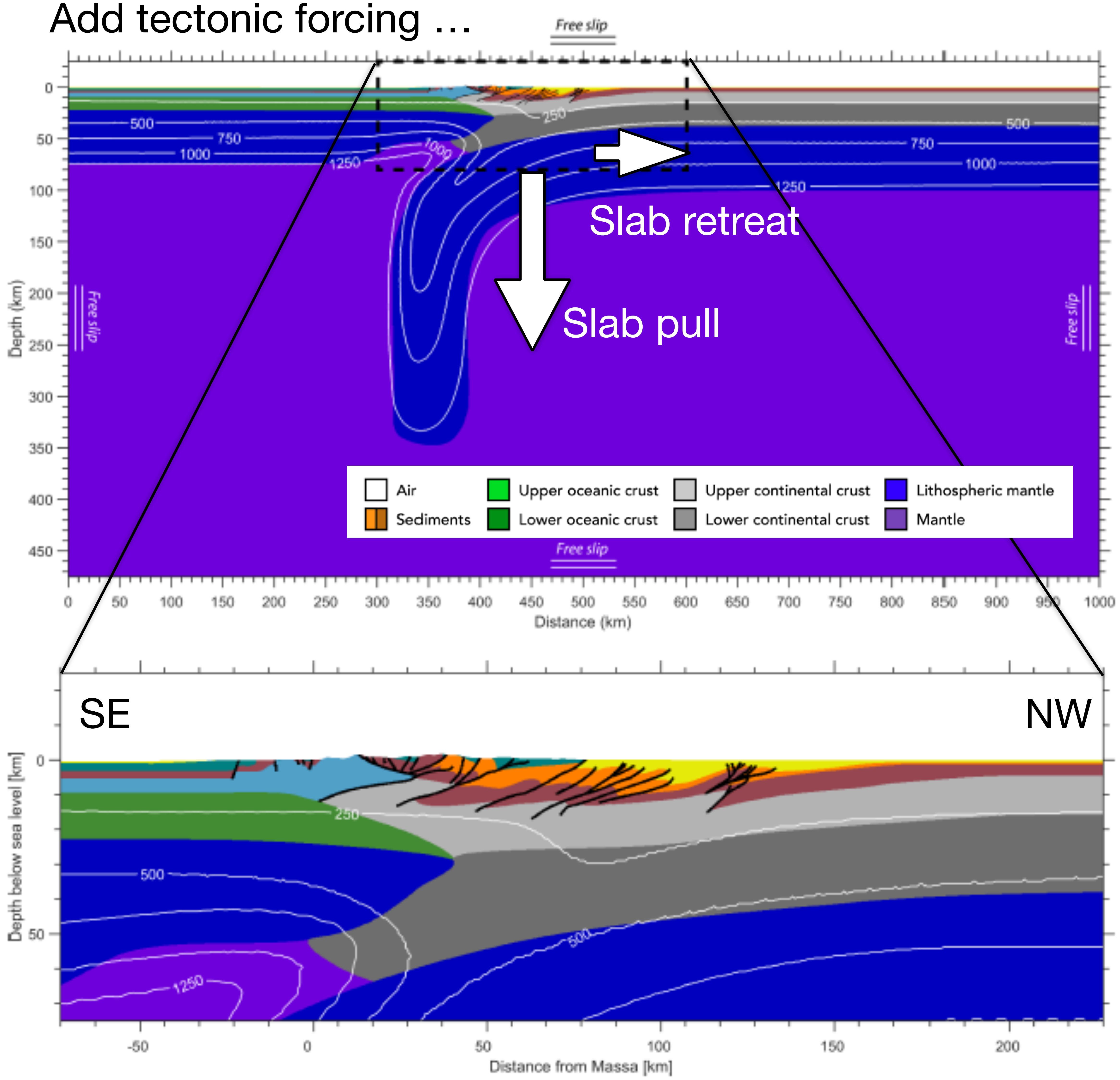
Building an instantaneous model

- Combine available information to build regional model of Northern Apennines

Compile geological information ....



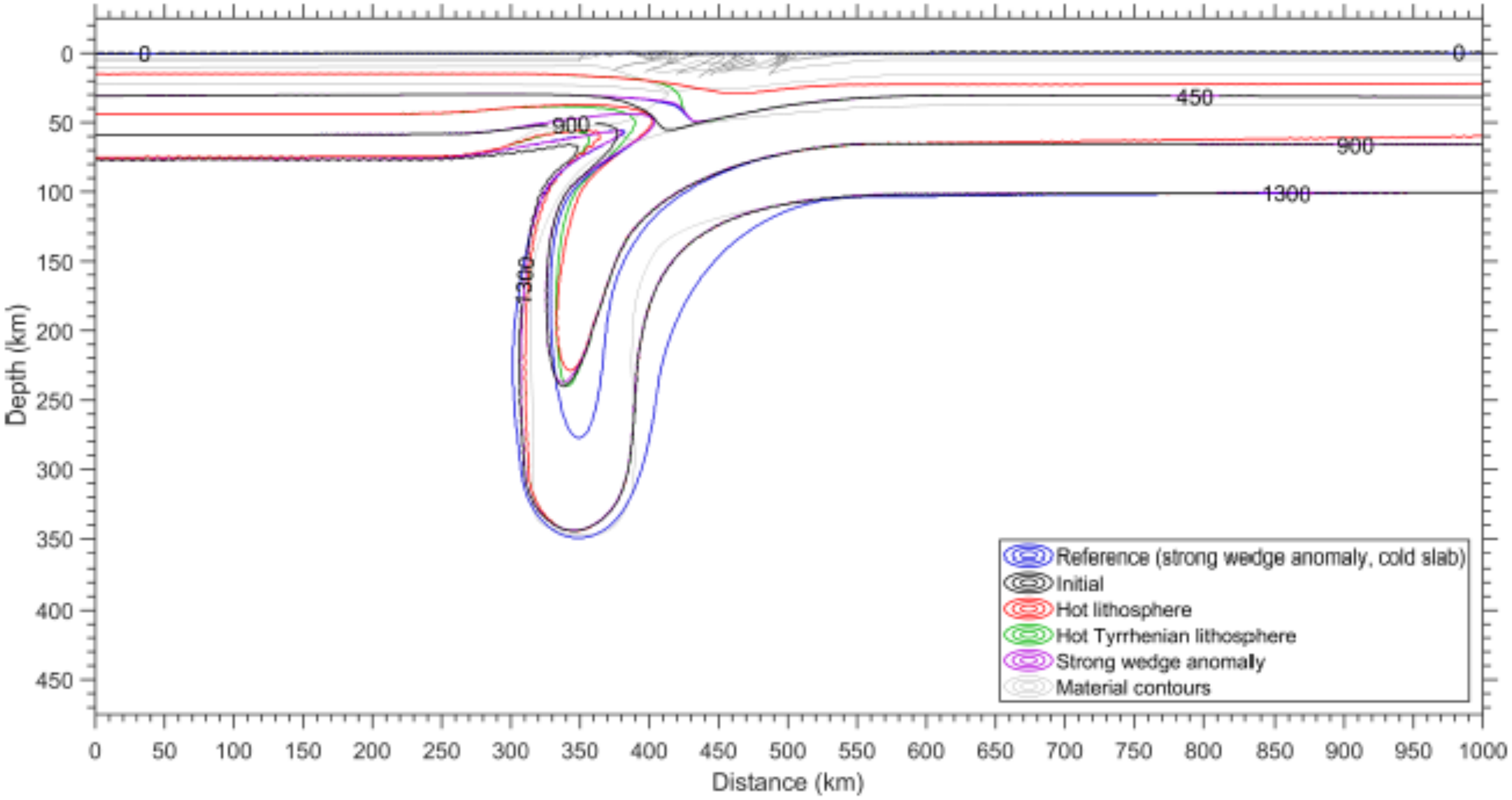
Add tectonic forcing …



D'Acquisto et al., JGR, subm. following Dal Zilio et al., EPSL, 2018

Add thermal model

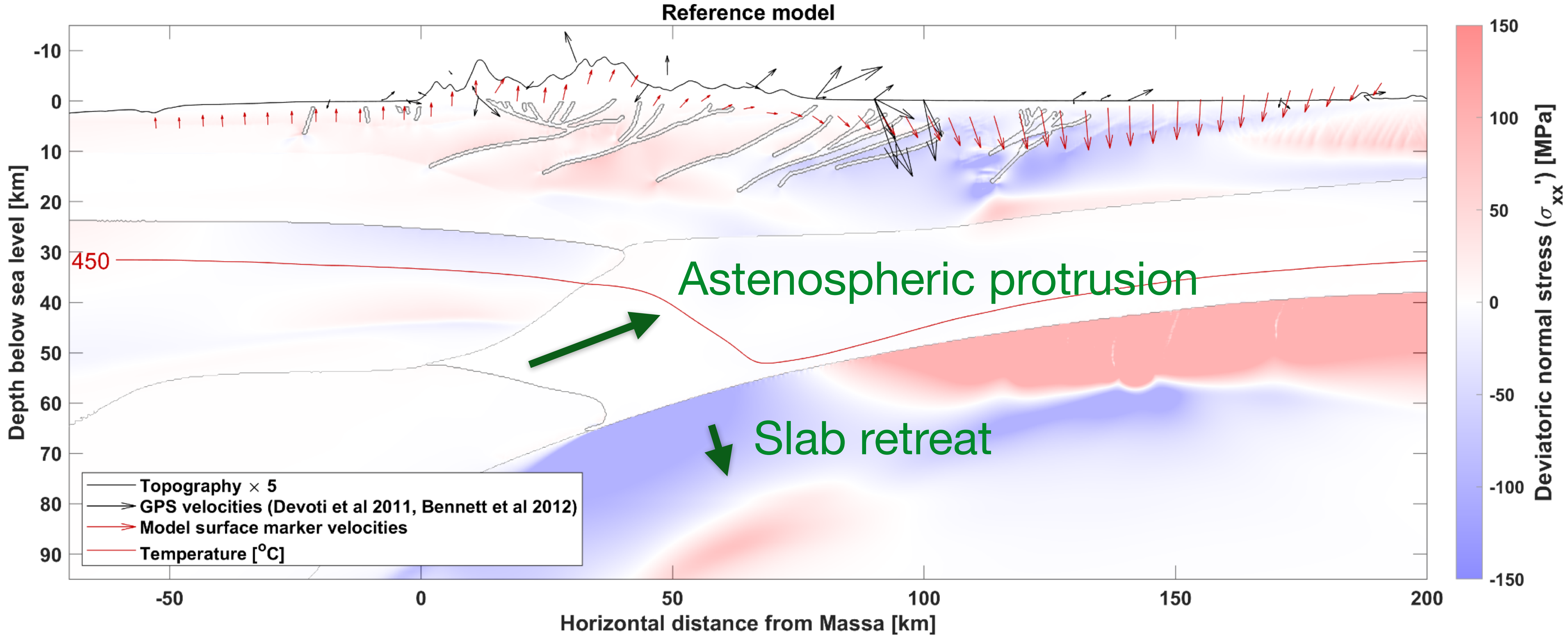
- Using generic slab retreating simulations



Long-term dynamics needs buoyant and highly ductile material beneath suture zone

- Run to sensible long-term deformation regimes
- To agree with stress regime and surface displacements need → → →
  - weak lower crust
  - high mantle wedge temperatures

