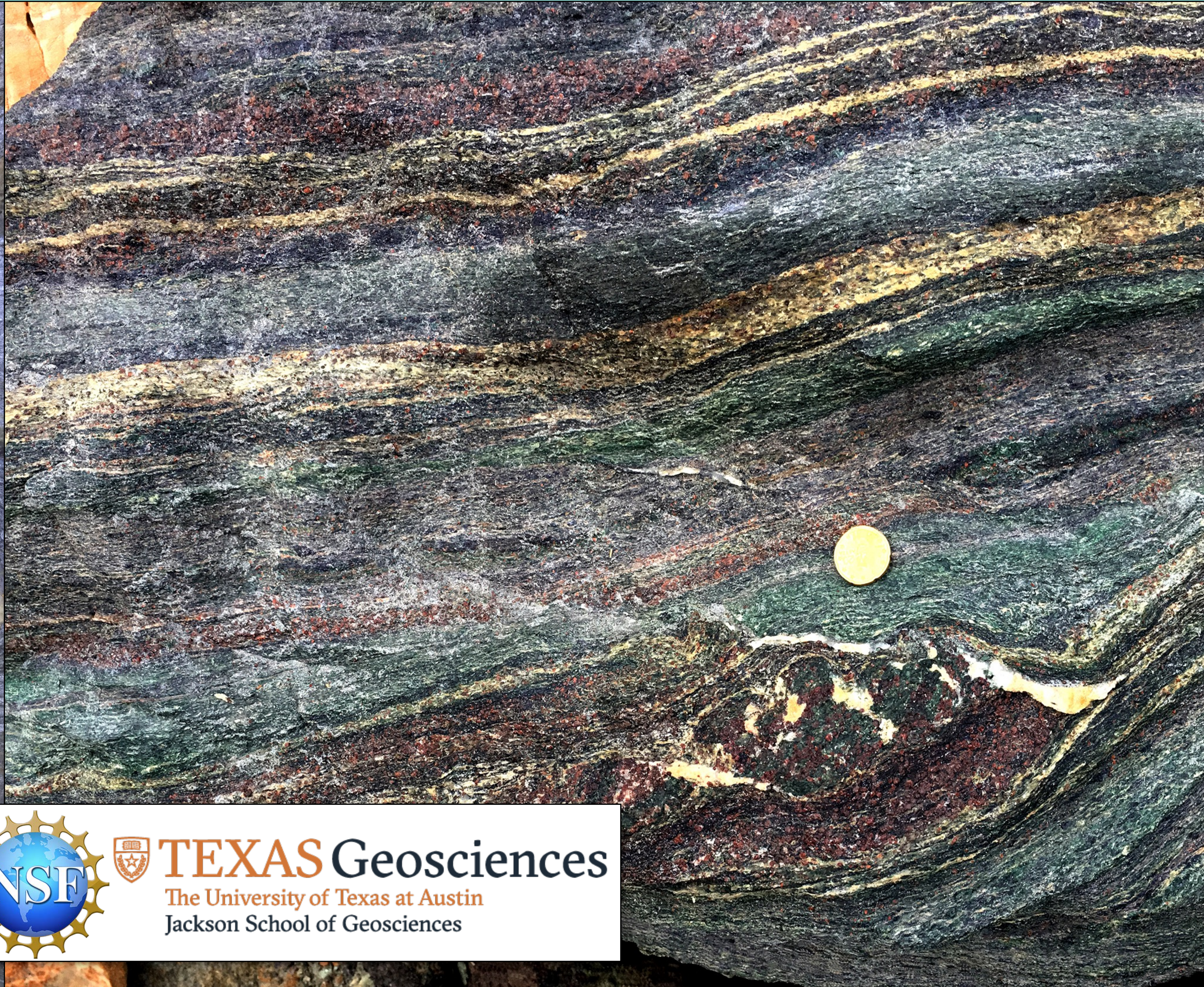
Plate Speeds Modulated by Sediment Subduction

Whitney Behr (wbehr@ethz.ch), EGU SHARING GEOSCIENCE ONLINE 2020, *Slides for Discussion*

collaborators: Adam Holt, Thorsten Becker, Claudio Faccenna

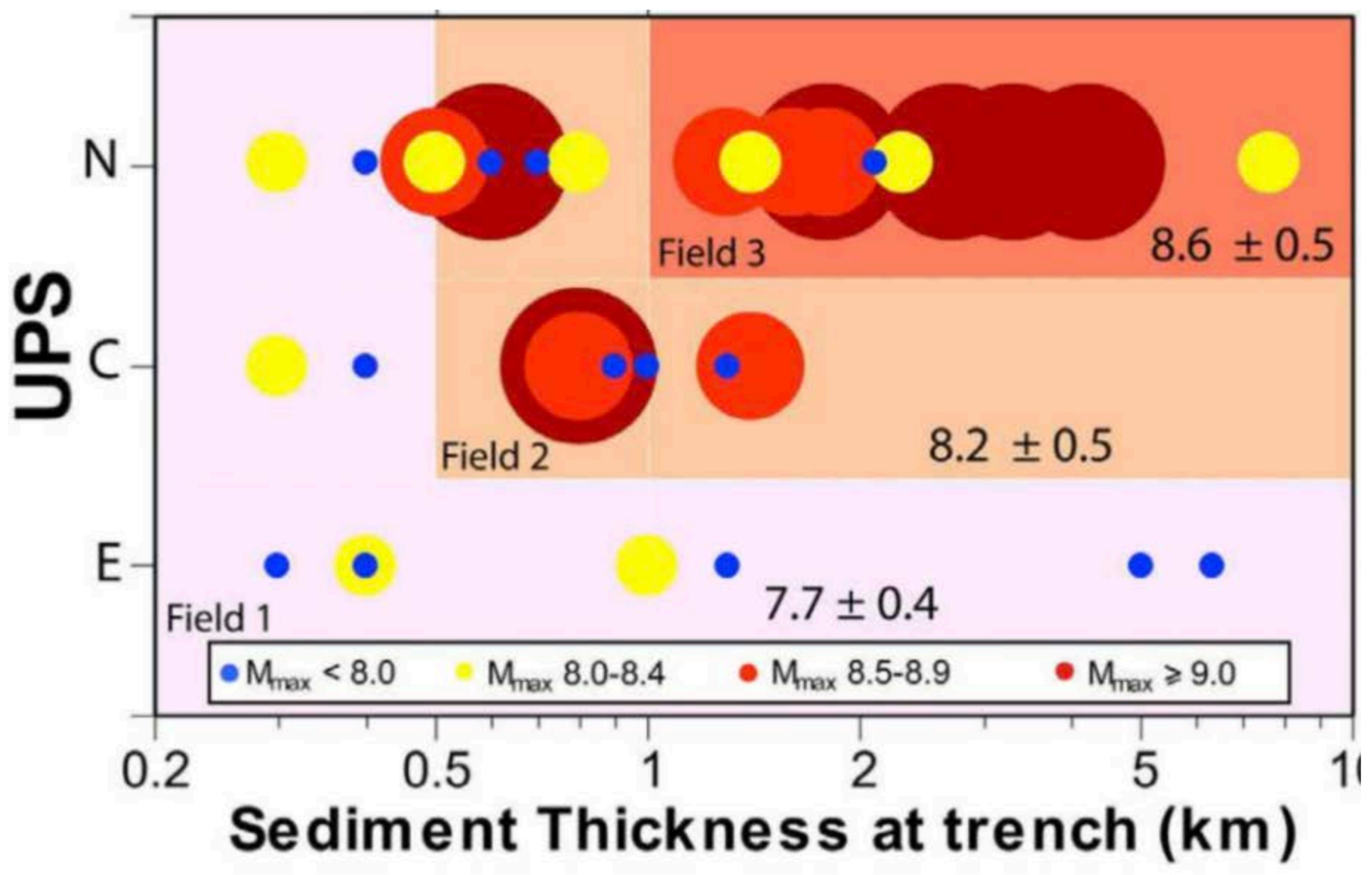


ETH zürich · SGT ETHZ · NSF · TEXAS Geosciences, The University of Texas at Austin, Jackson School of Geosciences