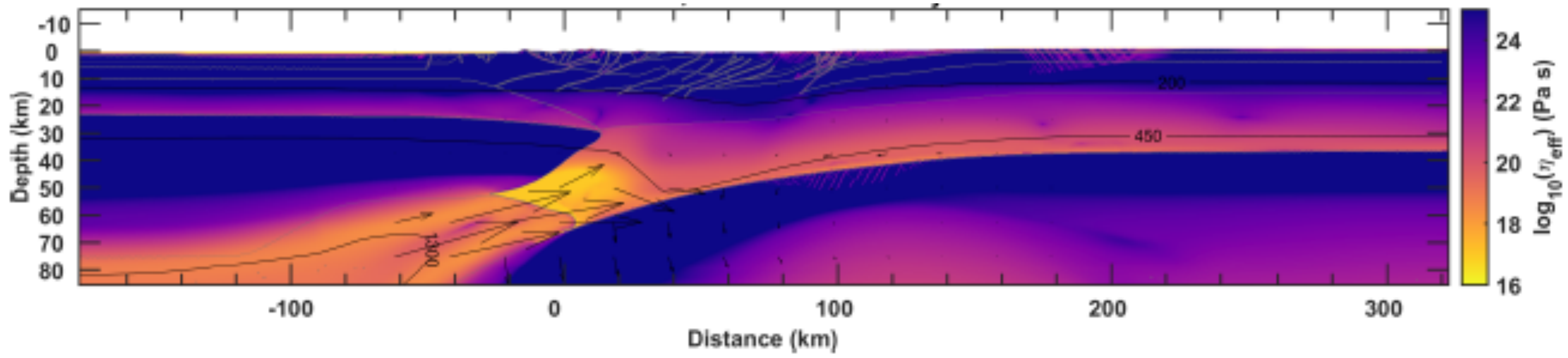
World Stress Map: extension compression



Extension and uplift in Apennine range

Compression and subsidence in Po basin

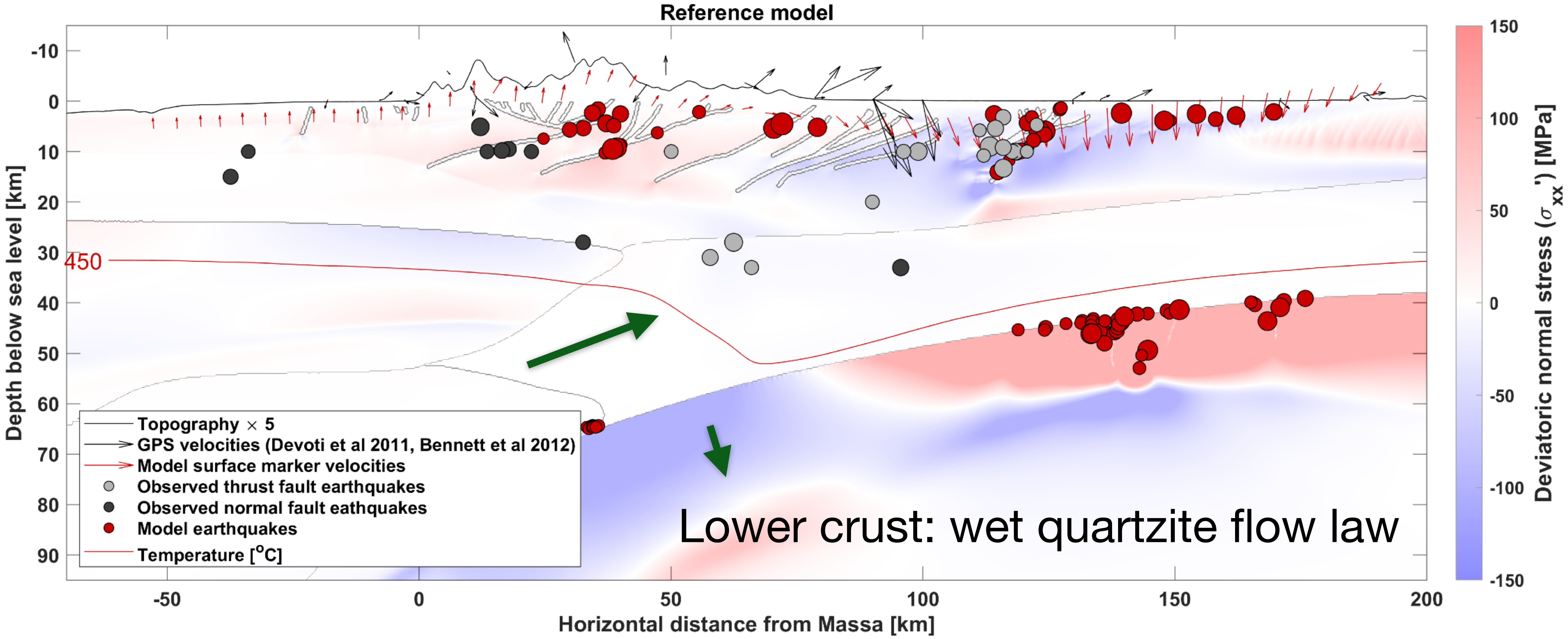
Viscosity distribution



Seismicity broadly agrees with data

- Switch to 1 year time steps

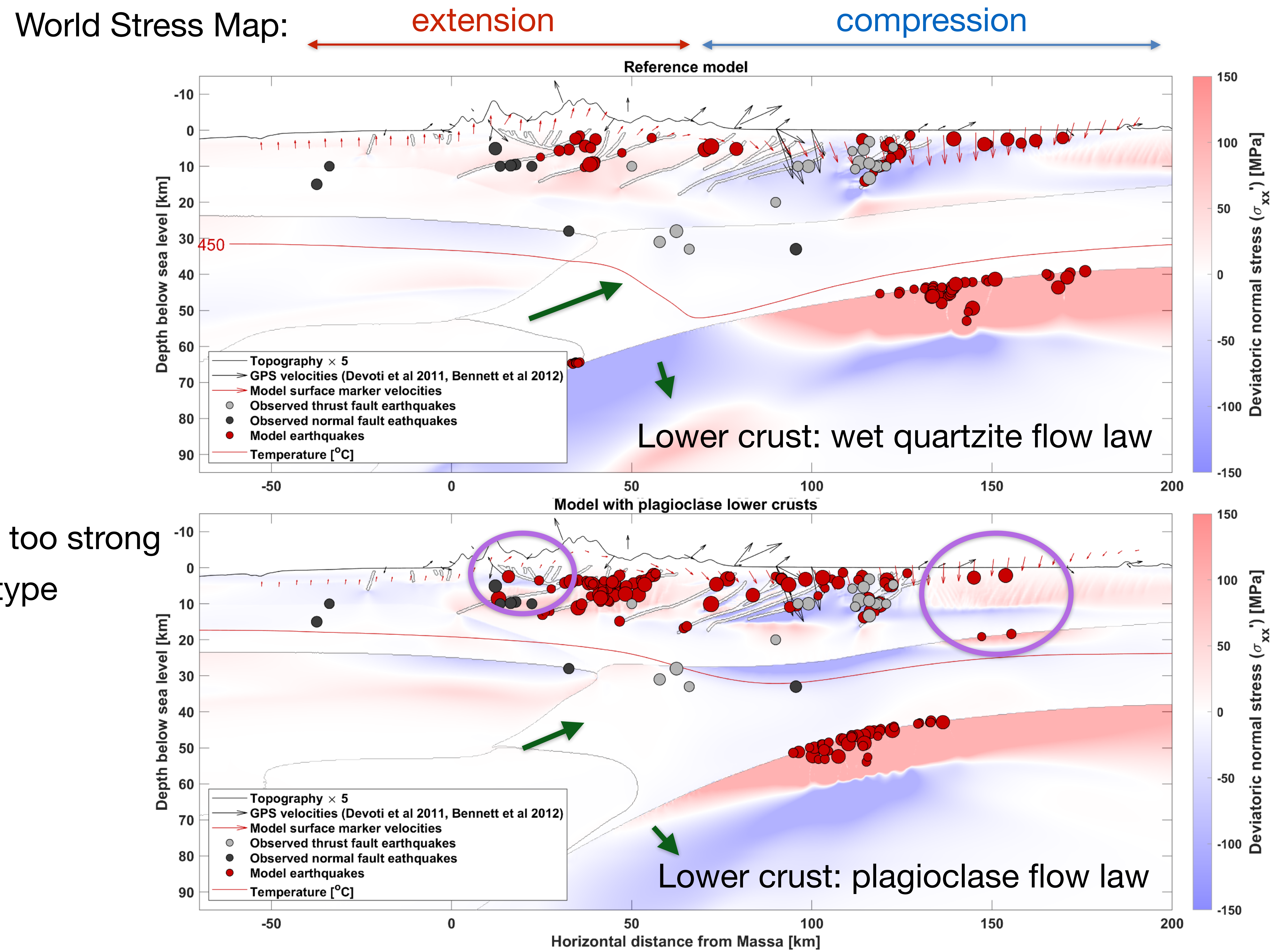
World Stress Map: extension compression



Normal faulting events in Apennine range

Thrust faulting events in Po basin

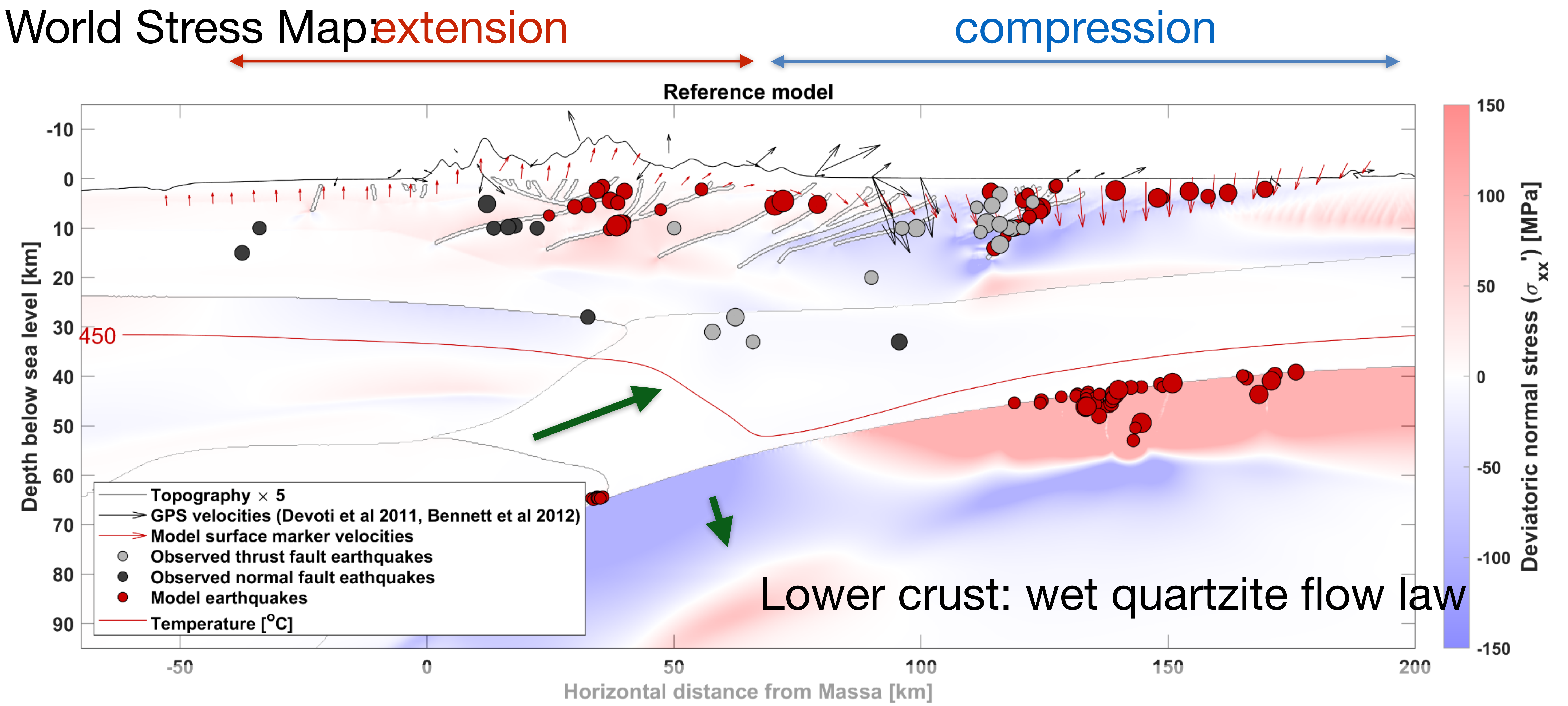
Lower crustal rheology affects stresses and seismicity



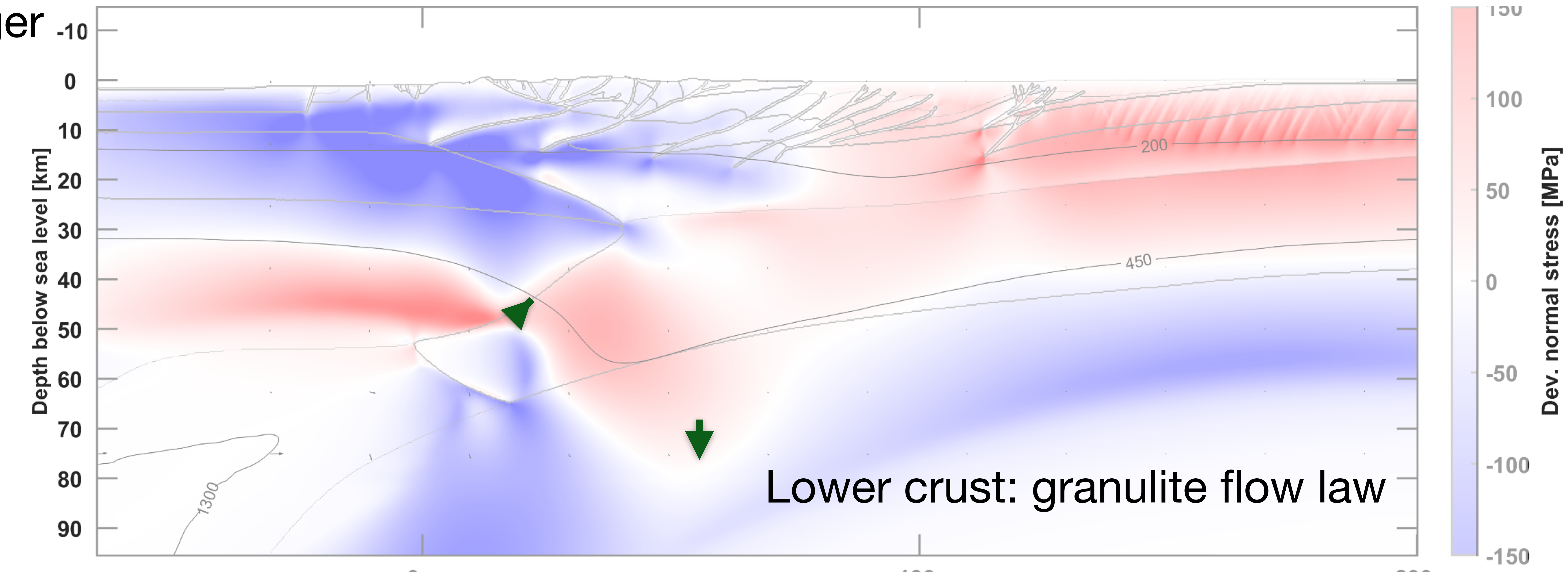
- Plagioclase flow law for lower crust is too strong
  - » Mismatch stress and earthquake type

D'Acquisto et al., JGR, subm.

Lower crustal rheology affects stresses and seismicity

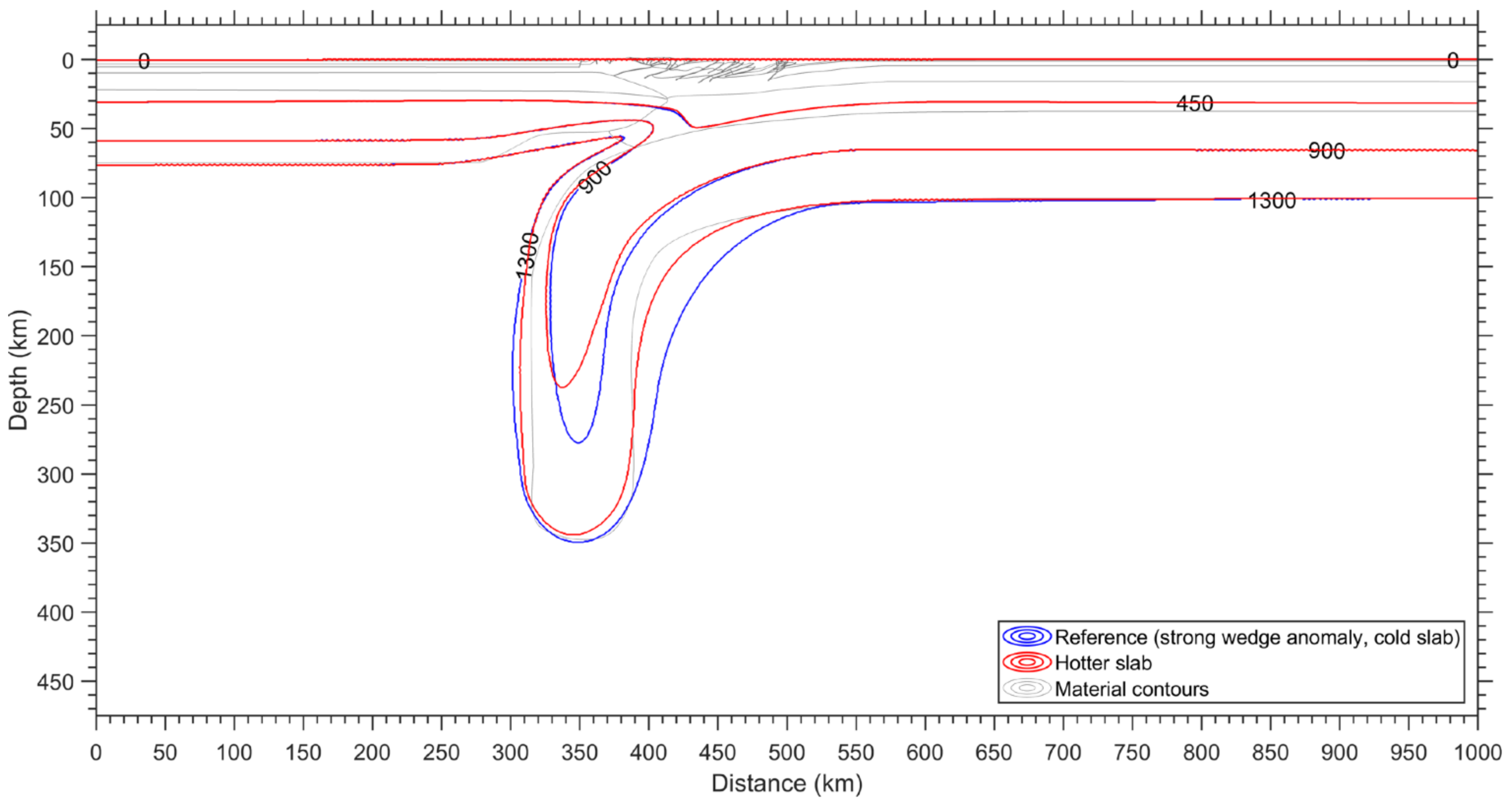


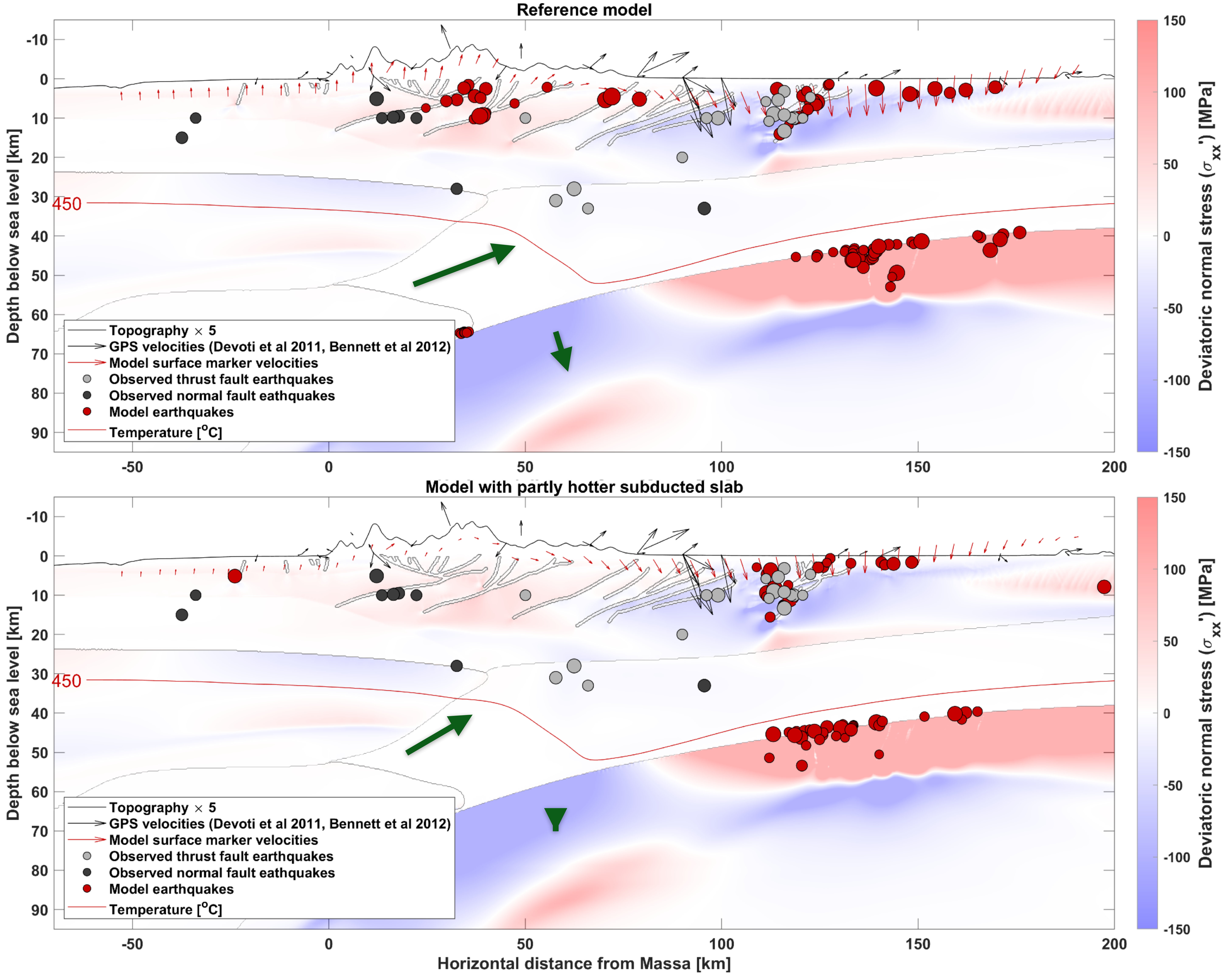
- Granulite flow law for lower crust is even stronger
  - » Complete mismatch stress regime
  - » Need protrusion, delamination, retreat



Large-scale dynamics affects seismicity

World Stress Map: extension compression





- Reduce slab pull
  - » Shuts down extensional seismicity in range

» Should care about depths larger than ~15km

- Seismicity can be another observable to constrain rheologies and structure

Presentation objectives

» Illustrate how lithosphere- and mantle dynamics, structure and rheology can influence shallow tectonics and seismicity

- Does incoming sediment thickness increase maximum earthquake magnitude?
- Do lower crustal and mantle depth temperature and rheology affect seismicity and tectonics?
- **Does the mantle affect surface displacements at time scales of minutes to days?**

Pure Appl. Geophys.

https://doi.org/10.1007/s00024-019-02250-z

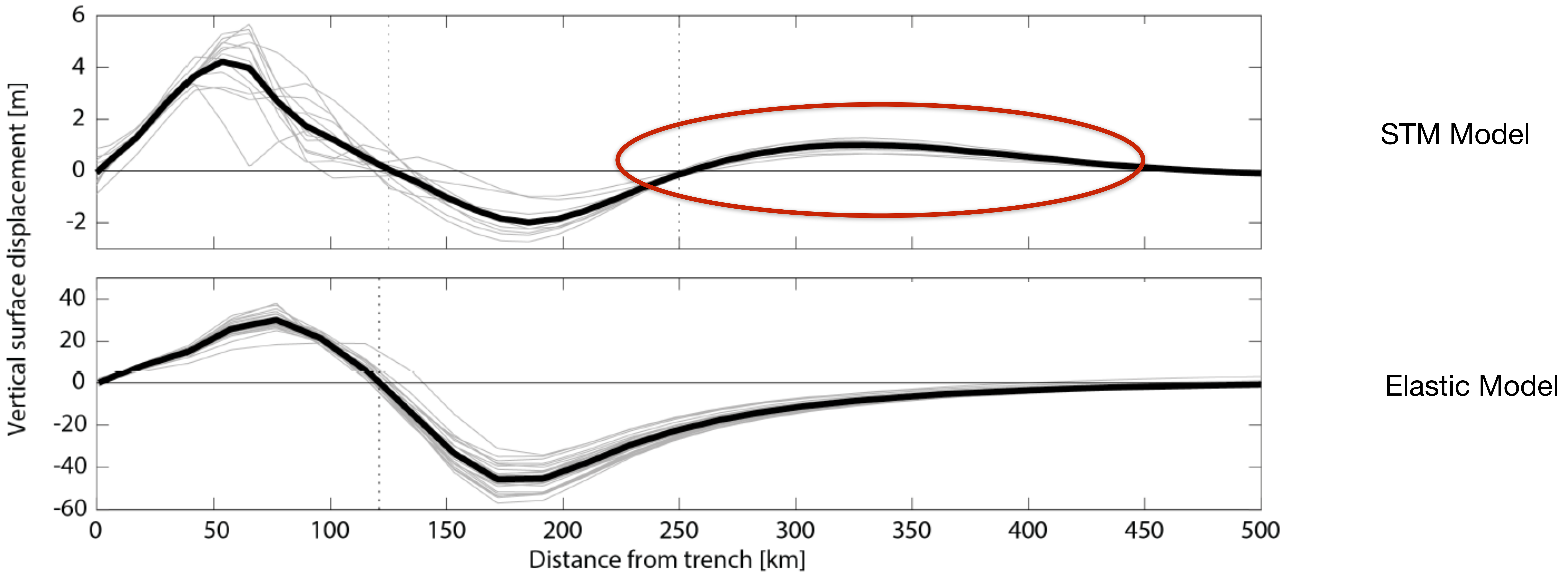
Pure and Applied Geophysics

A Secondary Zone of Uplift Due to Megathrust Earthquakes

Ylona van Dinther,[1,2] Lukas E. Preiswerk,[1,3,4] and Taras V. Gerya[4]

A secondary zone of coseismic uplift

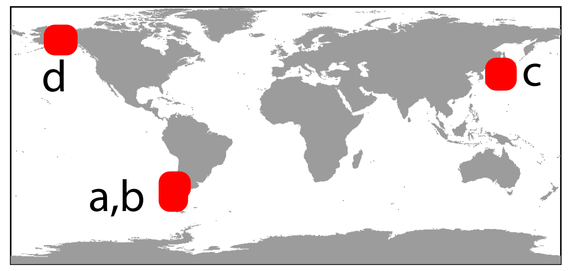
- STM models identified a new physical phenomena: a secondary zone of coseismic uplift

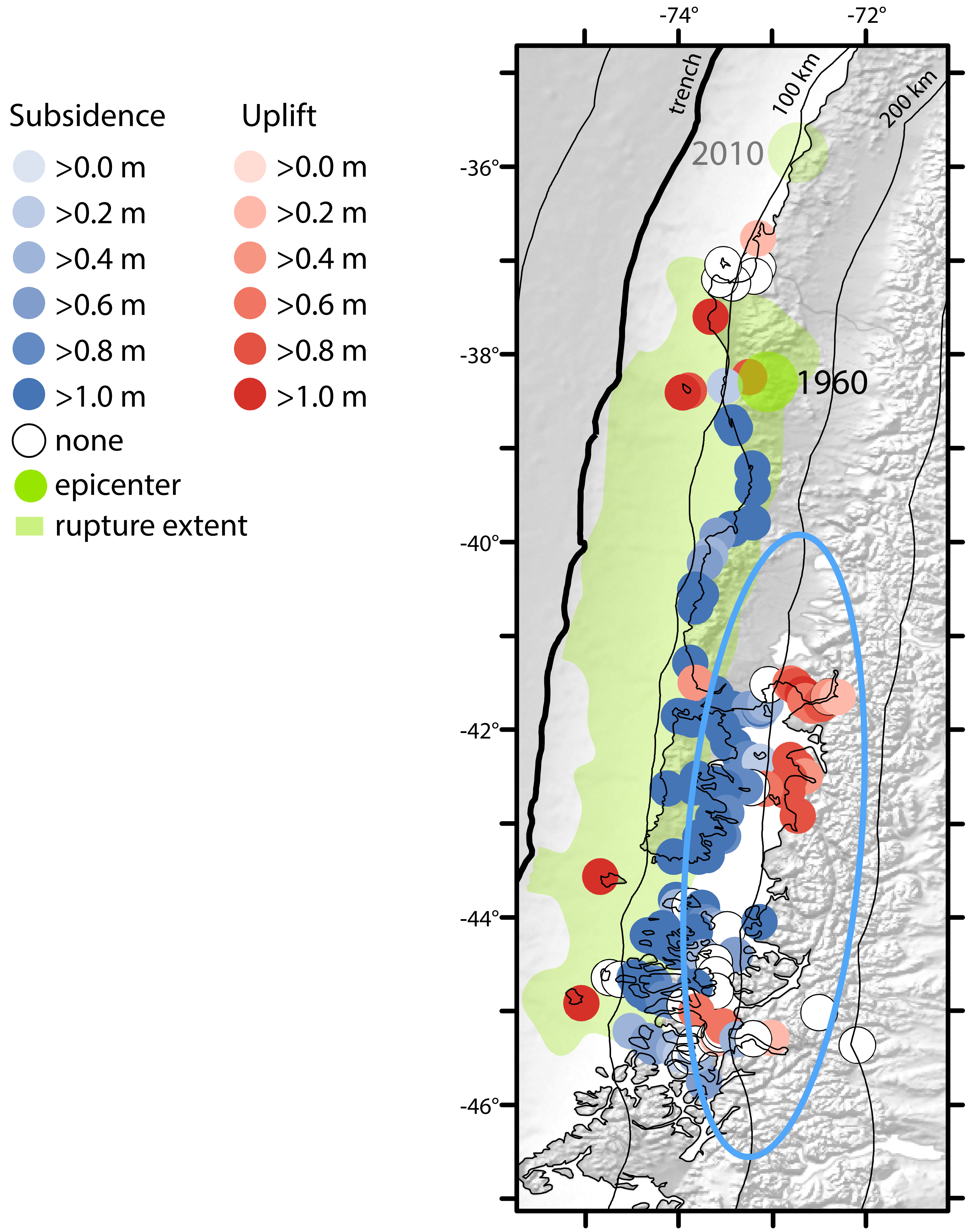


van Dinther et al., PAGeoph, 2019

A secondary zone of coseismic uplift exists

- STM models identified a new physical phenomena: a secondary zone of coseismic uplift
- Its existence is confirmed for 4 out of 4 megathrust earthquakes analyzed, albeit at different distances and extents





1960 M9.5 Valdivia earthquake

A secondary zone of coseismic uplift exists

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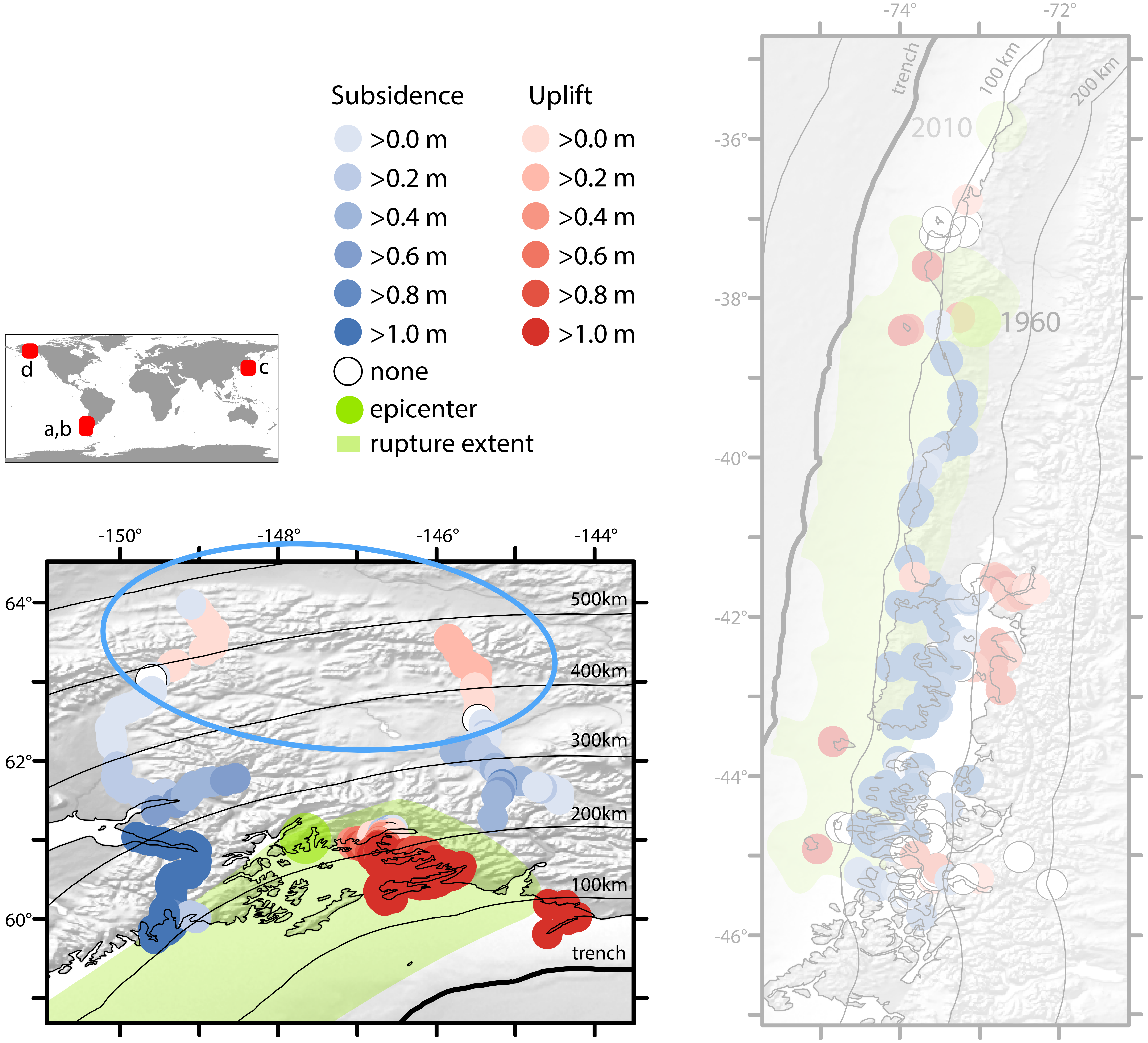

1964 M9.2 Alaska earthquake

A secondary zone of coseismic uplift exists

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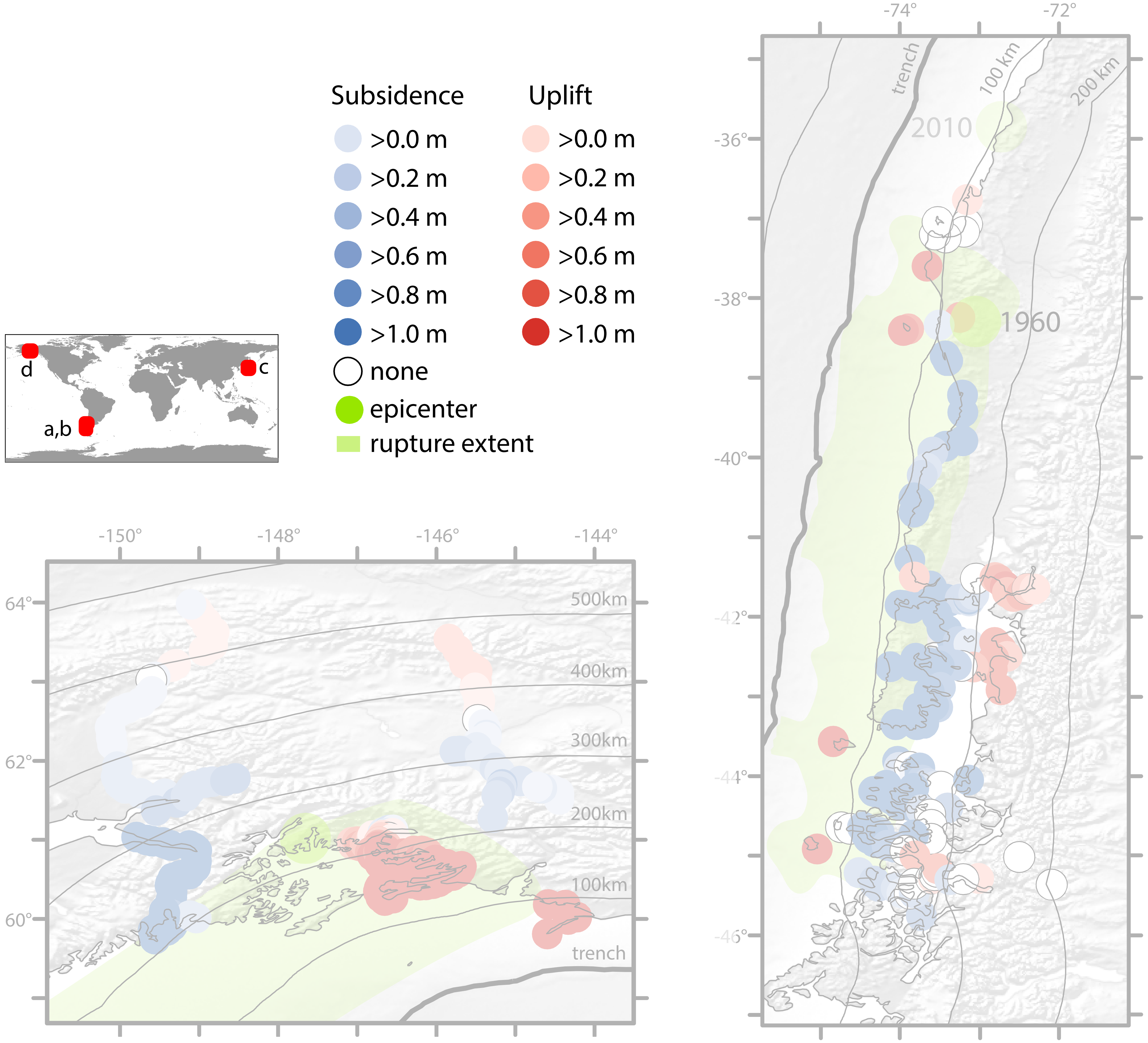