Sediments Are Fundamental to the Dynamics of Subduction Zones

They can influence:

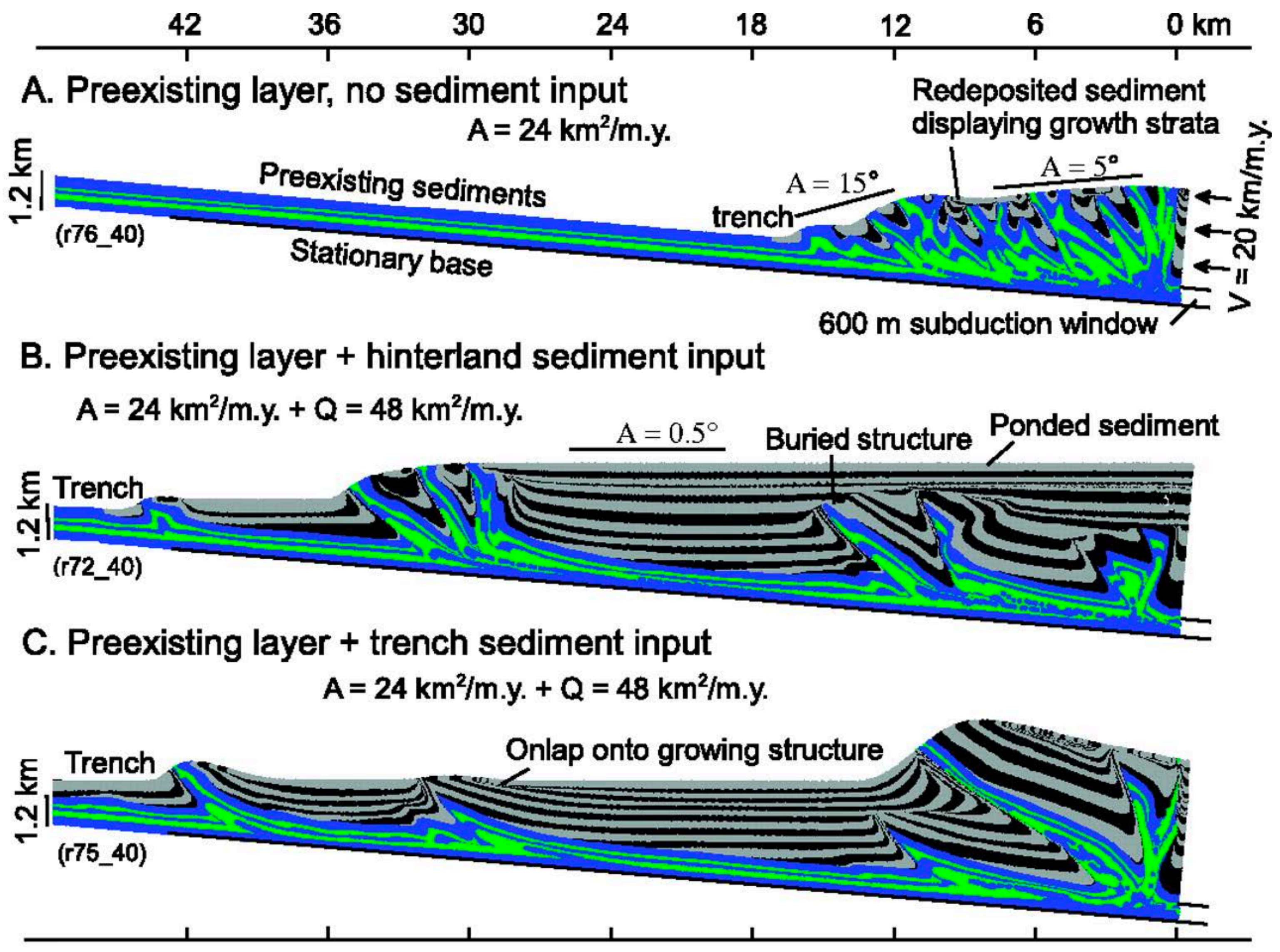
Megathrust EQ's



Heuret et al., 2012

Relation between subduction megathrust EQ's, trench sediment thickness and upper plate strain