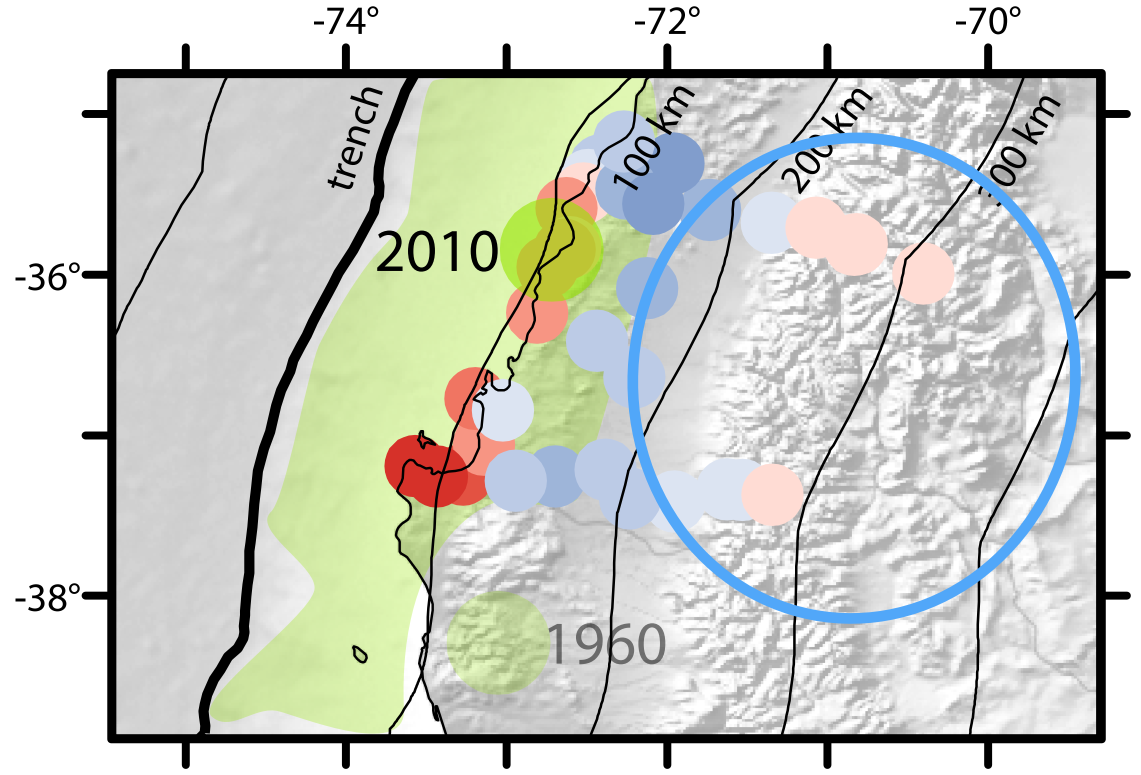

2010 M8.8 Maule earthquake

van Dinther et al., PAGeoph, 2019

A secondary zone of coseismic uplift exists

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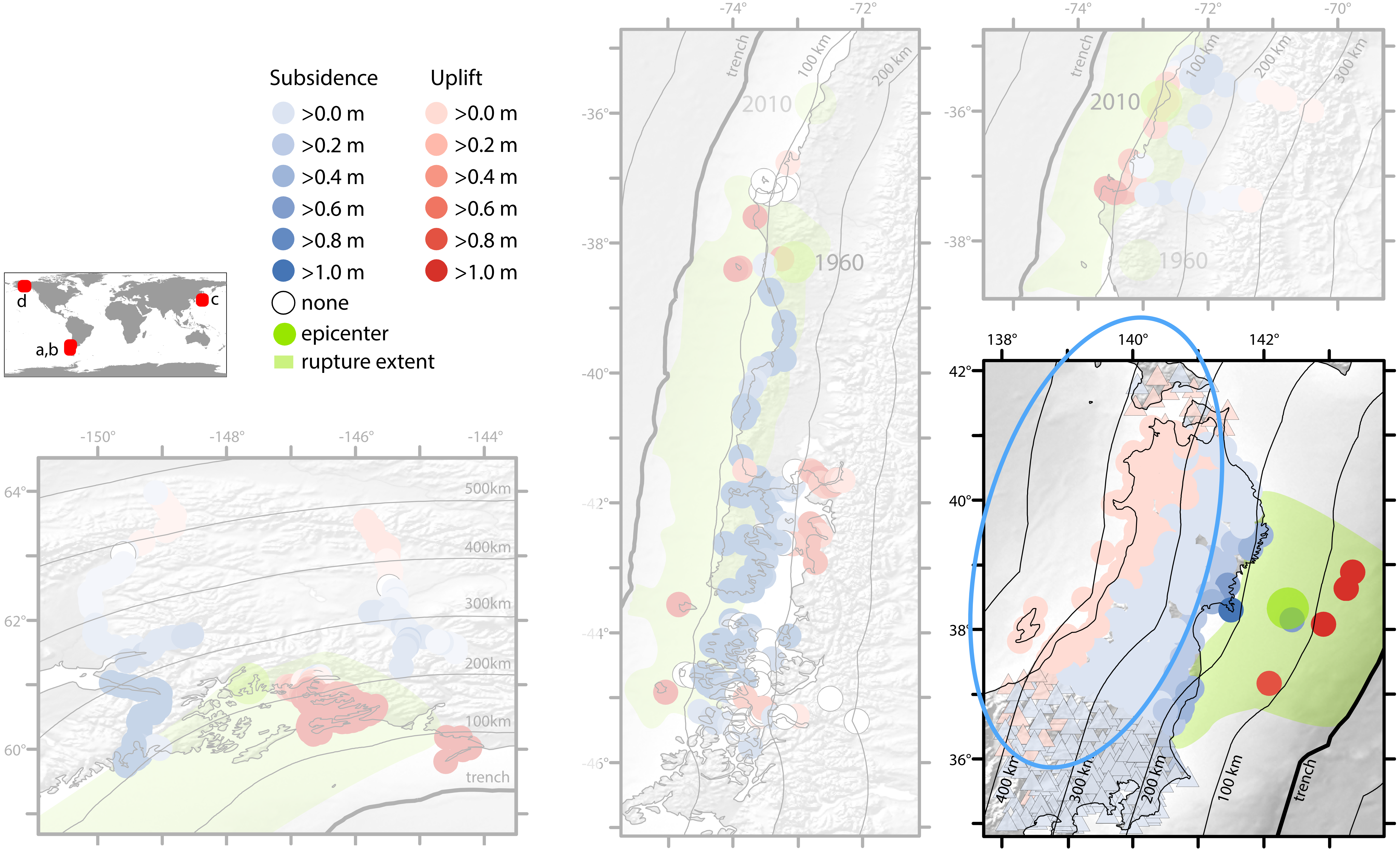
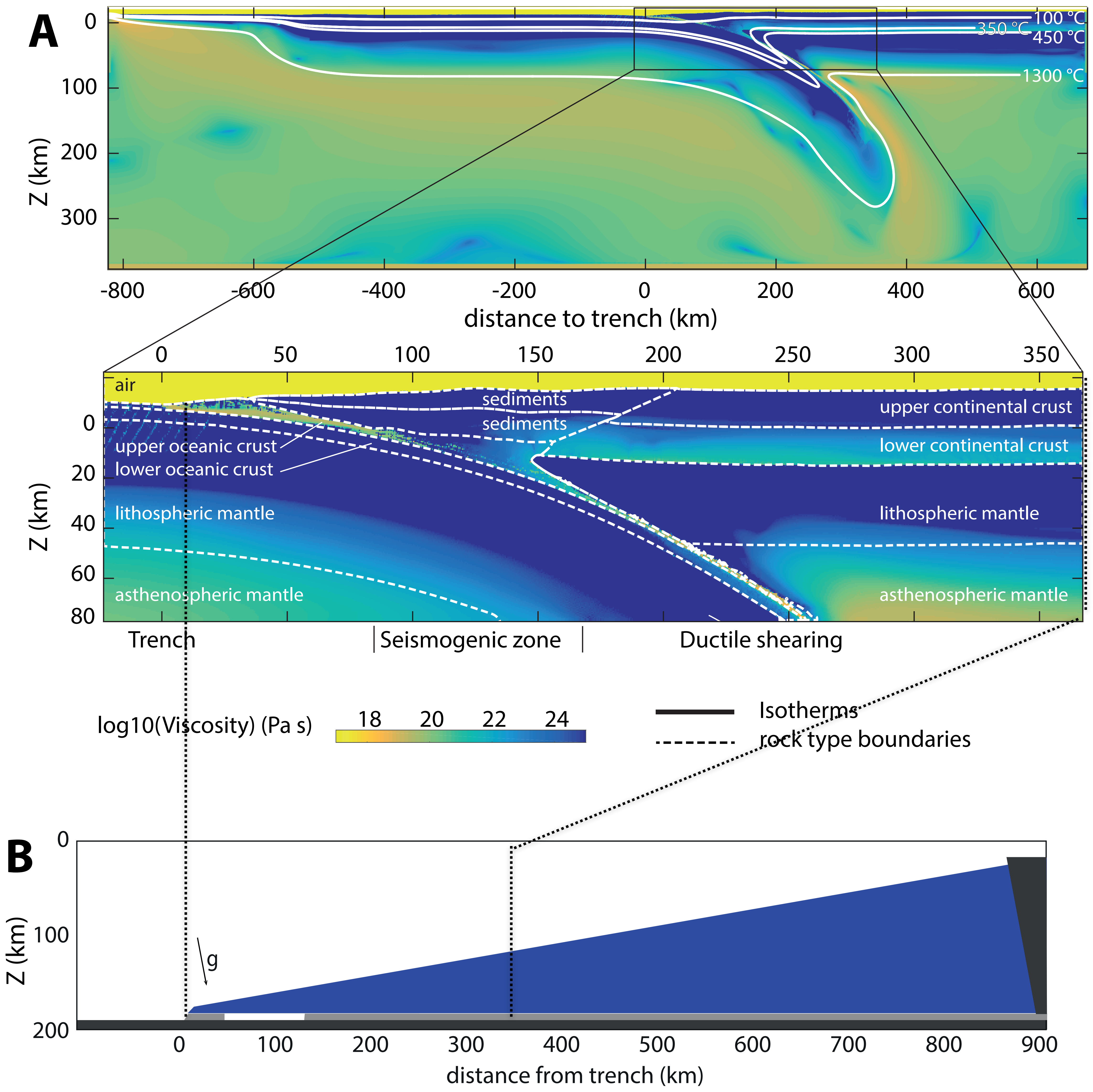


2011 M9.0 Tohoku earthquake

van Dinther et al., PAGeoph, 2019

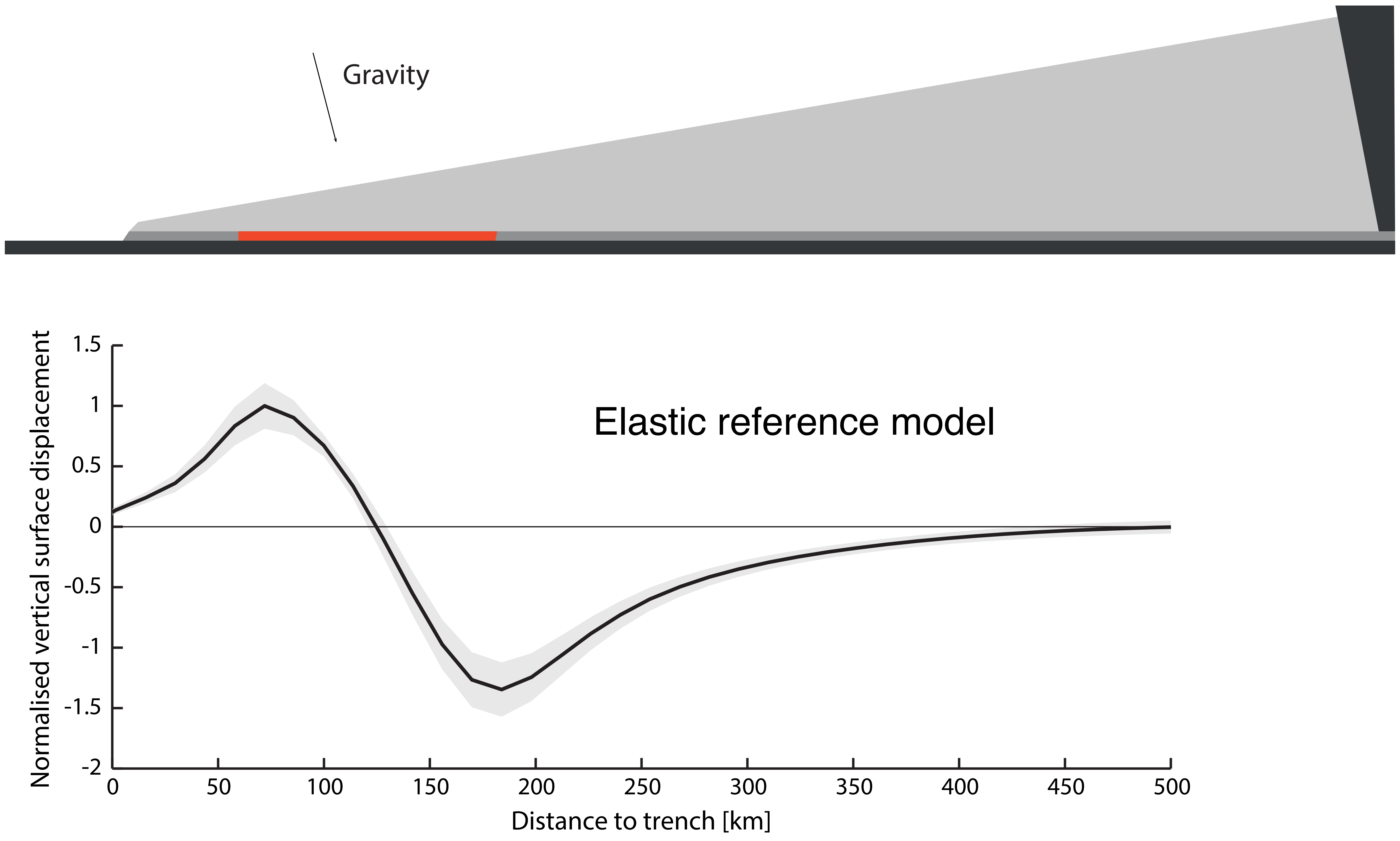
Systematic exploration through simple and complex models

- First attempt to understand based on simple models



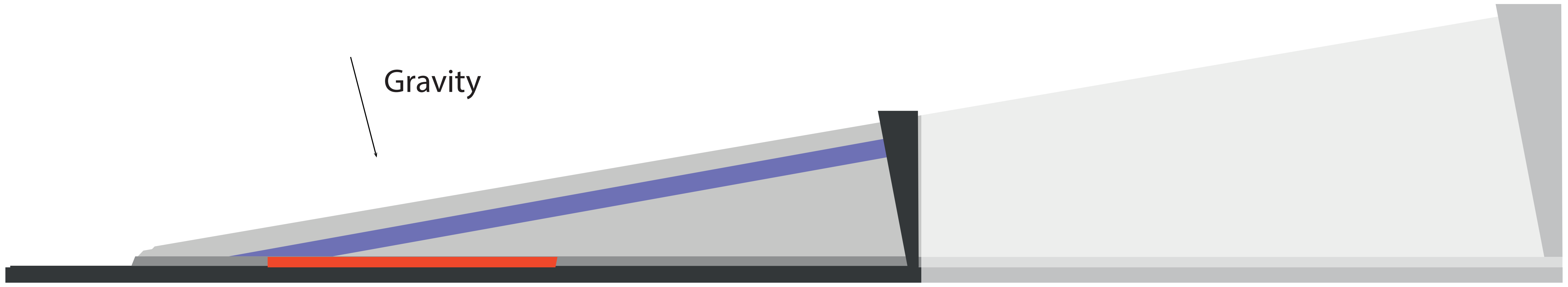
van Dinther et al., PAGeoph, 2019

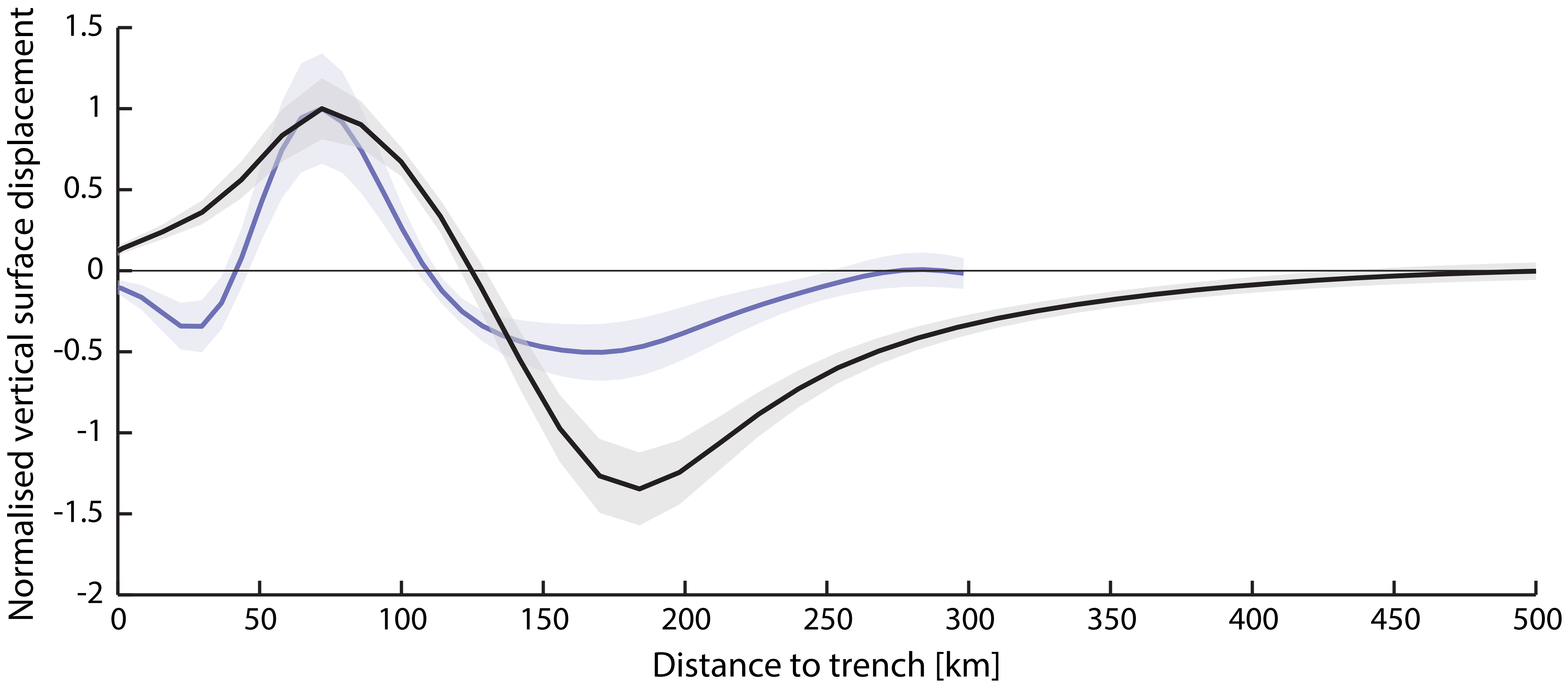
What is the governing physical mechanism?



What is the governing physical mechanism?

- (1) Elastic rebound after interseismic buckling of **visco**-elastically layered lithosphere



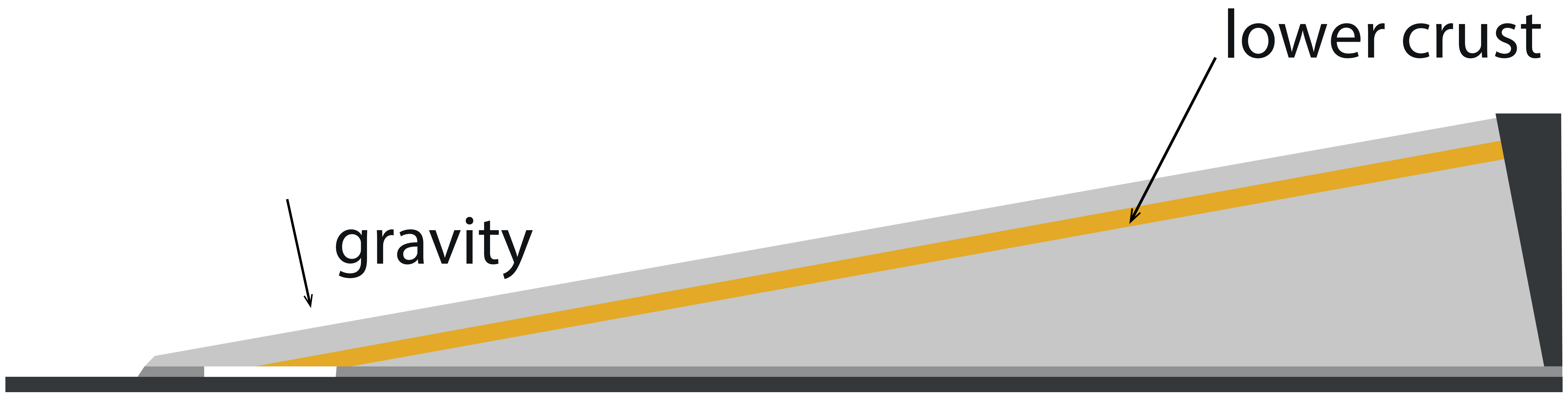


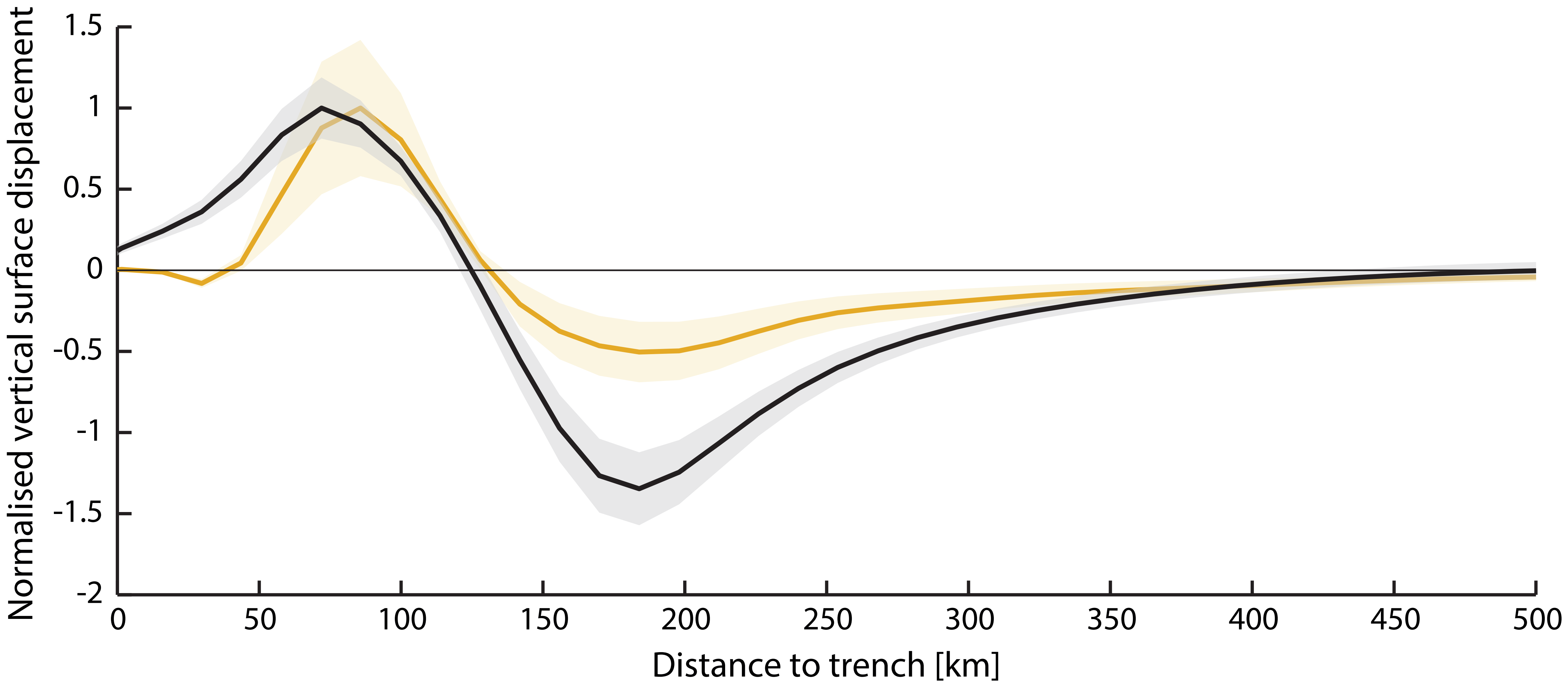
» Visco-elastic structure is important for surface displacements

» A back stop could play a role, but it is arguable if that is persistently present

What is the governing physical mechanism?

- (1) Elastic rebound after interseismic buckling of **visco**-elastically layered lithosphere





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van Dinther et al., PAGeoph, 2019

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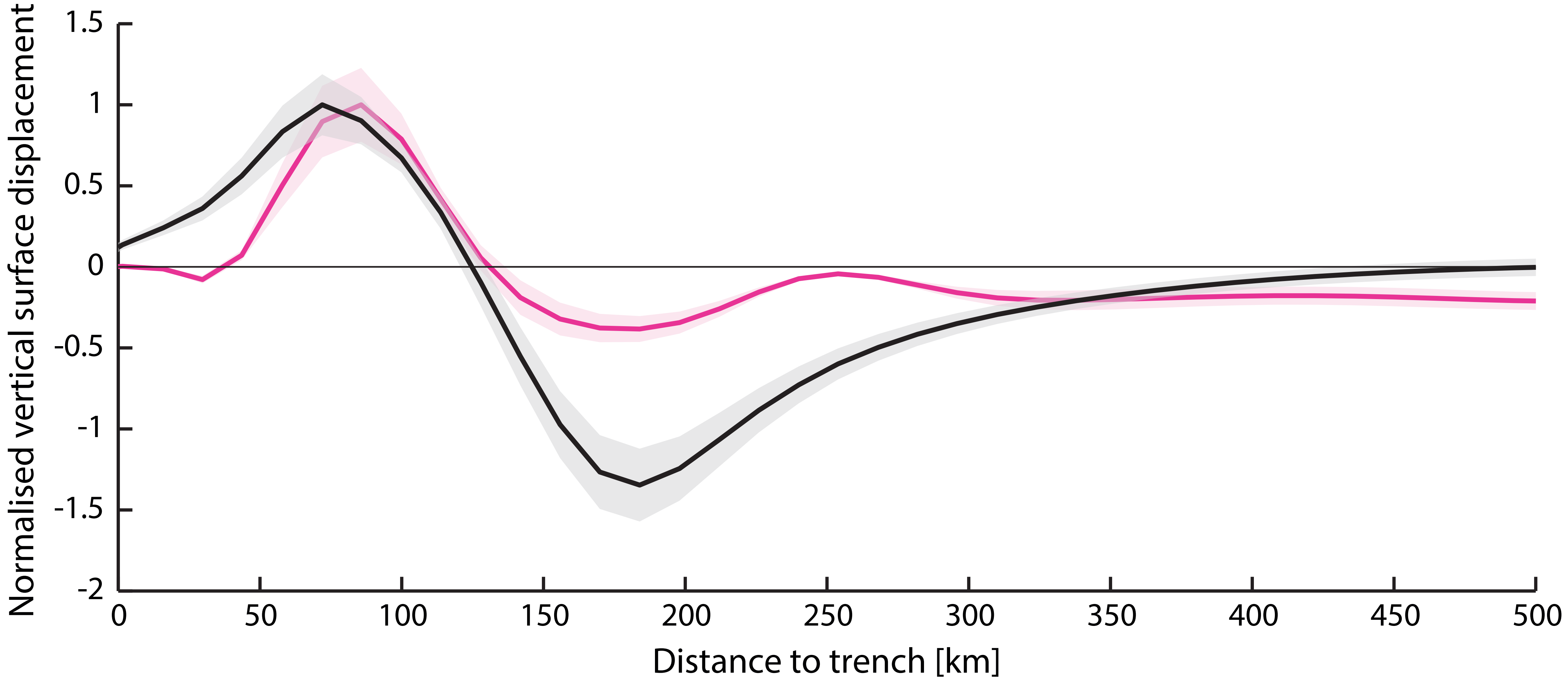
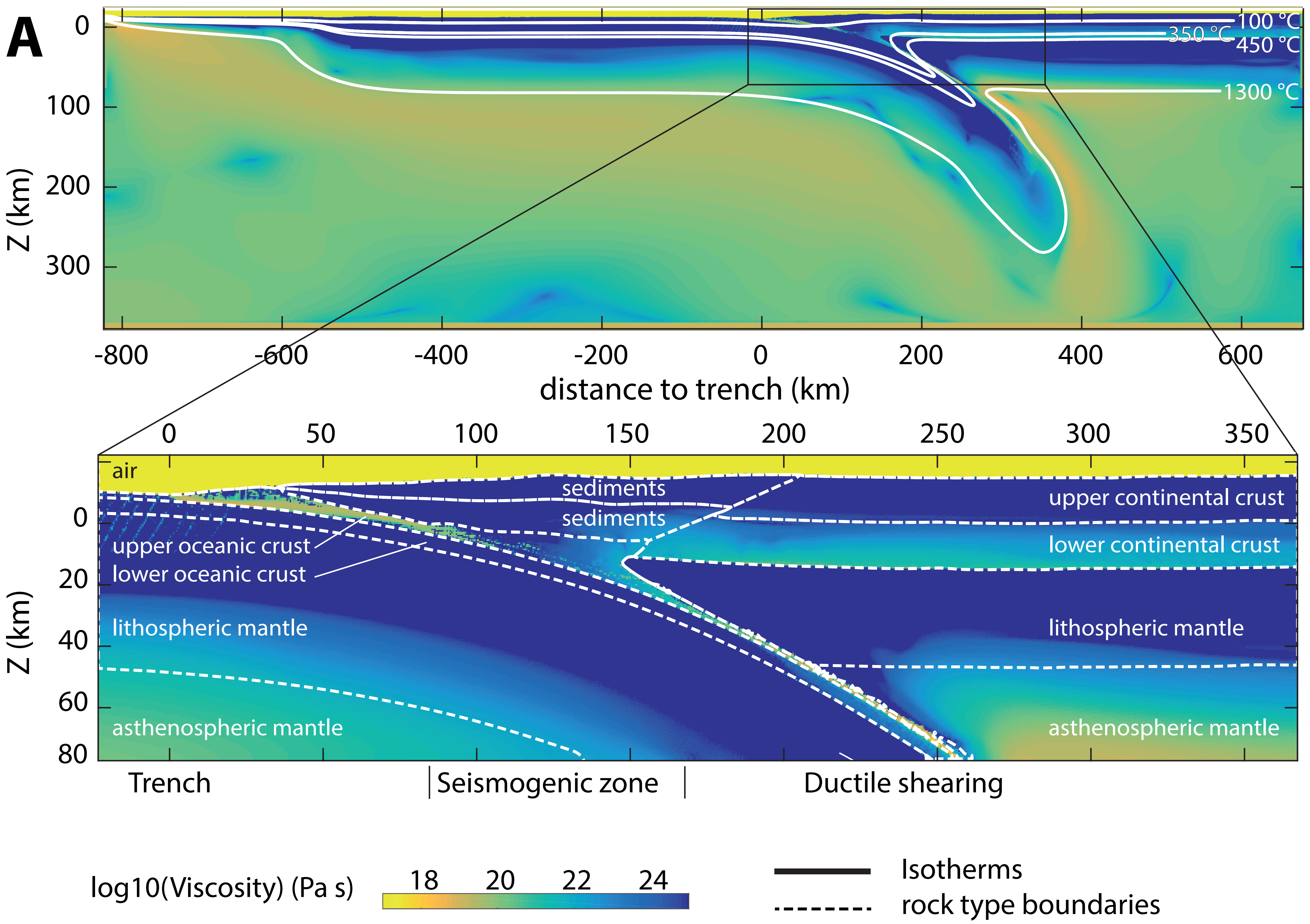


» Visco-elastic structure is important for surface displacements

Systematic exploration through simple and complex models

- First mechanism is rebound of elastically buckled lithosphere → assess more realistic models

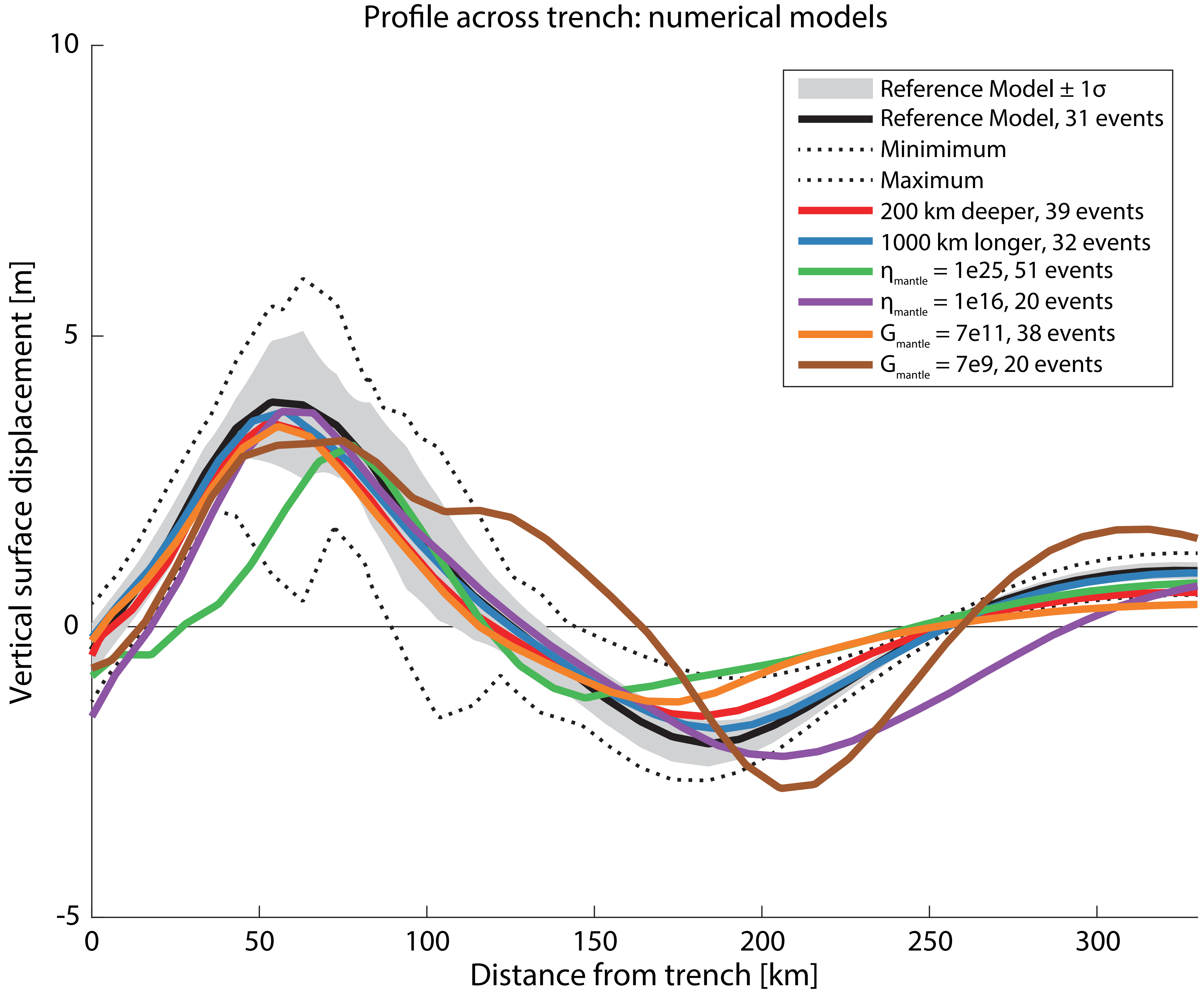


van Dinther et al., PAGeoph, 2019

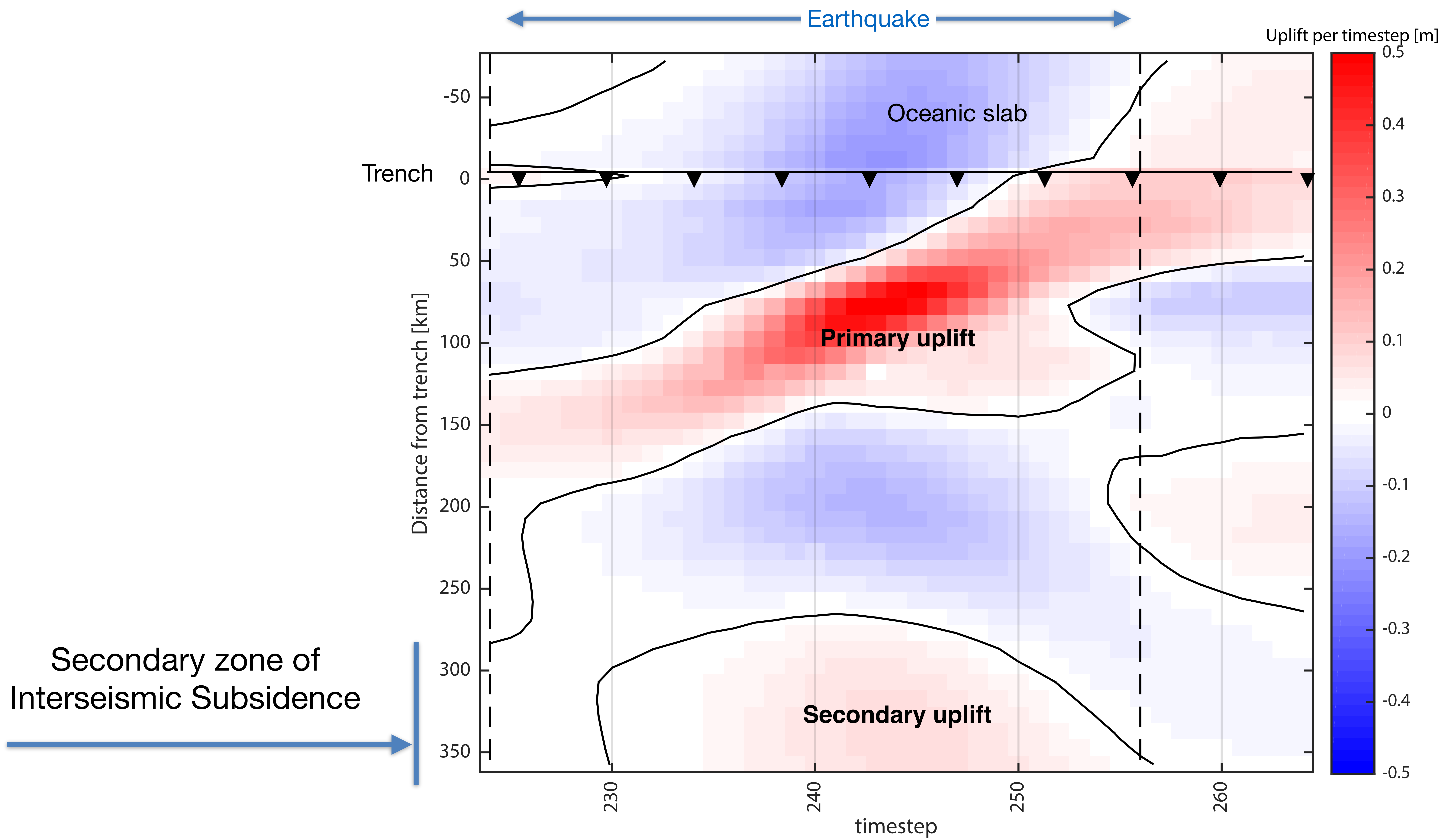
Consistent occurrence of secondary uplift

- In hundreds of realistic experiments we are not able to remove uplift
  - Also not when elastic buckling is inhibited

» basic mechanism is missing



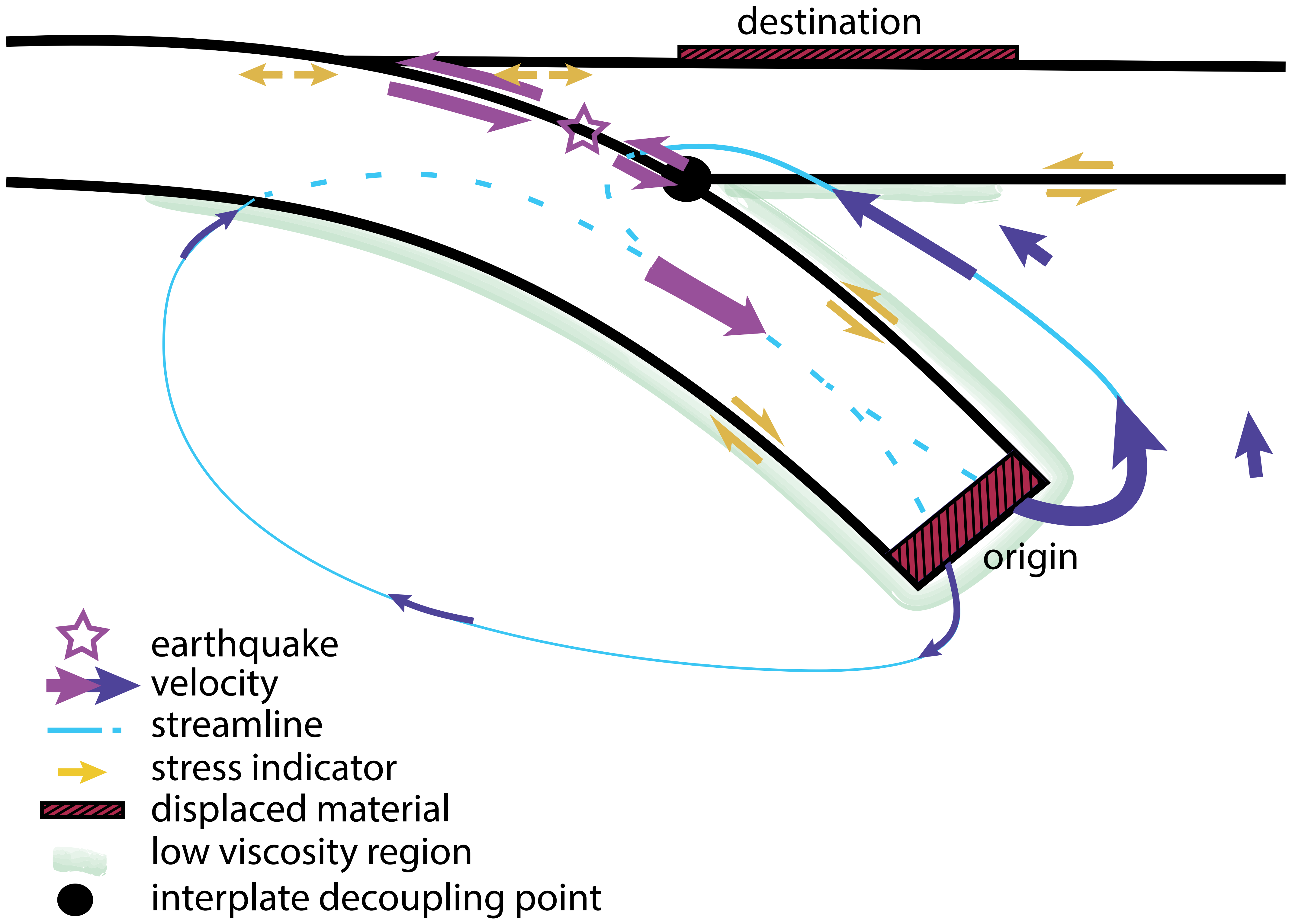
Spatiotemporal uplift in co- and postseismic period



van Dinther et al., PAGeoph, 2019

What is the governing physical mechanism?