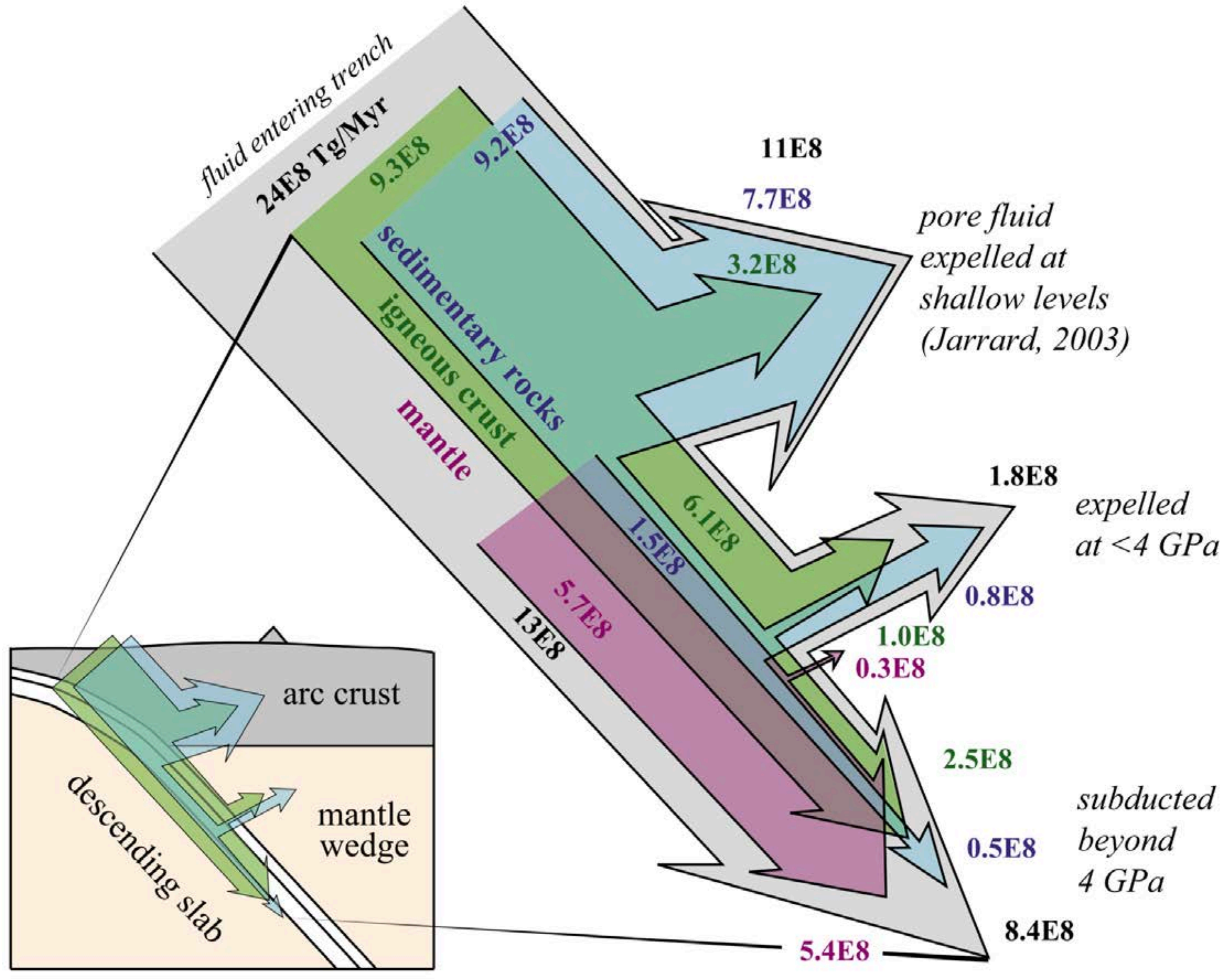
Wedge Morphologies



Simpson, 2010

Formation of accretionary prisms influenced by sediment subduction

Arc Magma genesis



Hacker, 2008

H2O subduction beyond arcs

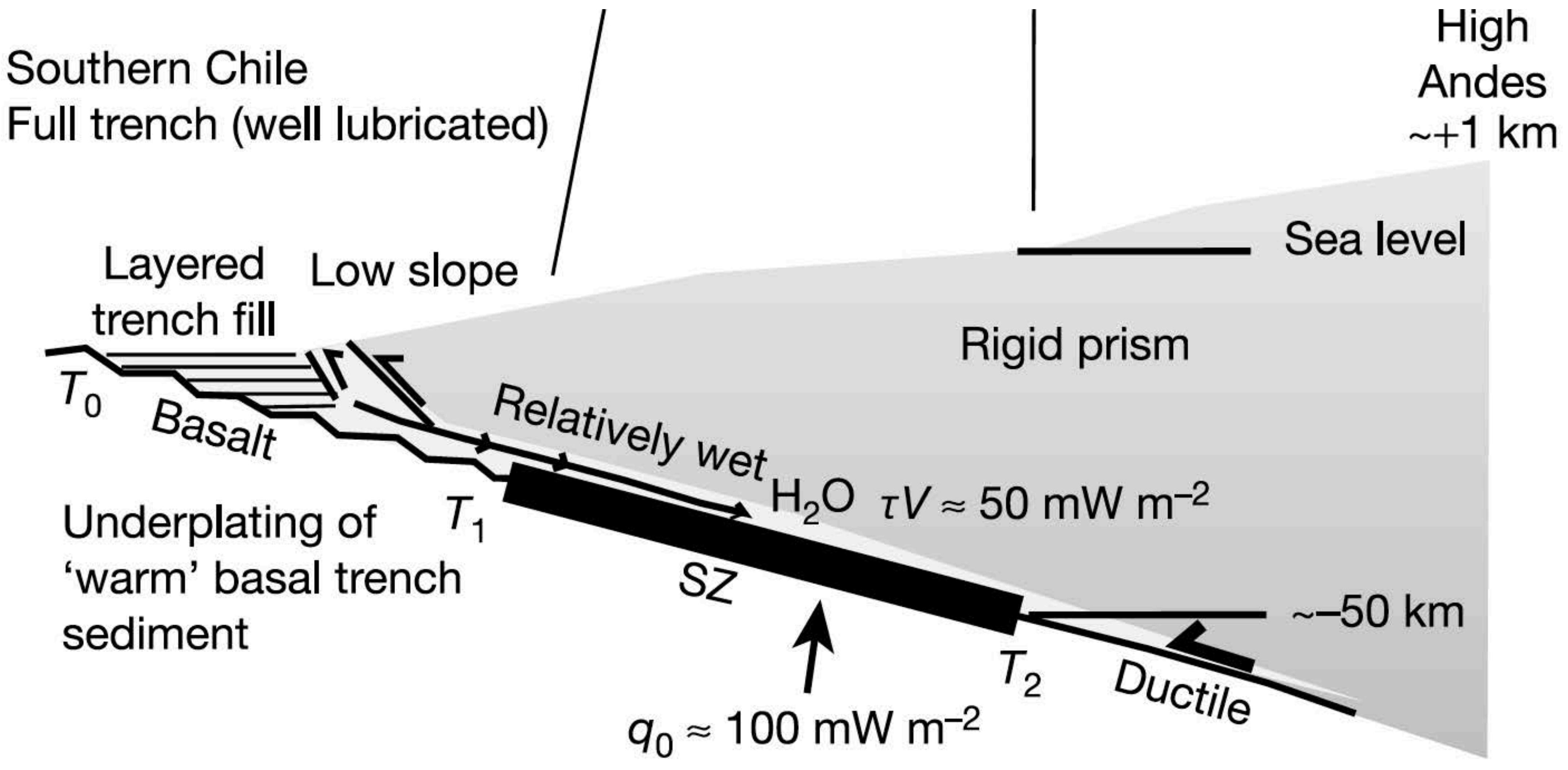
Sediments Particularly Important in `Lubricating' the Plate Interface

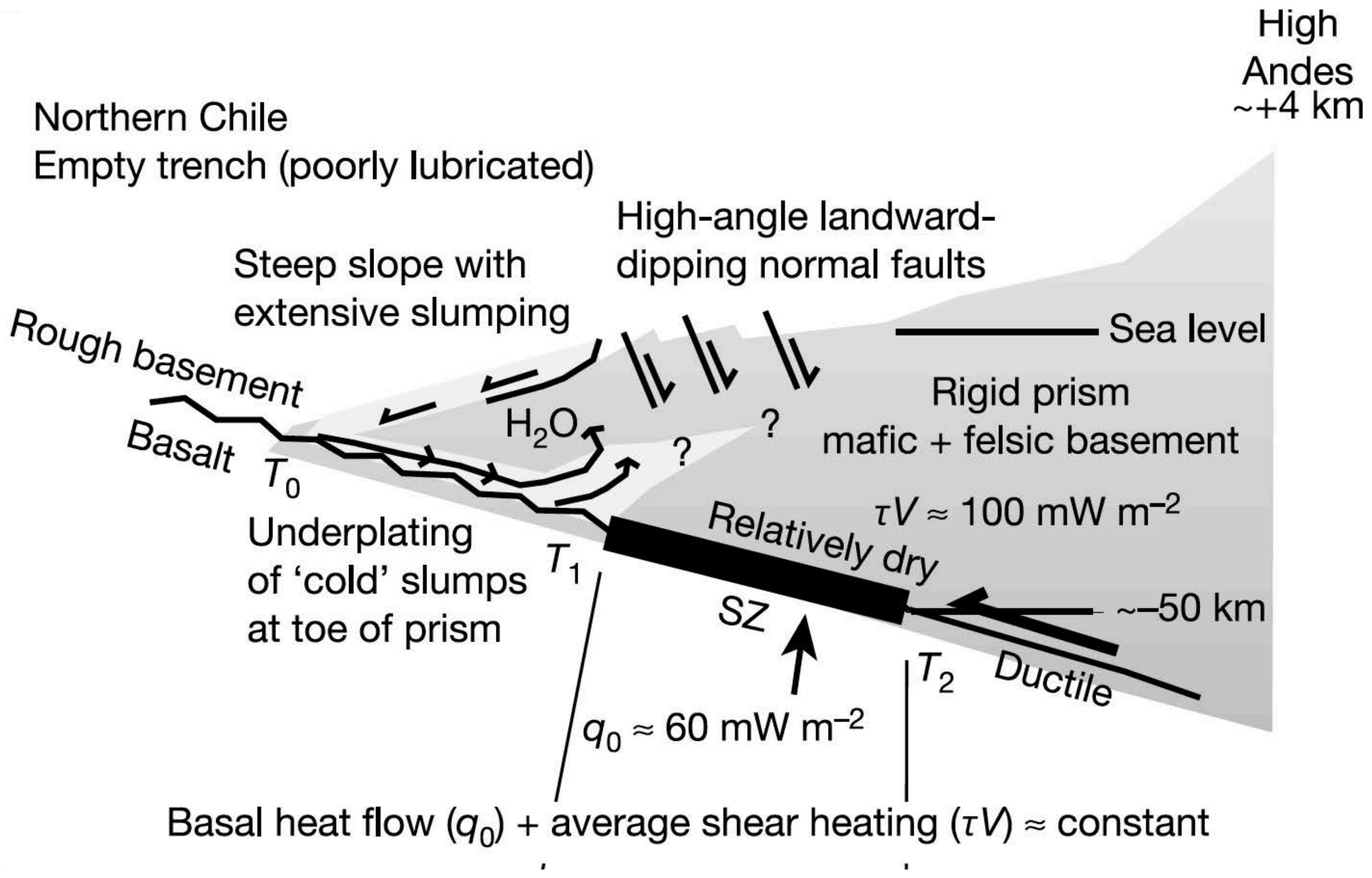
articles

Cenozoic climate change as a possible cause for the rise of the Andes

Simon Lamb[1] & Paul Davis[2]

NATURE | VOL 425 | 23 OCTOBER 2003 | www.nature.com/nature





Corollary of sediment lubrication: subduction plate speeds?

Plate Velocity (Vp) is a balance between:

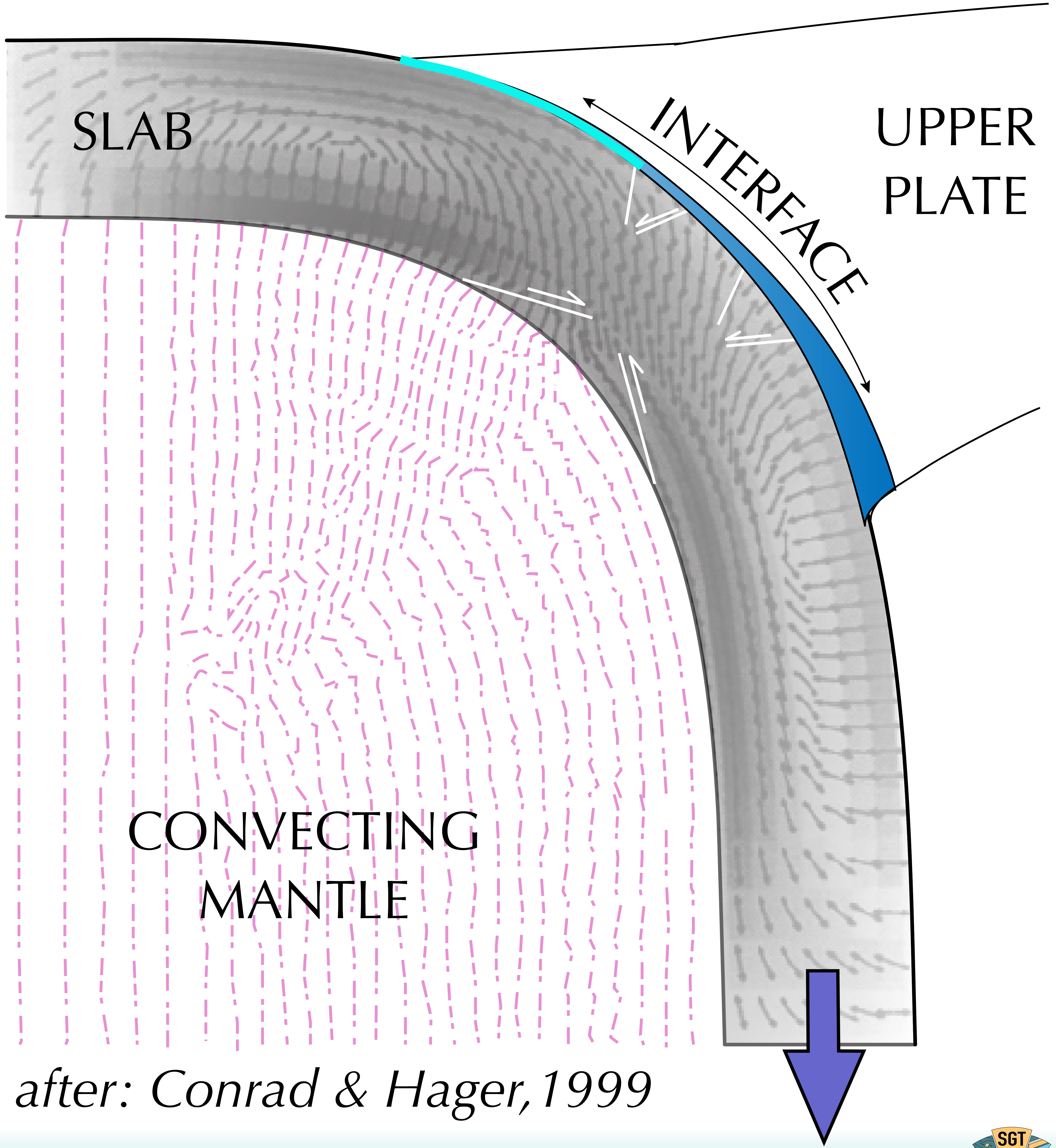
— *Potential energy of subducting slab (***+***)*

— *Dissipation into:*

  — *Surrounding mantle (***-***)*

  — *Slab bending (***-***)*

  — *Interface shear zone (***-***)*



after: Conrad & Hager, 1999

Corollary of sediment lubrication: subduction plate speeds?

Plate Velocity (Vp) is a balance between:

— *Potential energy of subducting slab (**+**)*

— *Dissipation into:*

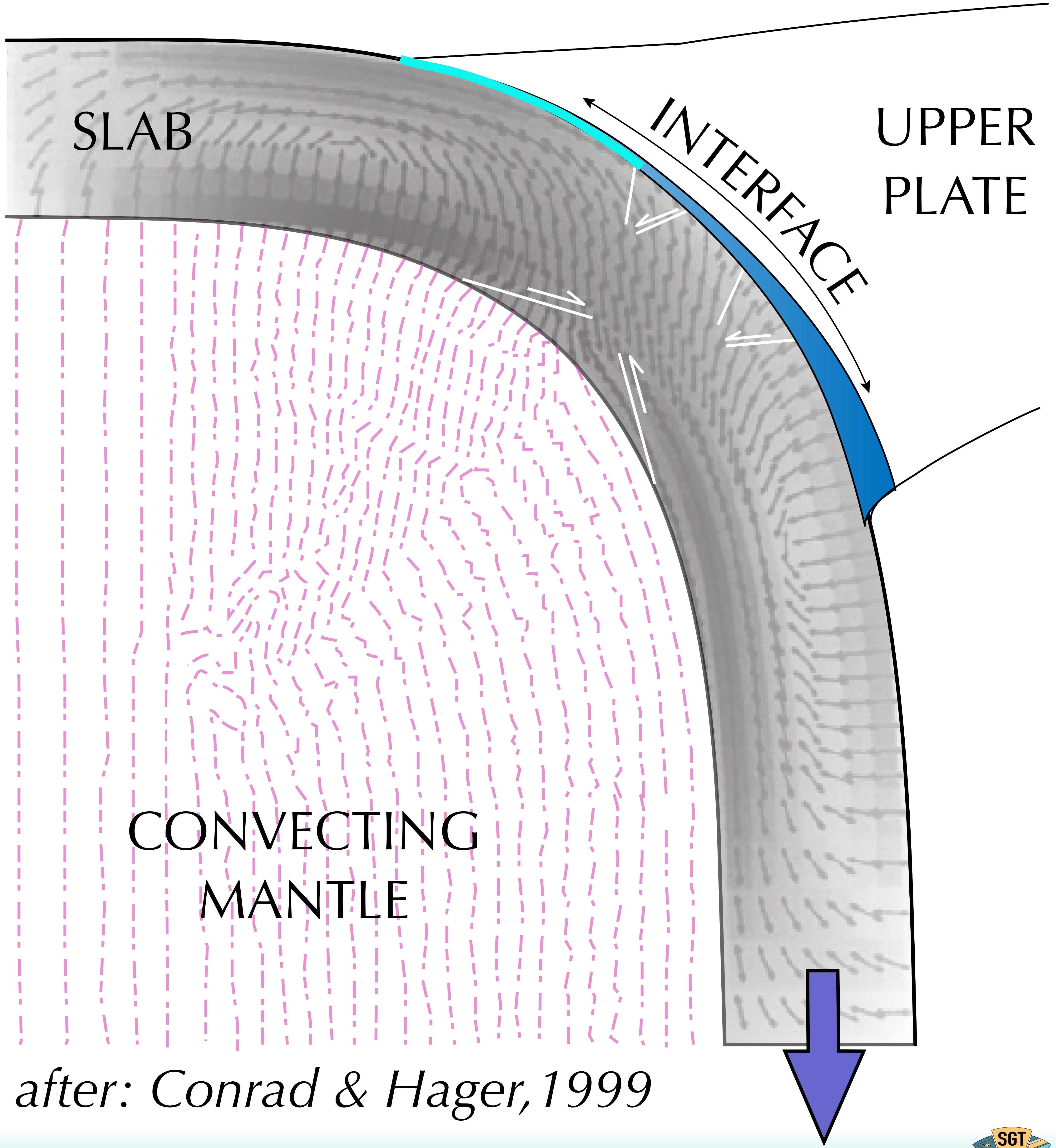
— *Surrounding mantle (**-**)*

— *Slab bending (**-**)*

— *Interface shear zone (**-**)*

Traditionally assumed that slabs are strong…

Traditionally assumed that interface is weak…



after: Conrad & Hager, 1999

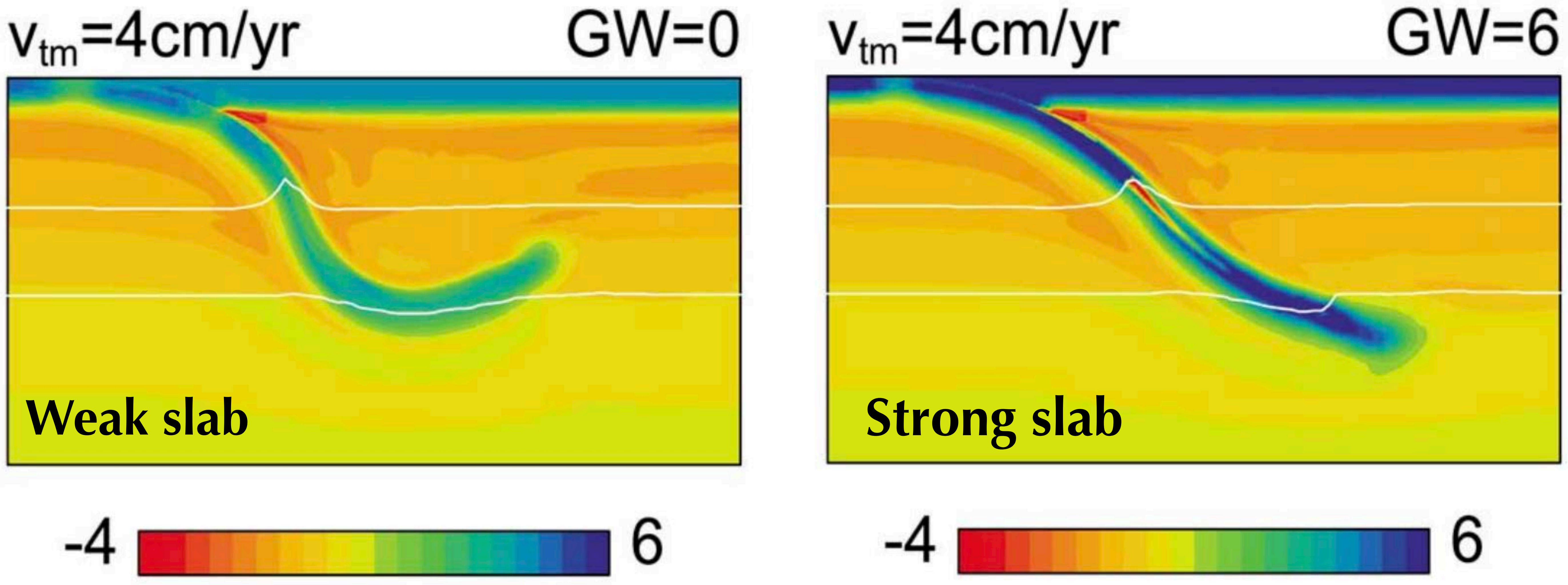
Corollary of sediment lubrication: subduction plate speeds?

Two reasons to revisit this:

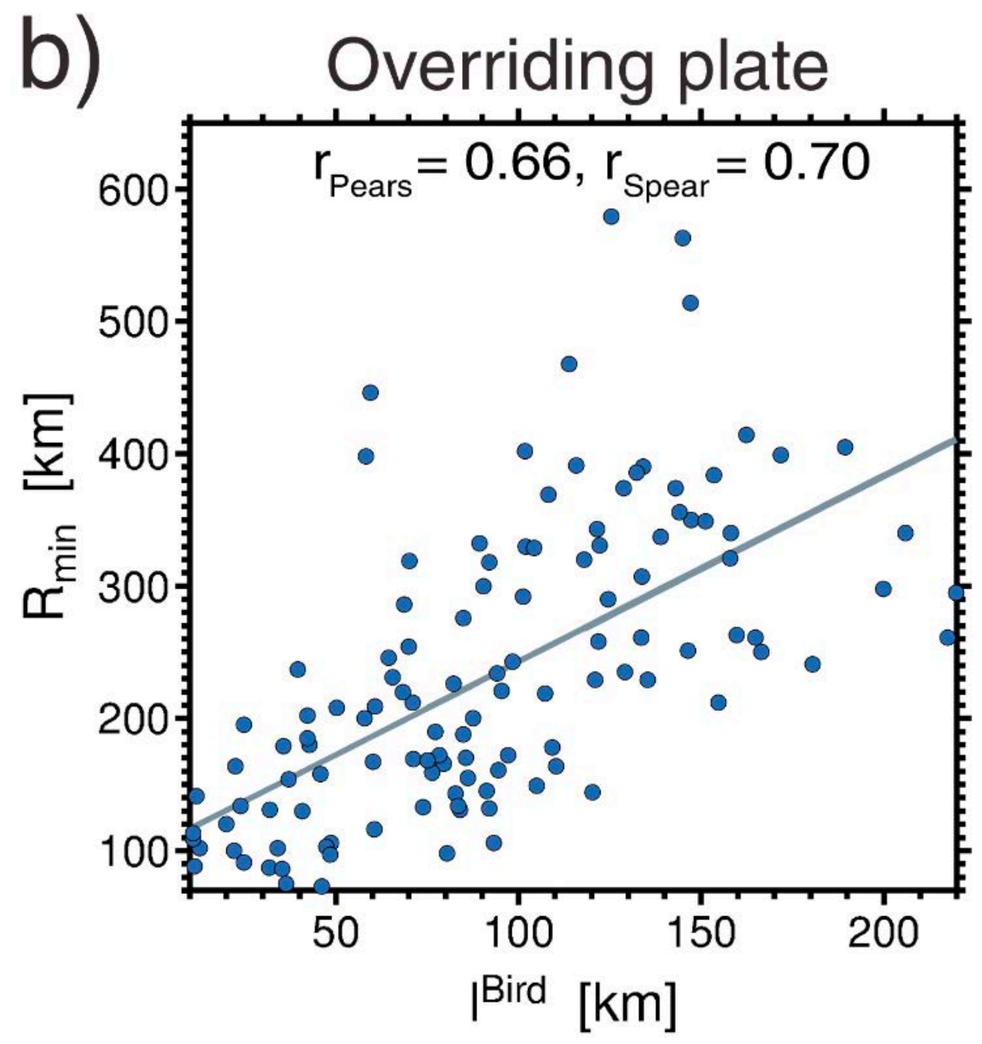
1. *Mounting evidence suggests* ***slabs are weak***

— Deflection of slabs at 660 km from tomography (e.g. Čížková et al, EPSL, 2002)

— Close correlation between slab radius of curvature and overriding plate thickness (e.g. Holt et al, GRL, 2015)