- (1) Flexural buckling of a thin upper crust facilitated by a visco-elastic lower crust and mantle /backstop
- (2) Penetration of oceanic slab that induces upward flow

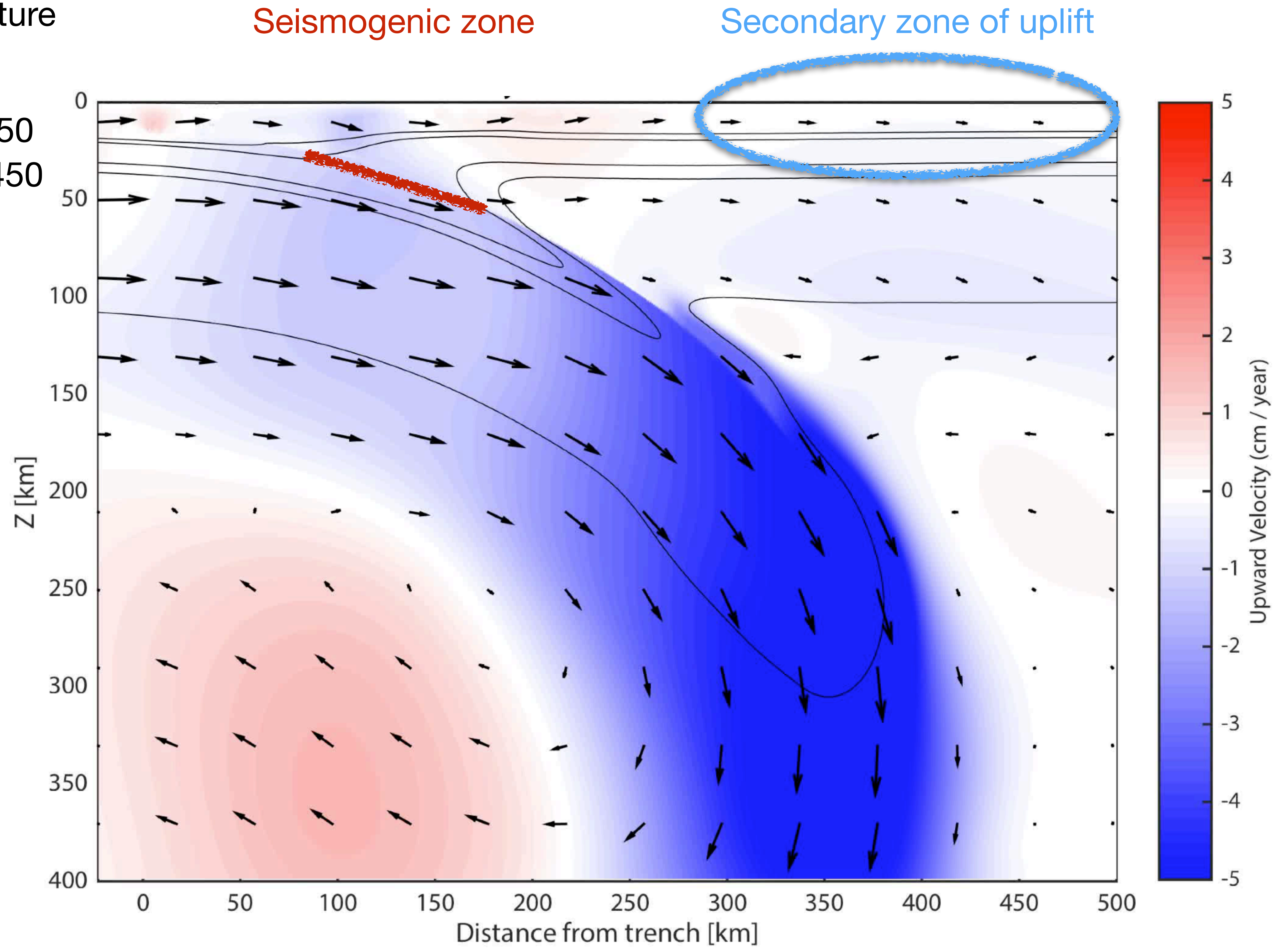


Temperature (in dC):

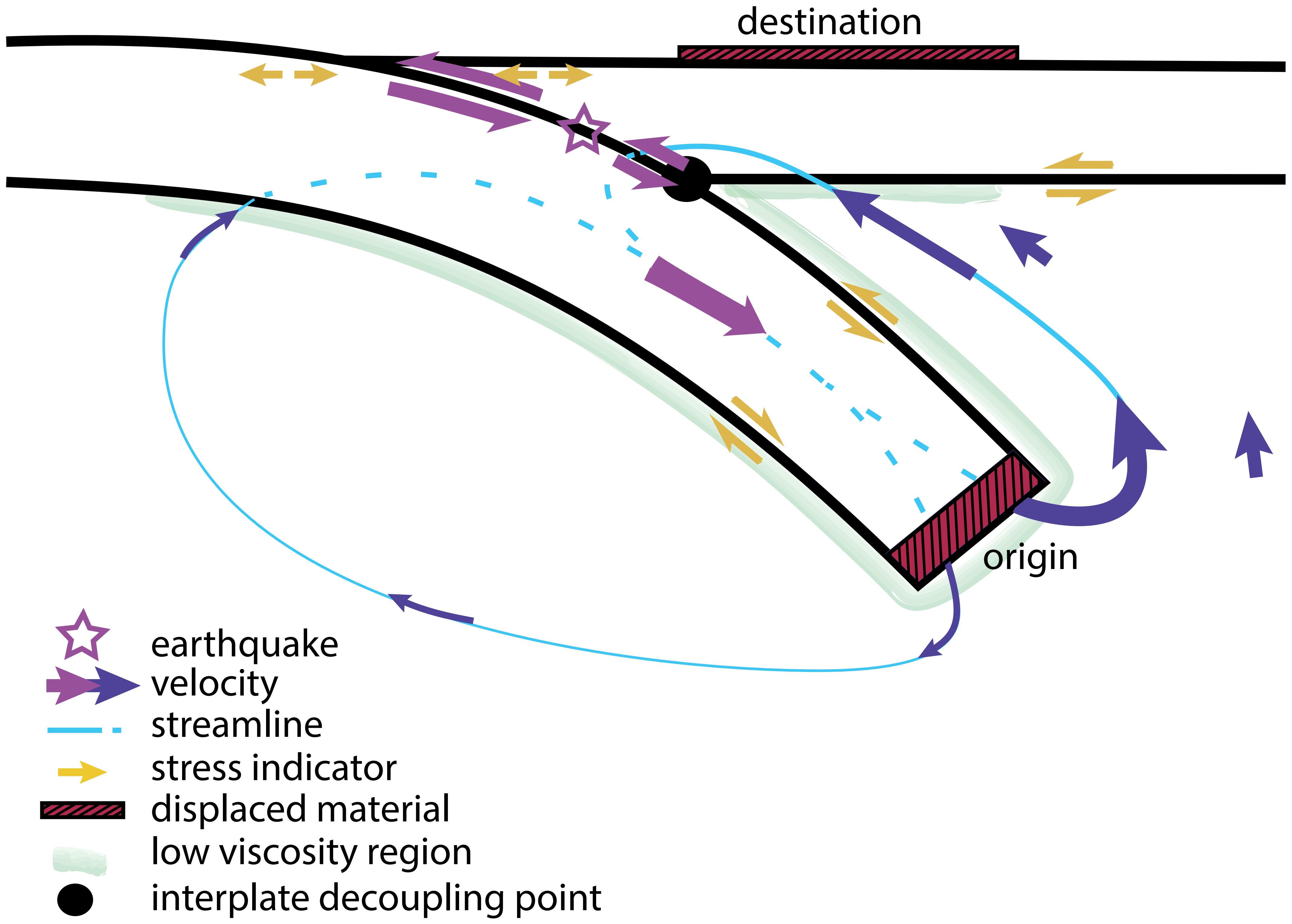
100-150

350 -450

1300



» **Deep mantle processes affect the shallow surface also at time scales of minutes and days**



» Subduction is NOT a gradual process

» Could see earthquakes as integral driver of mantle flow

- Difficult to apprehend slab-mantle response at such time scales?
  (know behaves elastically during seismic wave propagation)

- Several times over last years we tried to disprove it, but we could not…

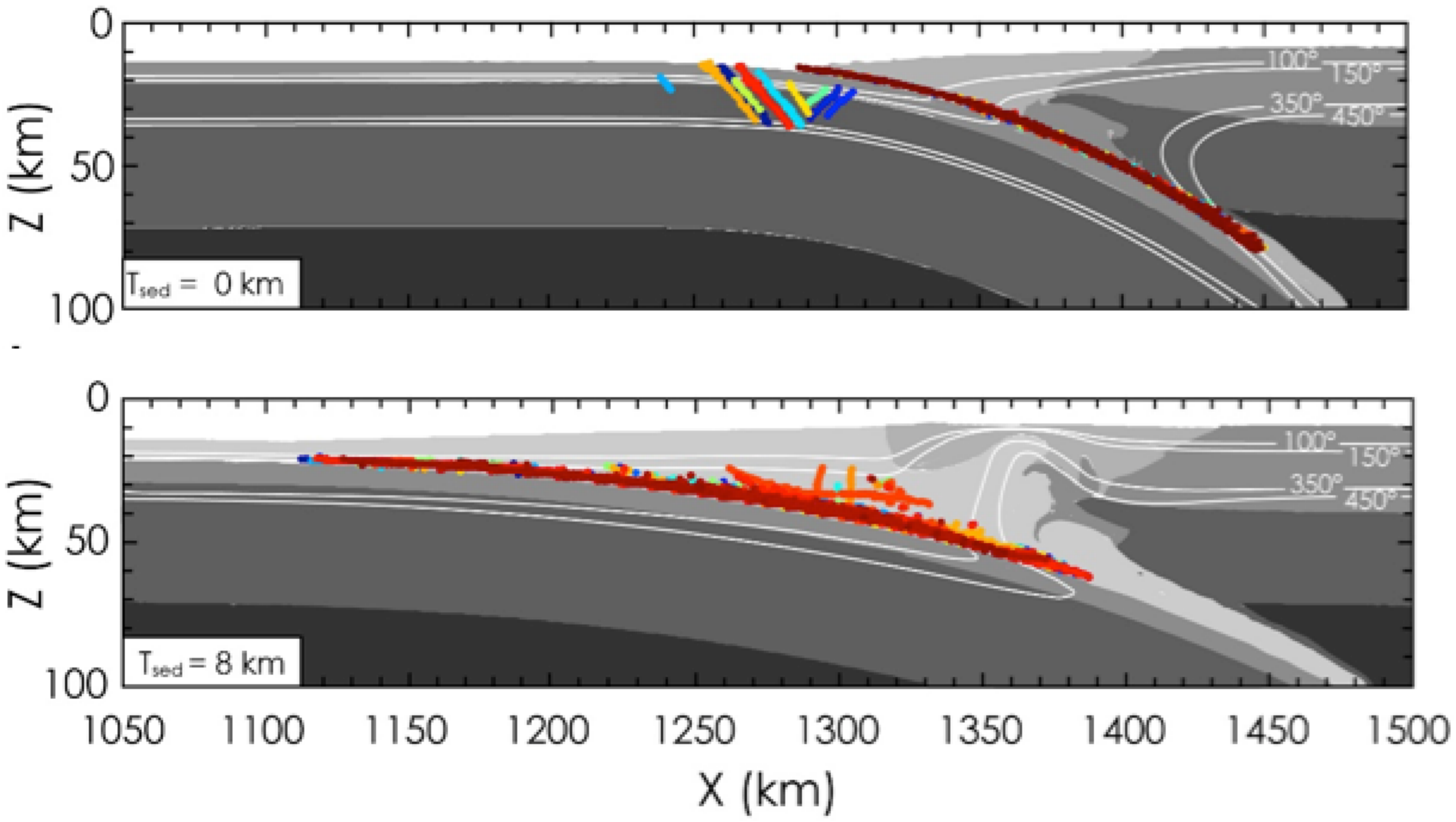
van Dinther et al., PAGeoph, 2019

What do new data show?

- Model predictions on secondary zone of uplift keep being confirmed by new data
  - Predicted Secondary Zone of Interseismic Subsidence is observed
    - Revealed across Northwest Pacific *(Bill Hammond et al.)*
  - Postseismic data 2010 and 2011 events show majority is coseismic
  - Korean peninsula uplifts in days after 2011 M9 Tohoku earthquake
    (Kim and Bae, 2012)

» **Illustrate how lithosphere- and mantle dynamics, structure and rheology can influence shallow tectonics and seismicity**

- Does incoming sediment thickness increase maximum earthquake magnitude?
  - Yes; larger sedimentary wedge → trench moves seaward and slab unbends → slab dip ↓ → seismogenic width ↑ → Mmax ↑
  - Modeling long-term dynamics and sediment presence increases Mmax by an order of magnitude !



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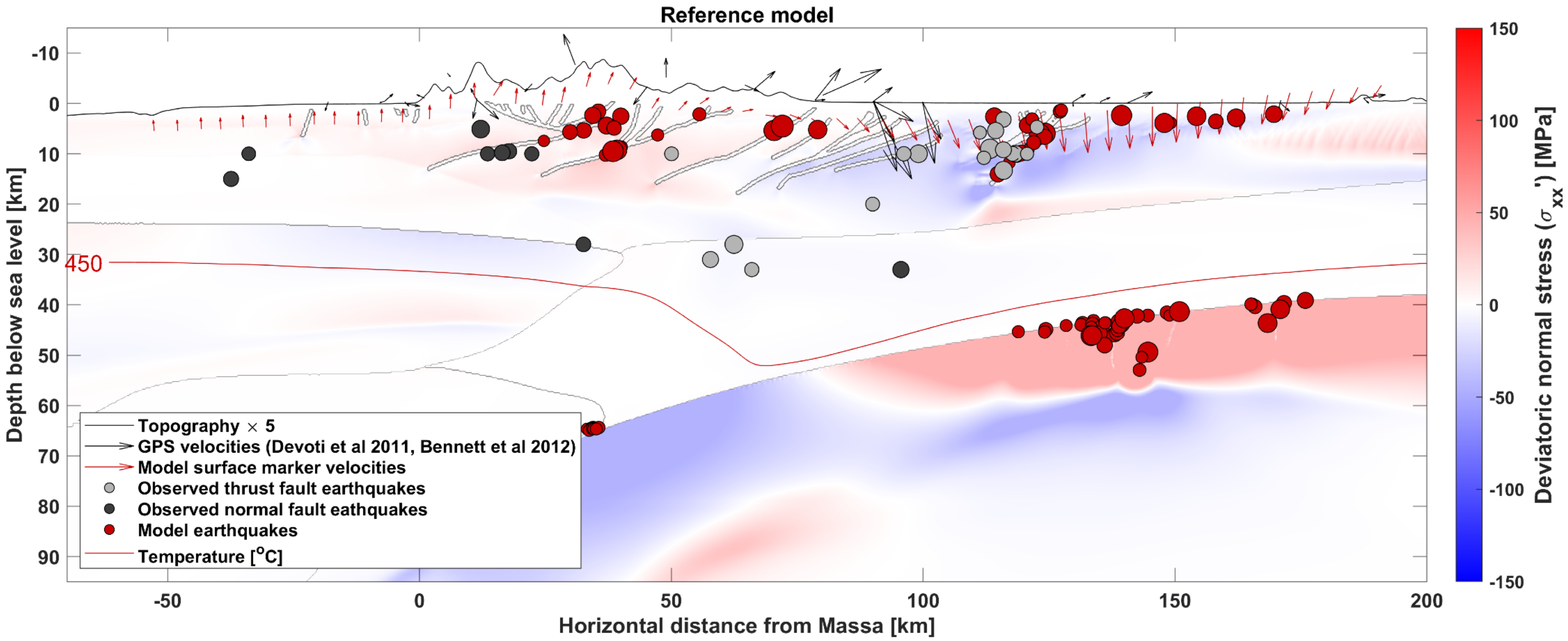
  - Yes, in complex tectonic settings driven by deep loading, such as Northern Apennines