Čížková et al, EPSL 2002

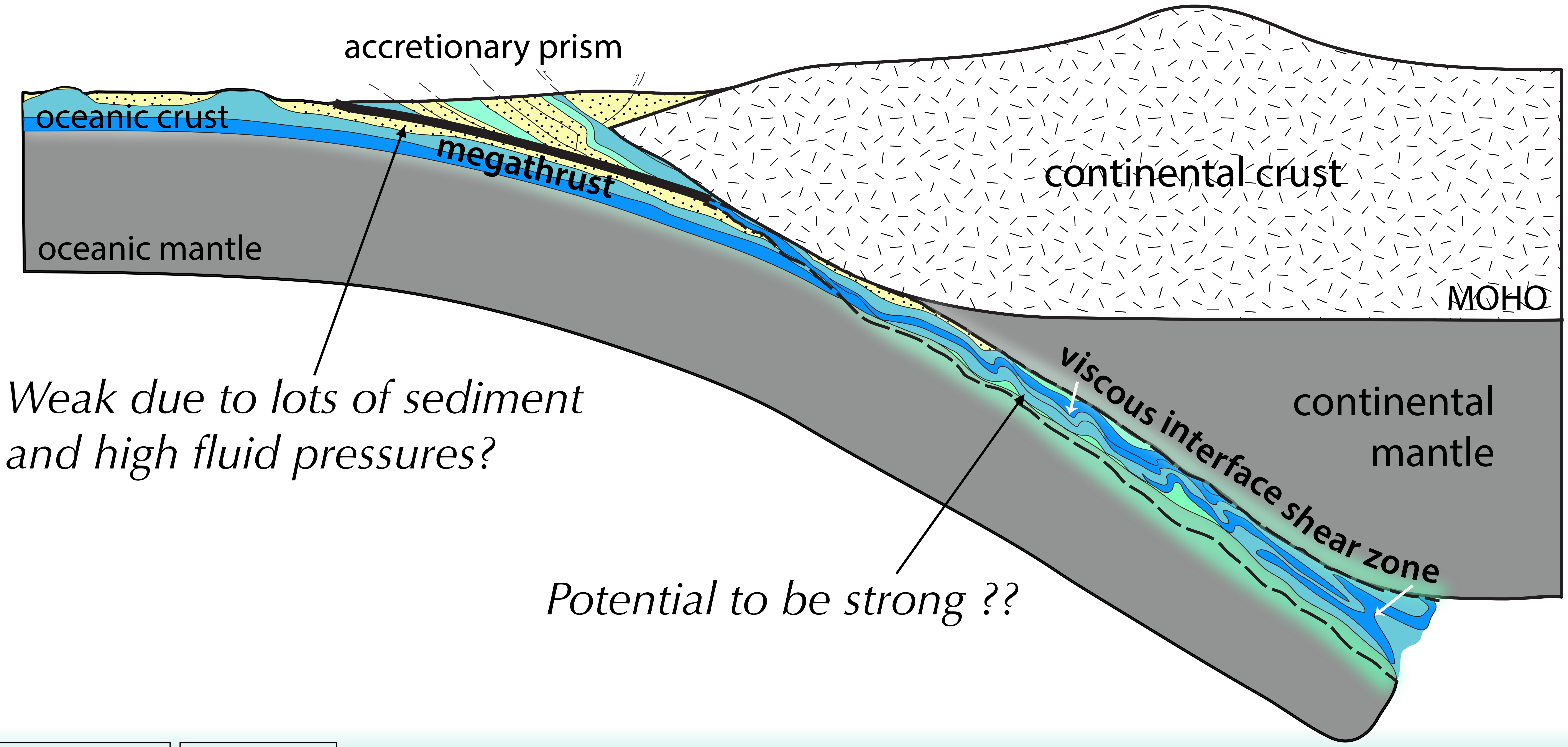


Holt et al., GRL 2015

Corollary of sediment lubrication: subduction plate speeds?

Two reasons to revisit this:

1. *Mounting evidence suggests slabs are weak*
2. *Resistance to subduction may be imparted by the **viscous** interface*



Exploring the role of interface viscosity in modulating plate speeds

Outline:

1. *Viscosity contrasts between sediments and mafic rocks: field and lab*
2. *Effect of deep interface viscosity on plate speeds*
3. *Possible example associated with India-Asia convergence*

What Controls Viscosity Along the Deep Interface?

Common Subduction Interface Protolith rock types

— *pelagic sedimentary cover (argillites)* → *schists w/low q:mica ratios*

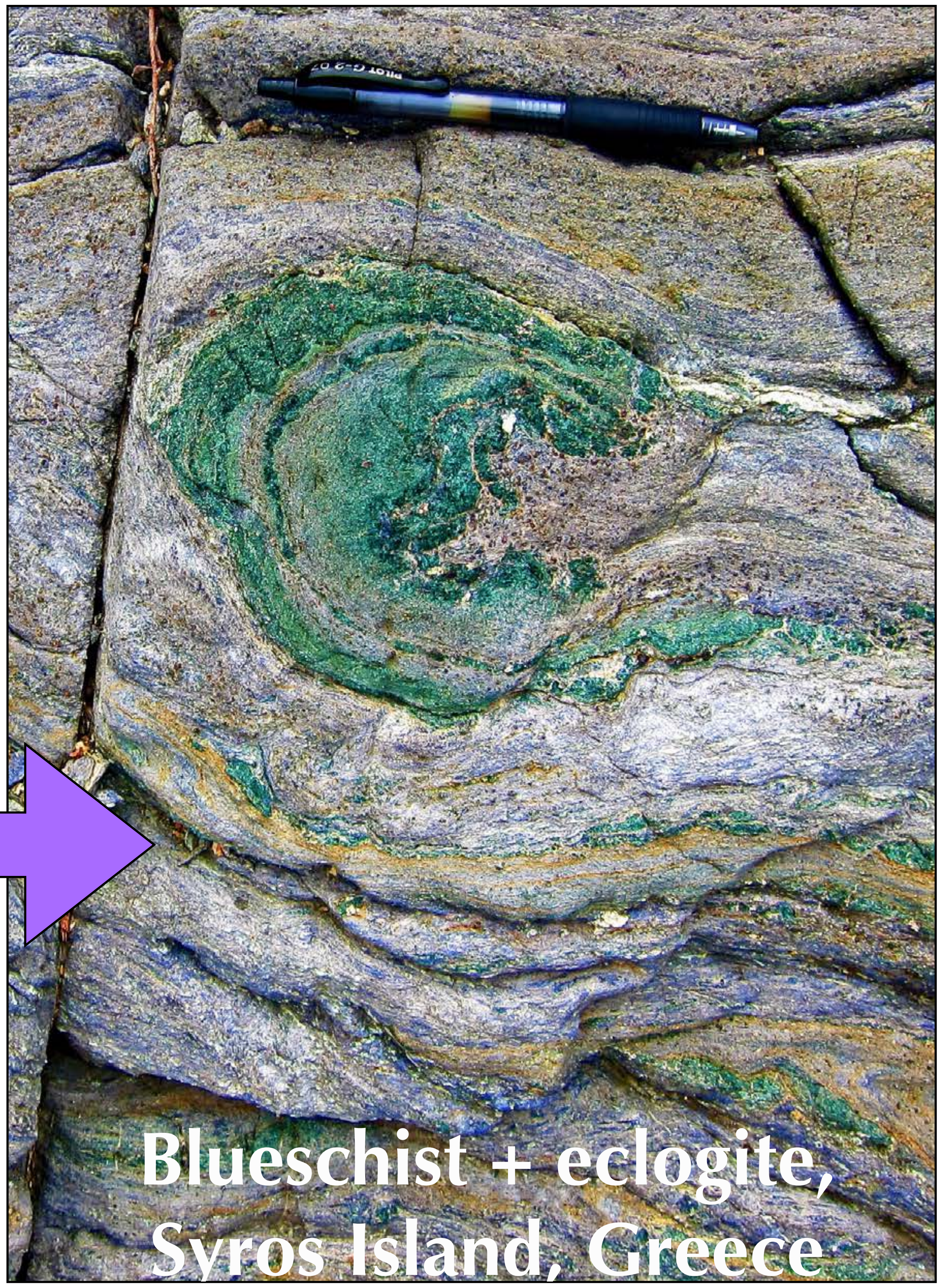
— *siliciclastic trench fill (greywackes)* ***metamorphose to…*** → *quartzites & schists*

— *mafic oceanic crust (basalts)* → *blueschists & eclogites*

greywacke, Chugach Complex, AK

metagreywacke, Condrey Mountain, CA

pillow basalts, Chugach Complex, AK

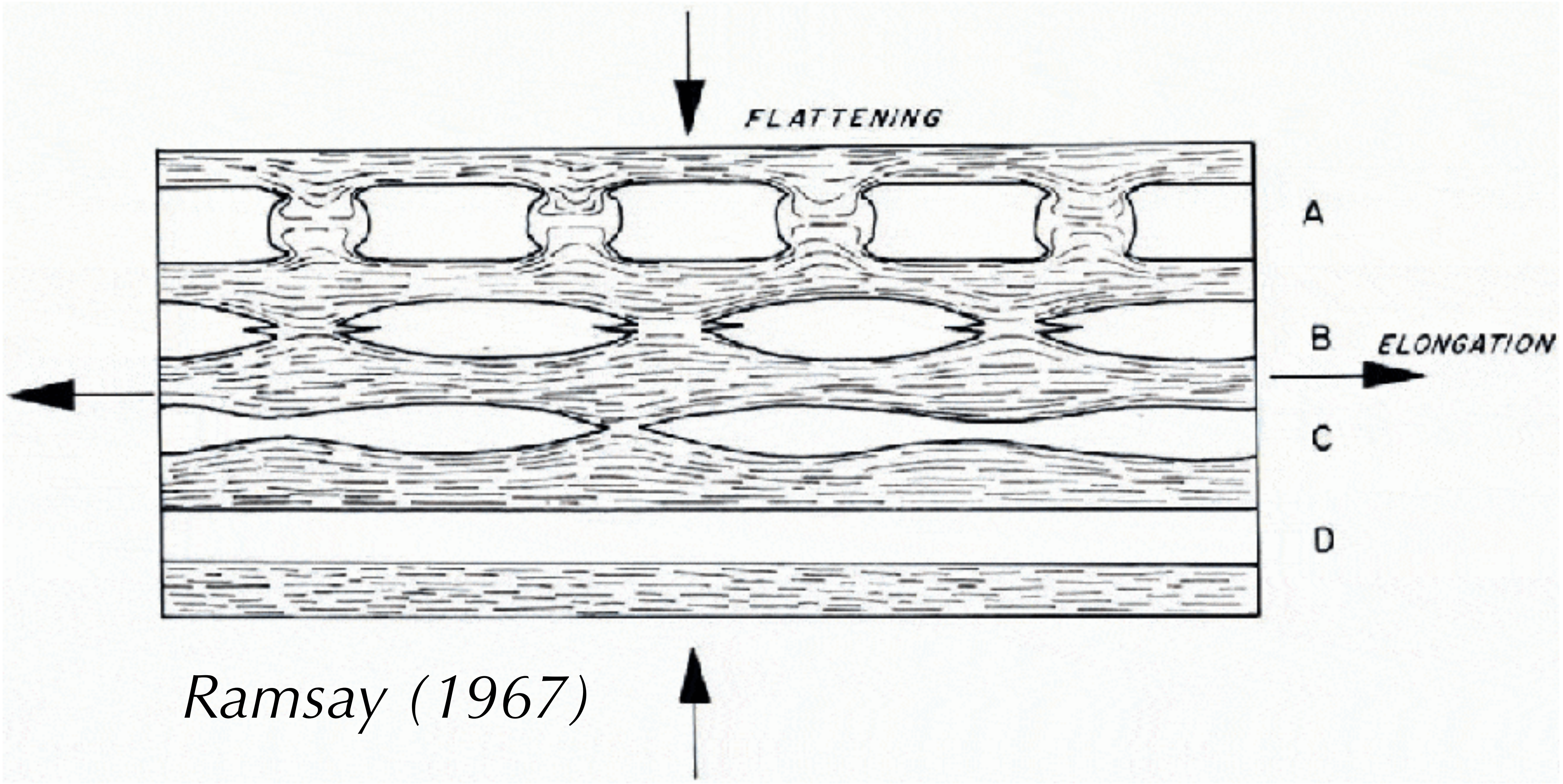


Blueschist + eclogite, Syros Island, Greece

What Controls Viscosity Along the Deep Interface?

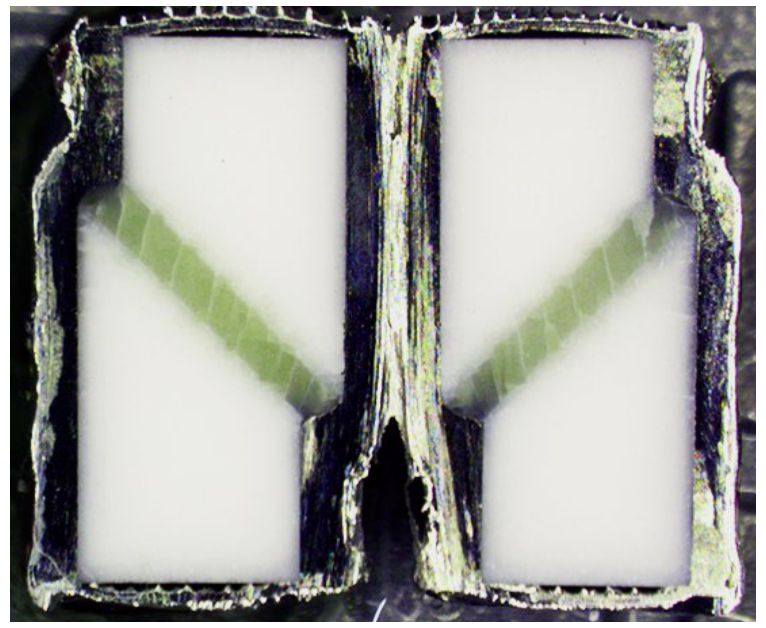
Two ways of evaluating viscosity contrasts:

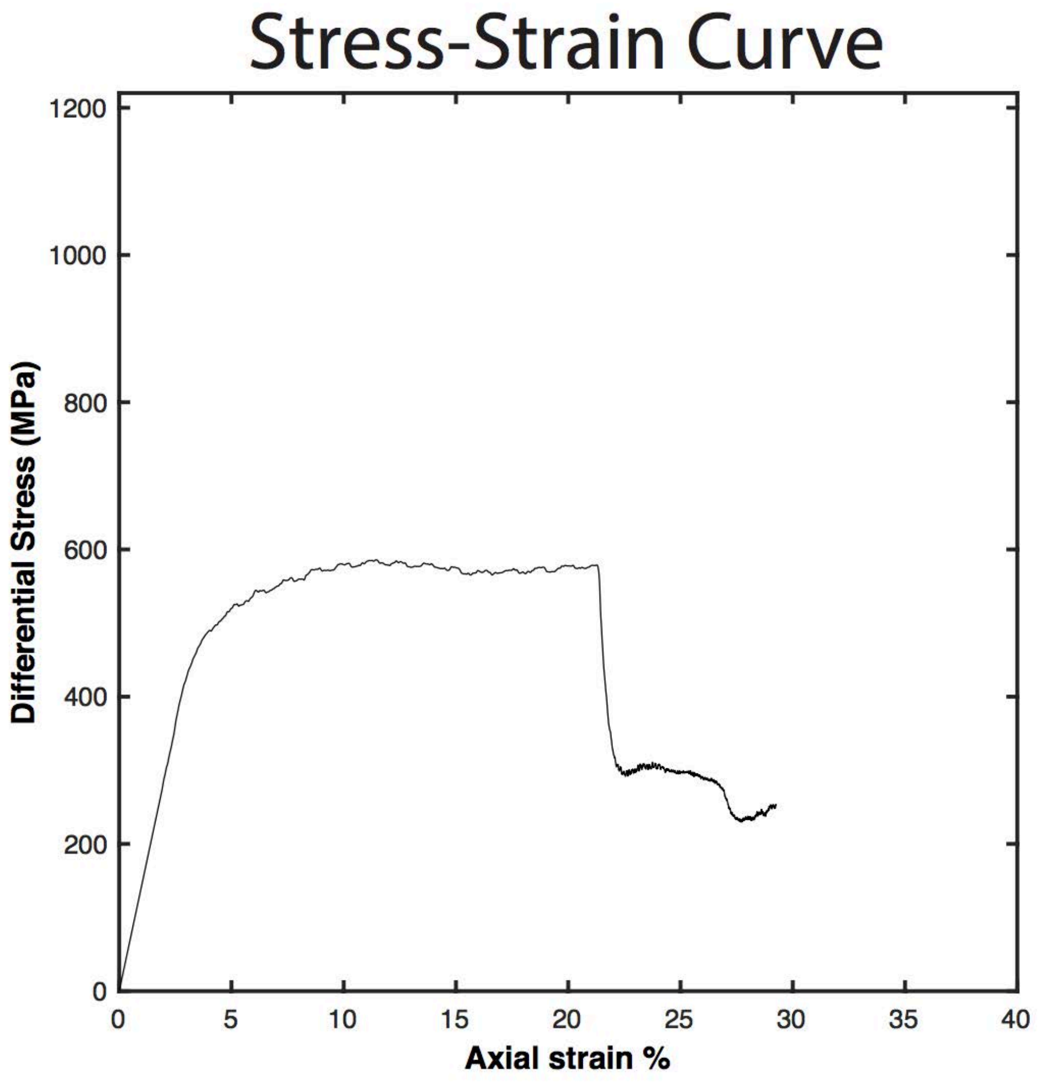
Boudin-matrix relationships (qualitative)