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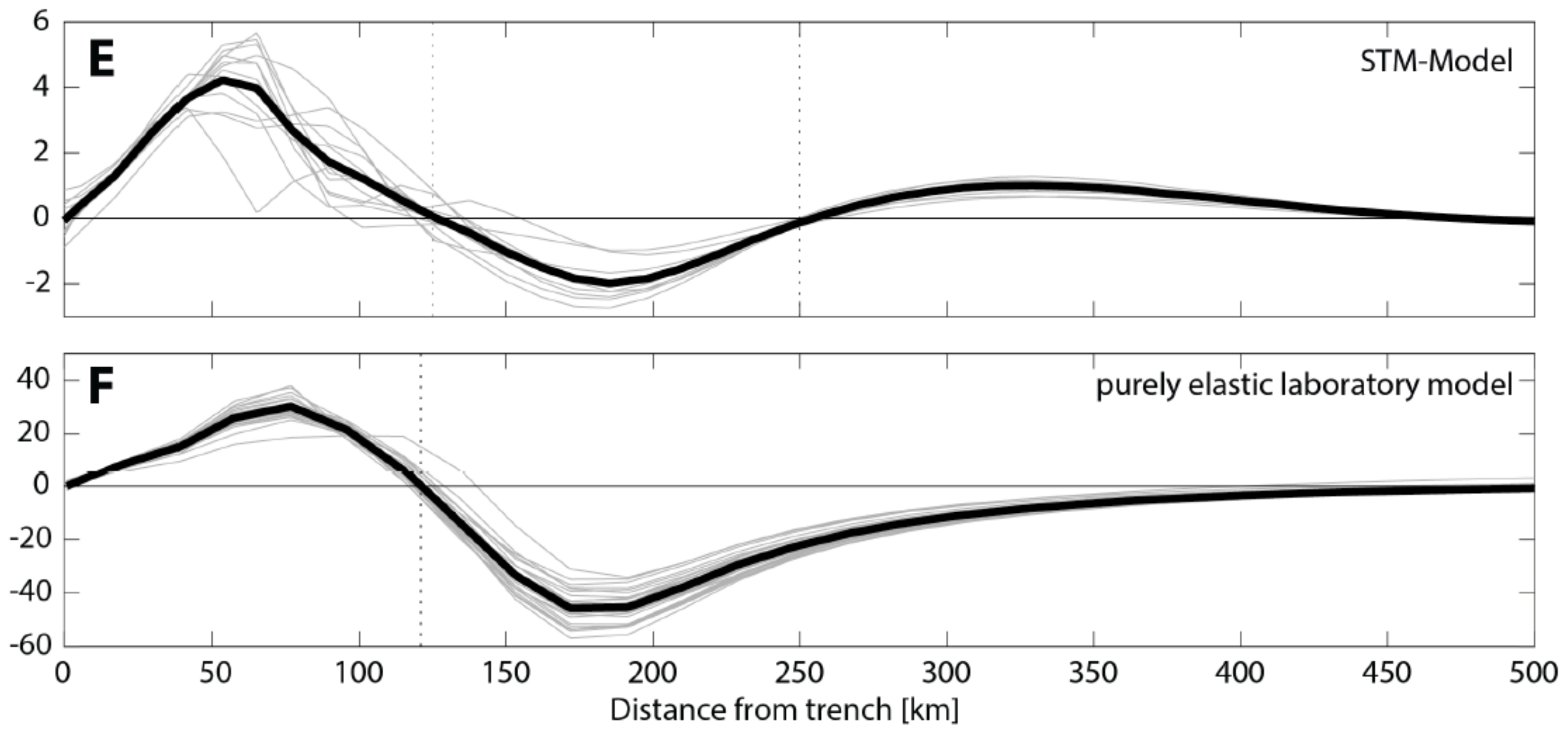
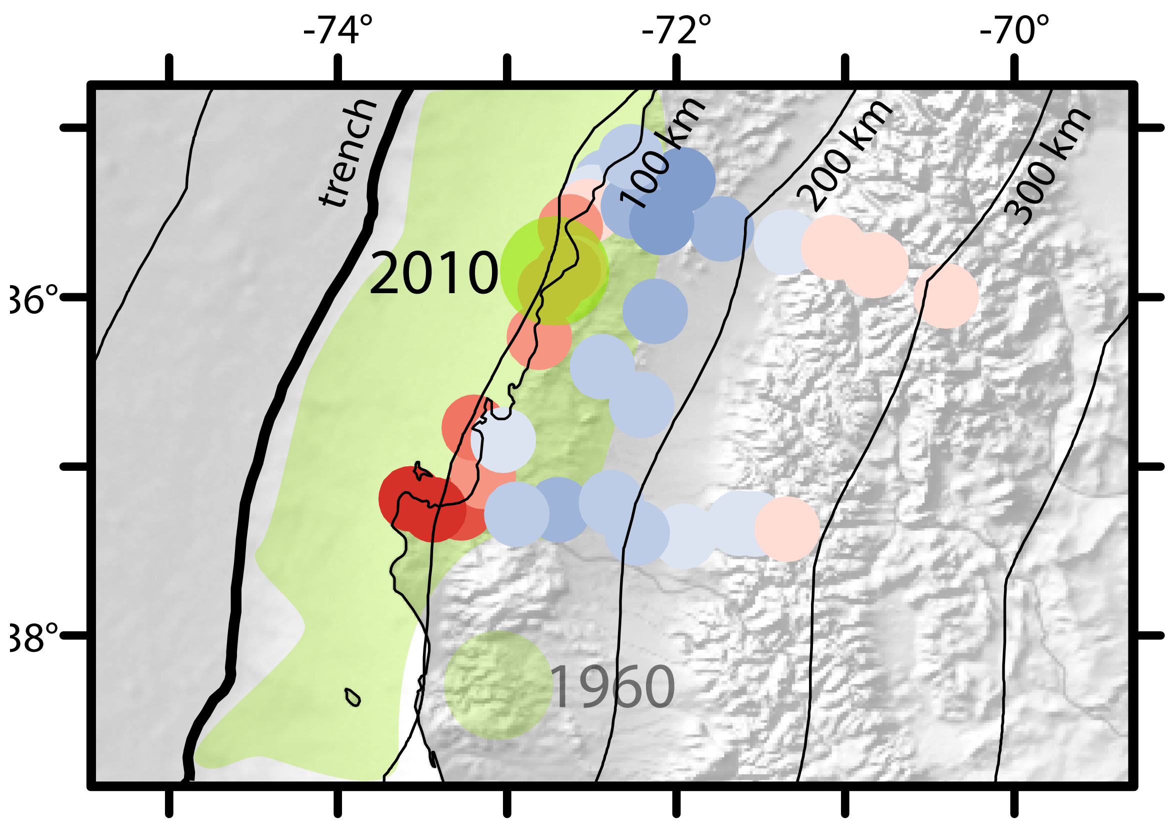
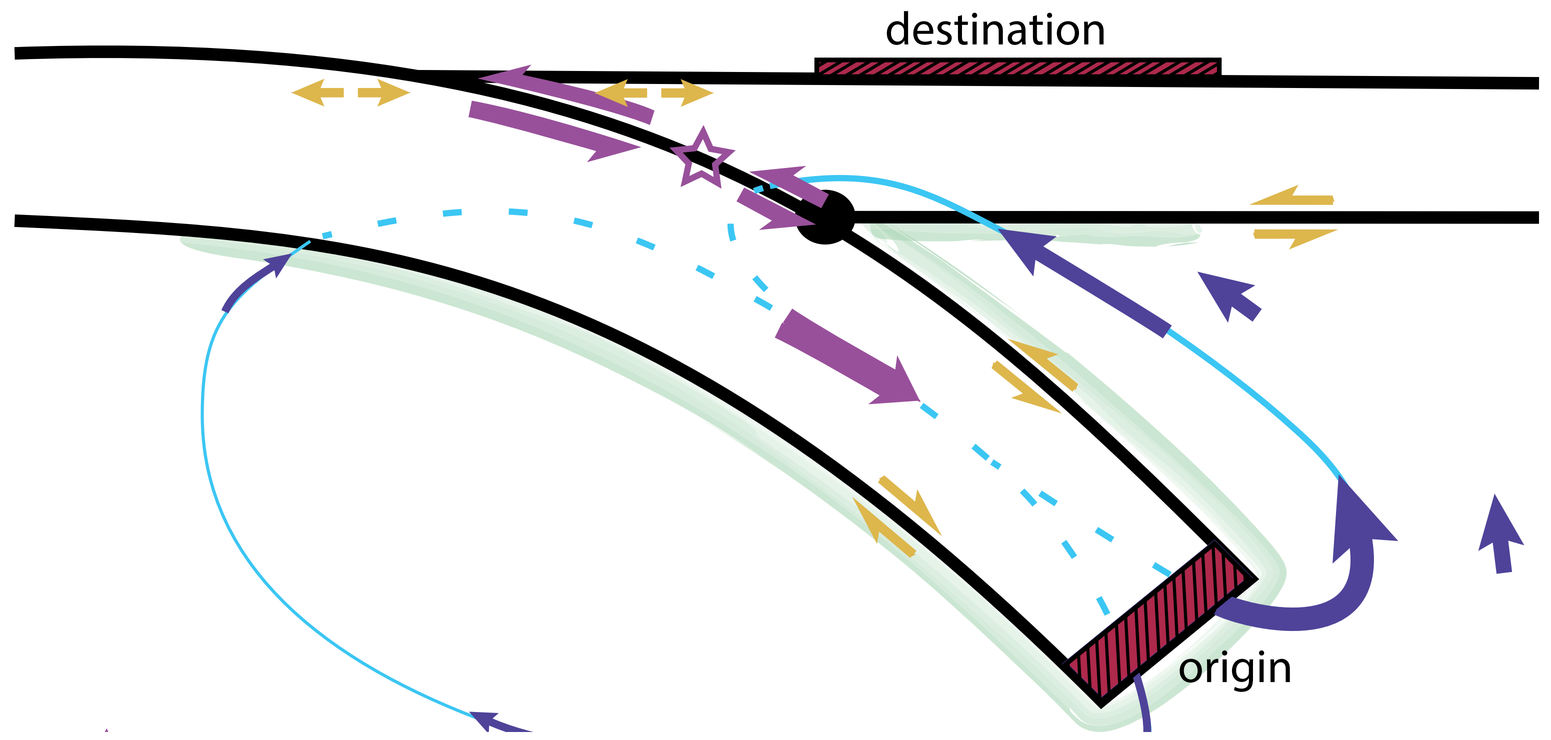
- Do lower crustal and mantle depth temperature and rheology affect seismicity and tectonics?
  - Yes, in complex tectonic settings driven by deep loading, such as Northern Apennines

- Does the mantle affect surface displacements at time scales of minutes to days?
  - Yes, STM models predicted a secondary zone of “coseismic” uplift, which was confirmed by observations of 4 out of 4 great megathrust earthquake
  - Accelerated slab penetration causes upward return “flow”







Utrecht University

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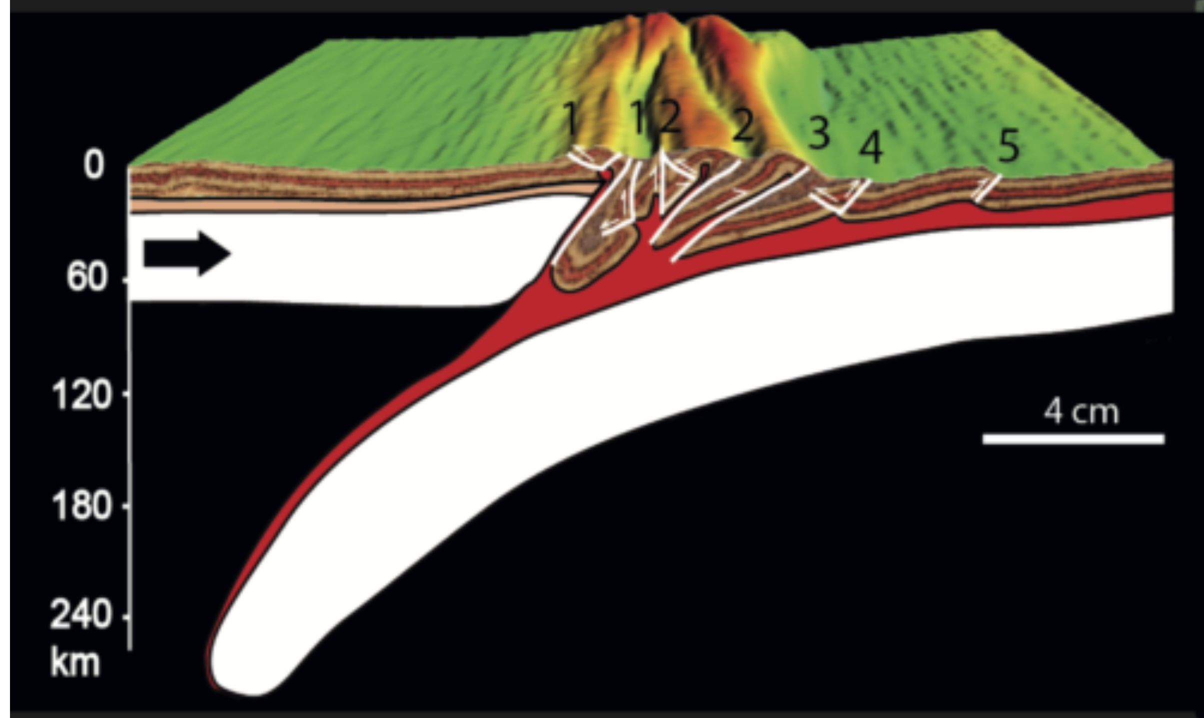
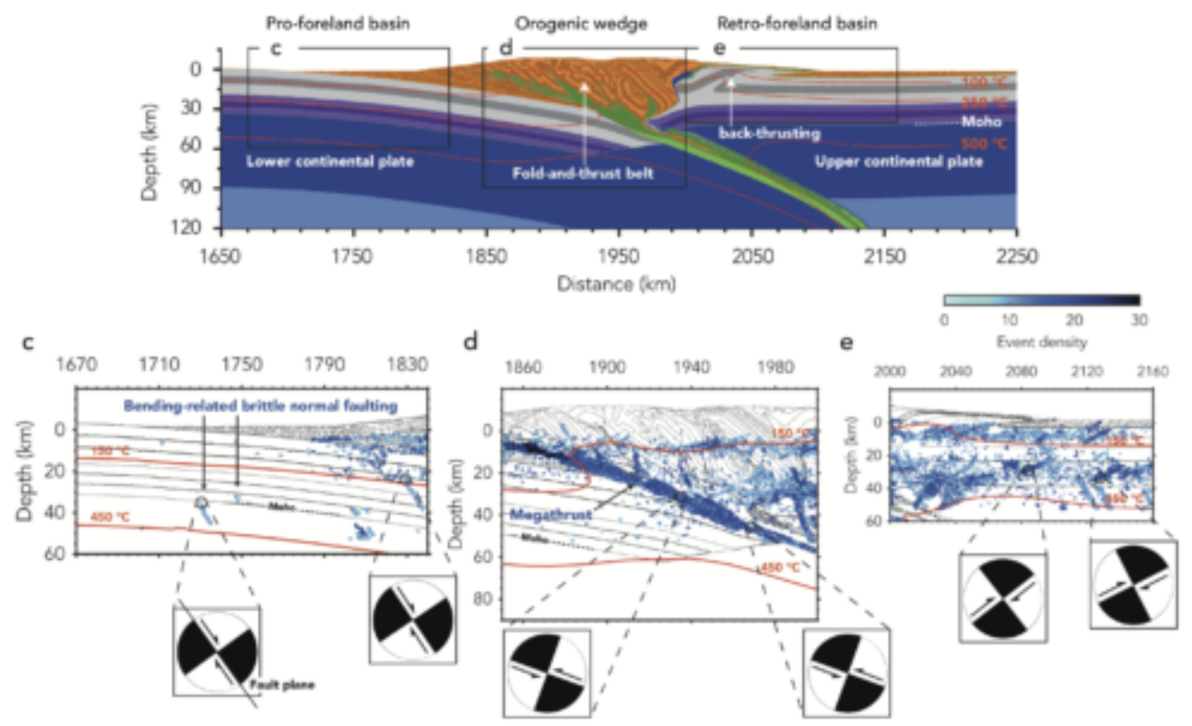
GeoMod 2020

Welcome Venue Programme Organization Deadlines Contact https://geomod2020.uu.nl





SAVE THE DATE: June 28 - July 2, 2020

Venue: Estate “Sunny Hill” near Utrecht, The Netherlands

Host: Utrecht University

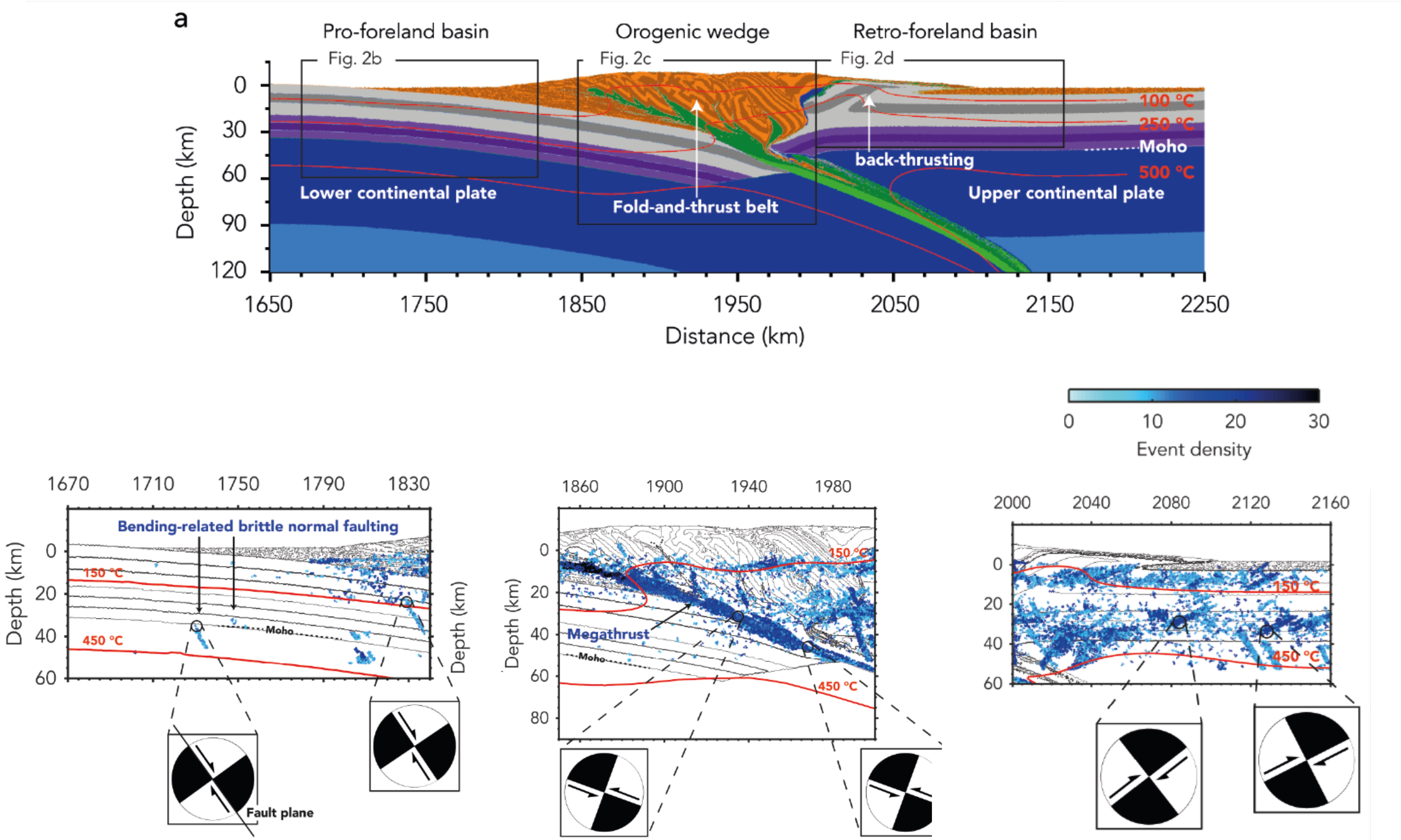
Programme:

- 7 topical sessions
- 18 key note presentations
- vivid poster presentations
- 2 evening lectures
- visit to the new Earth Simulation Laboratory at Utrecht University

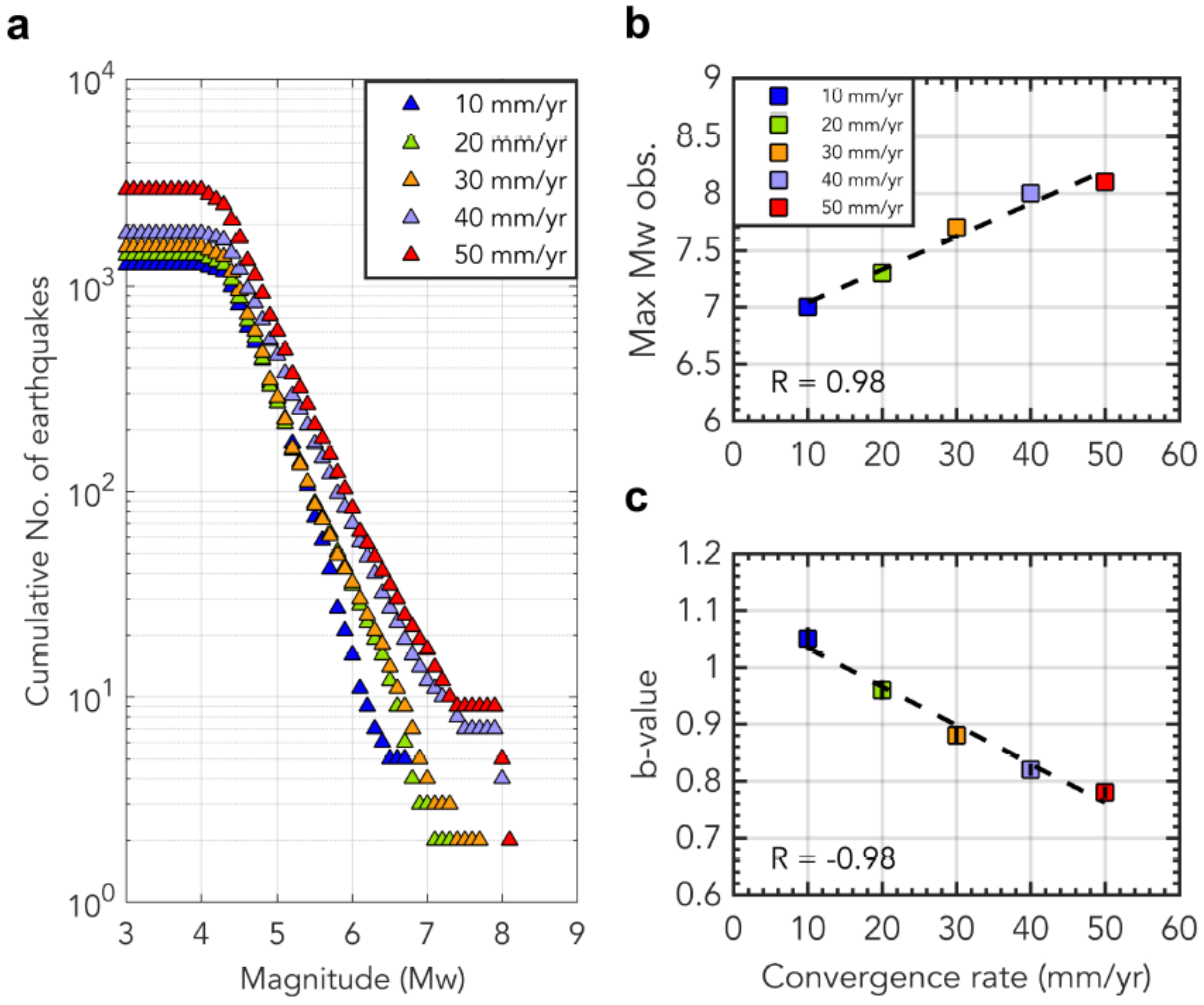
Earth Simulation Laboratory at UU

Role of convergence velocity *Vc*

- Mechanical experiments show *Vc* only increases seismic rate, not maximum magnitude Mmax (e.g., Corbi et al., GRL, 2017).
- Adding temperature and long-term dynamics changes the story…



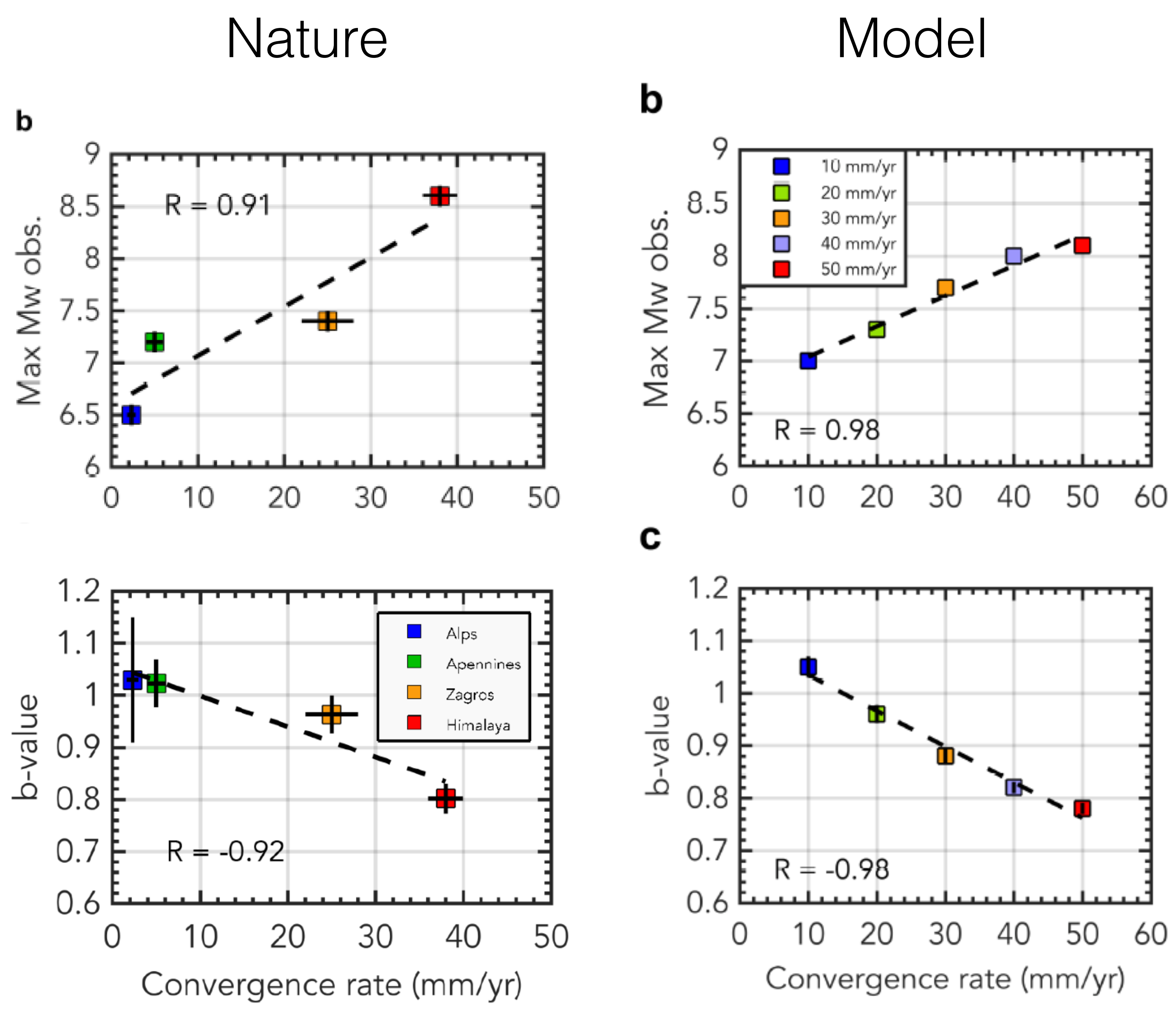
- Mmax does increase!



- Gutenberg-Richter distribution is obtained!

Role of convergence velocity highlights importance temperature

- Faster penetration of cooler temperatures to larger depths
- Larger brittle portion → larger and relative more larger events
- Relation and magnitude agree with regional observations



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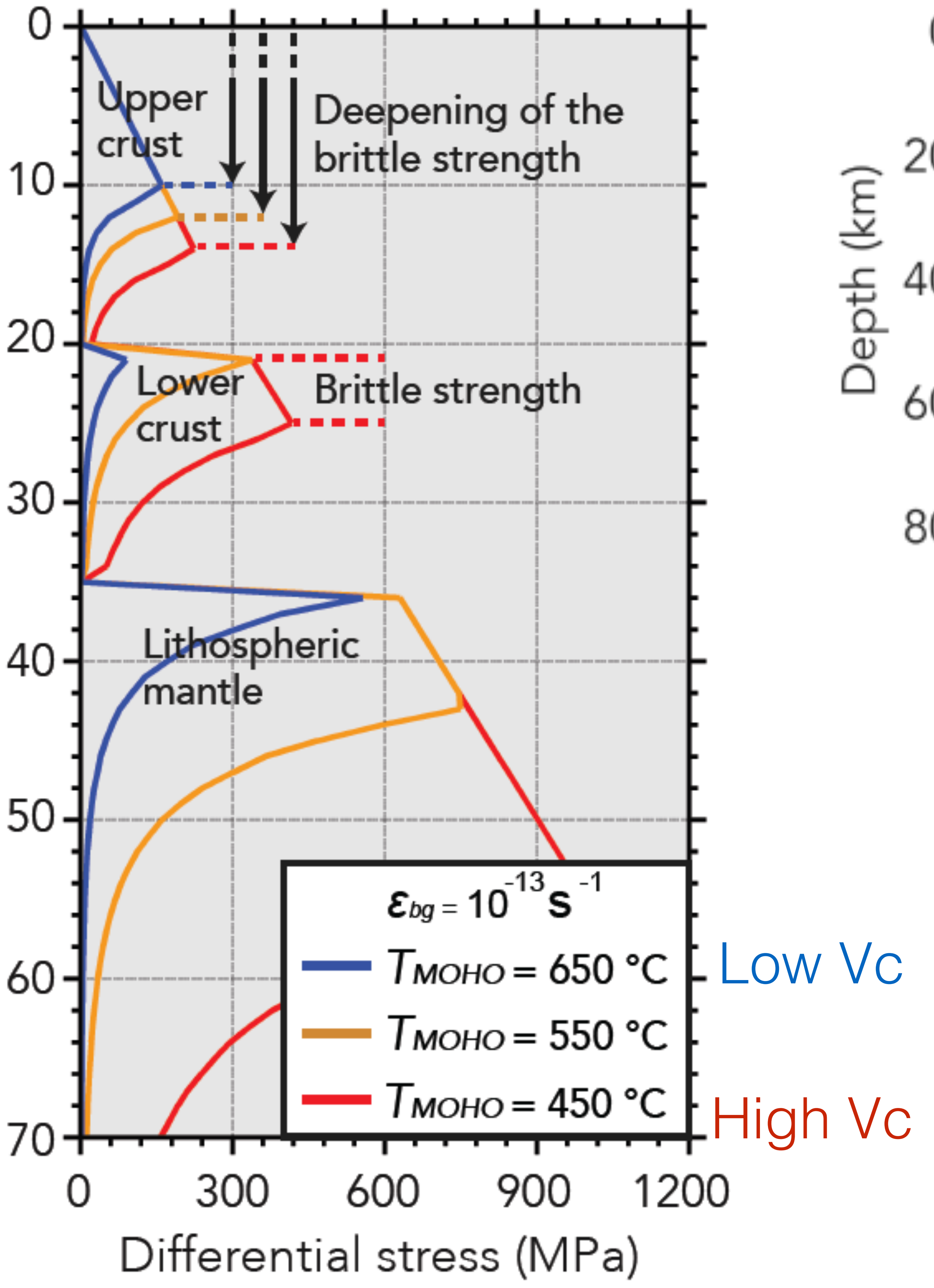

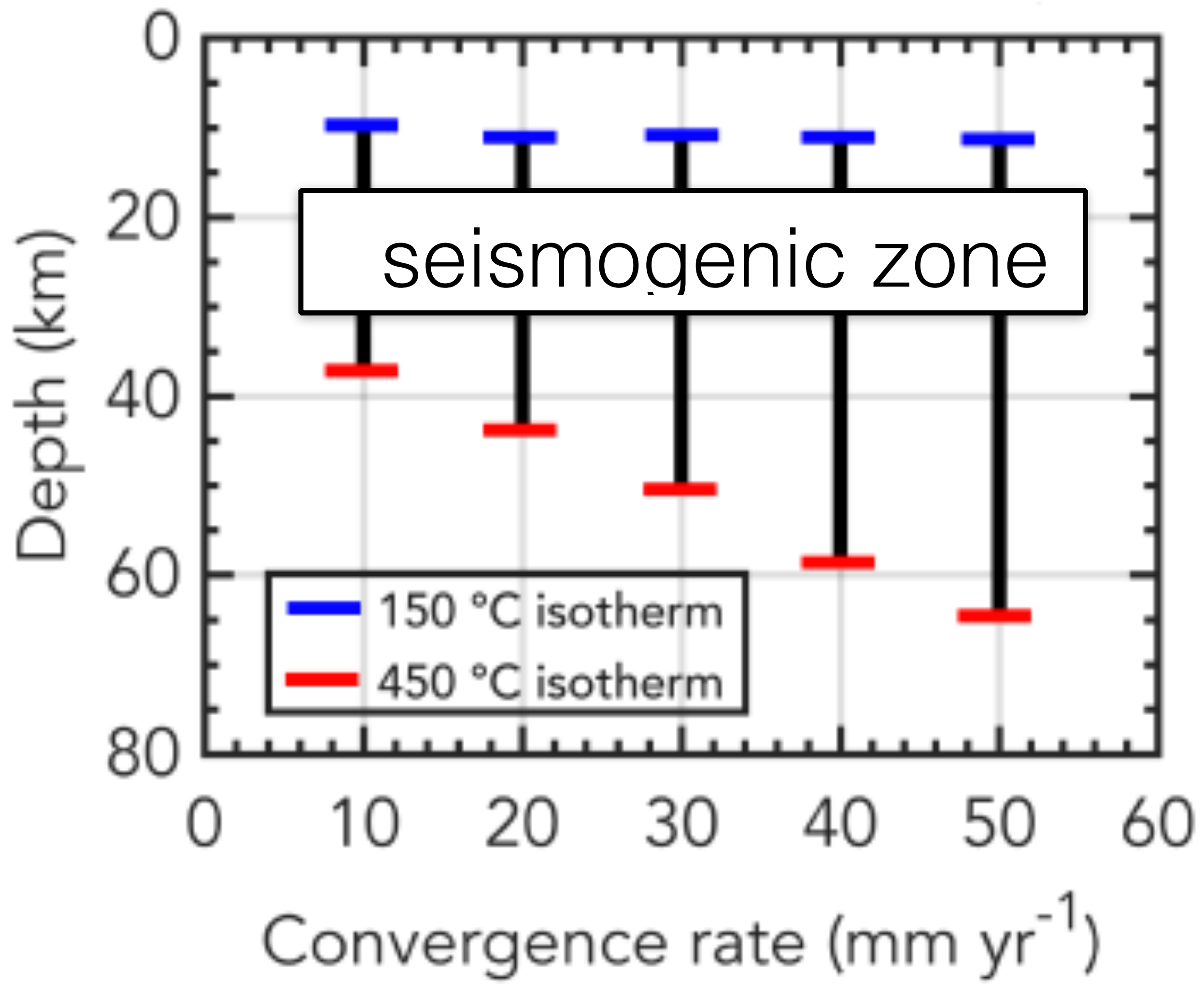

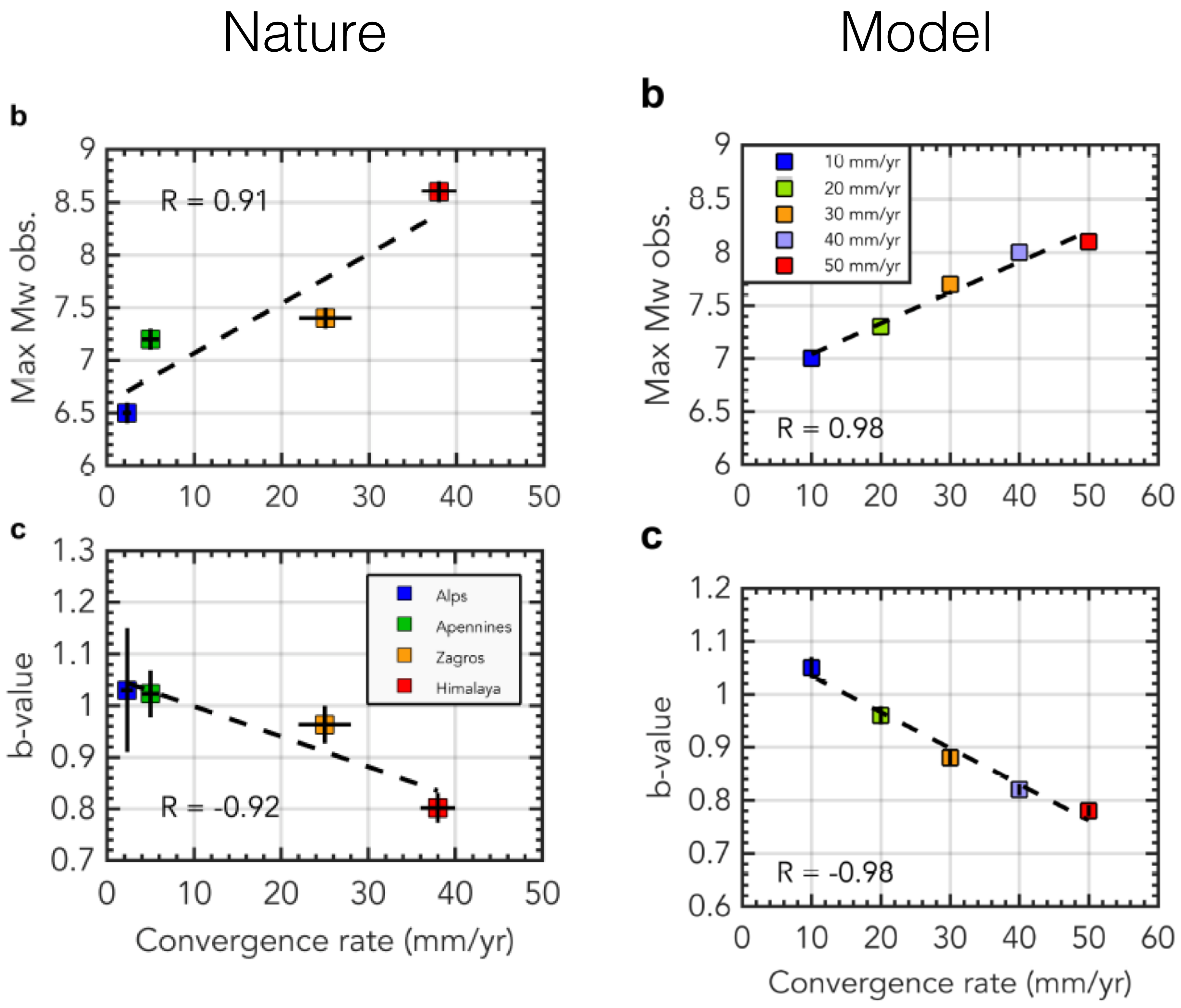

» More ductile deformation in Alps, so lower seismic hazard than in Himalaya