Ramsay (1967)

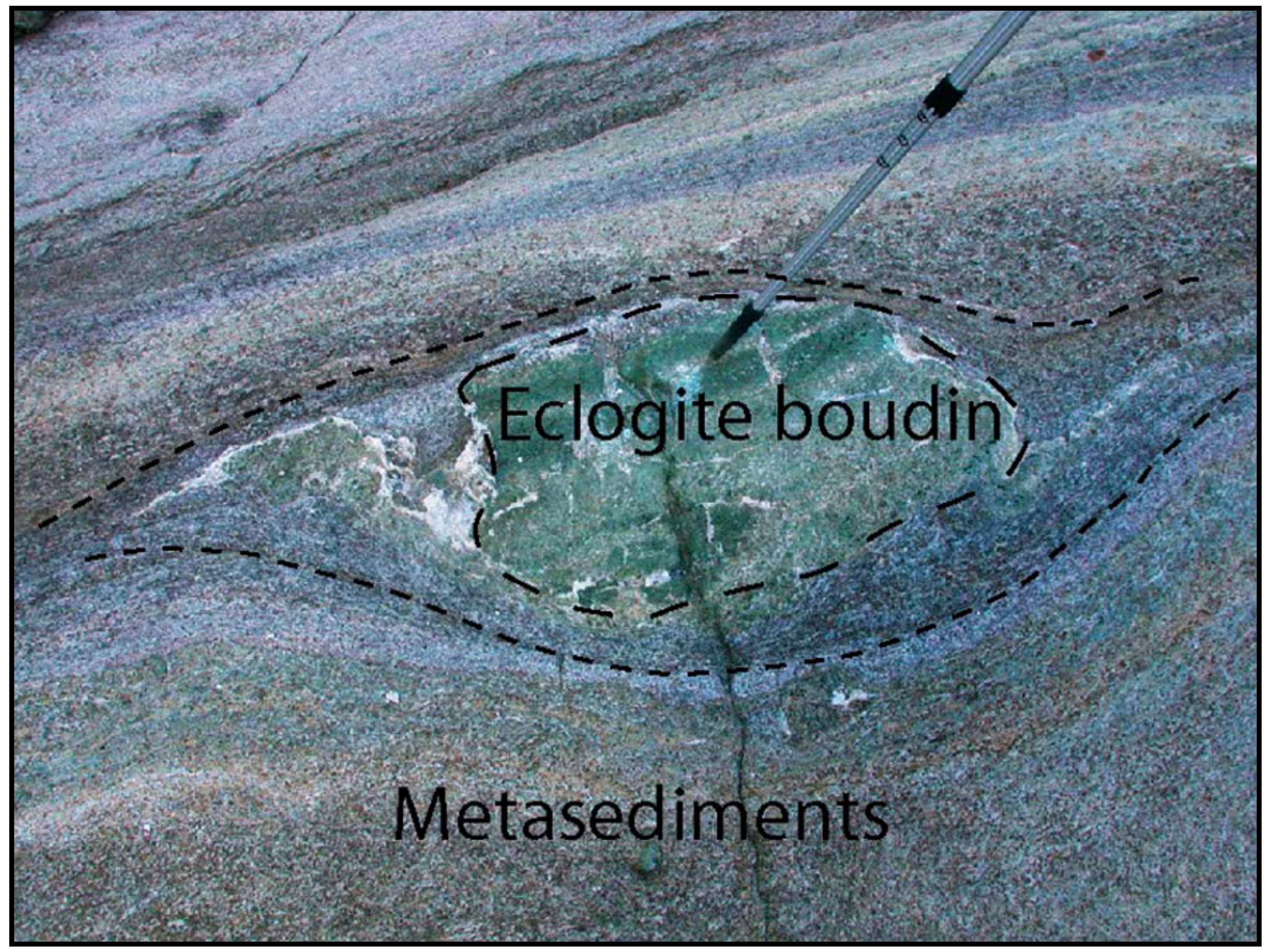
Experimentally-derived flow laws (quantitative, but extrapolated)

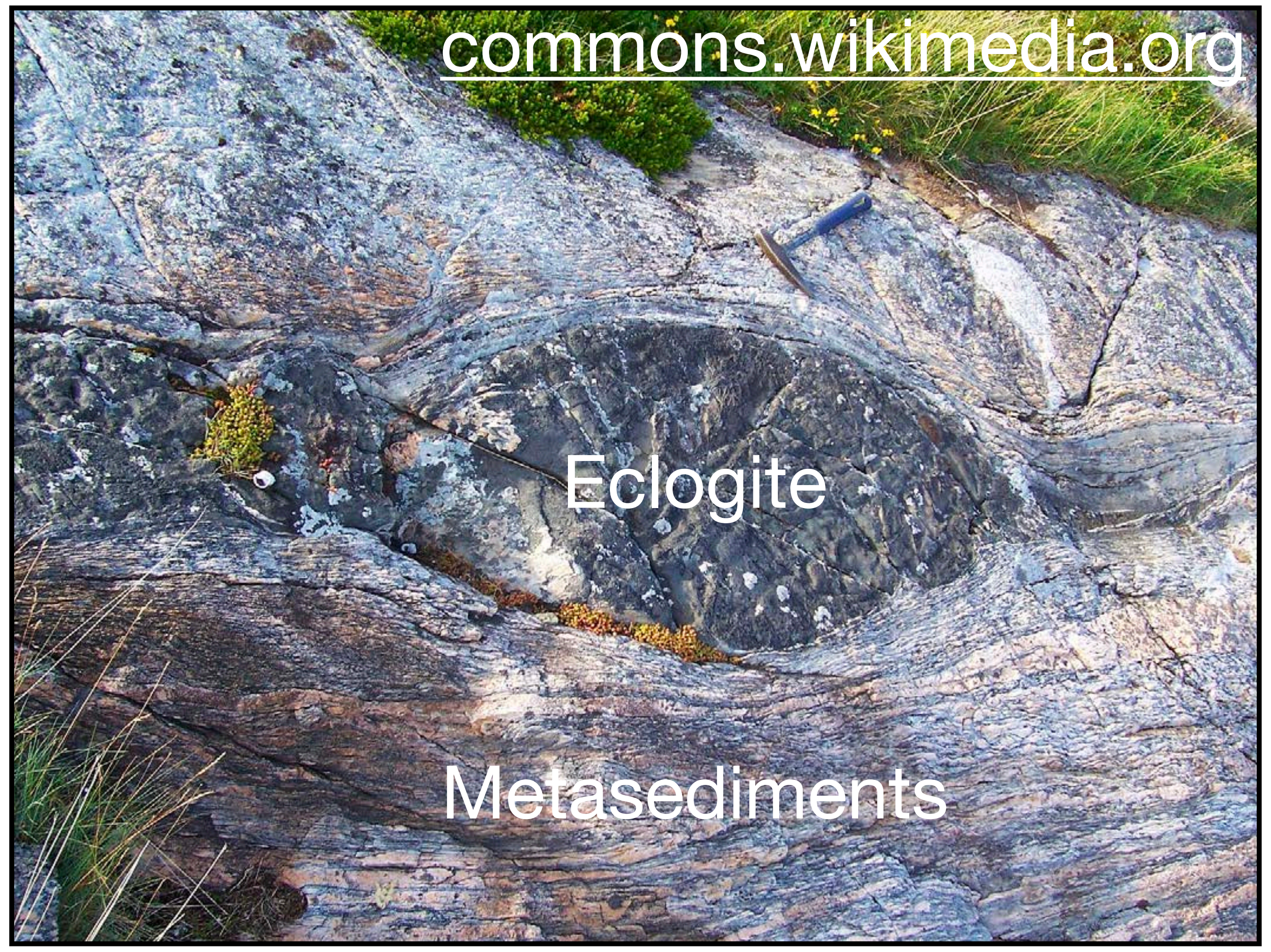


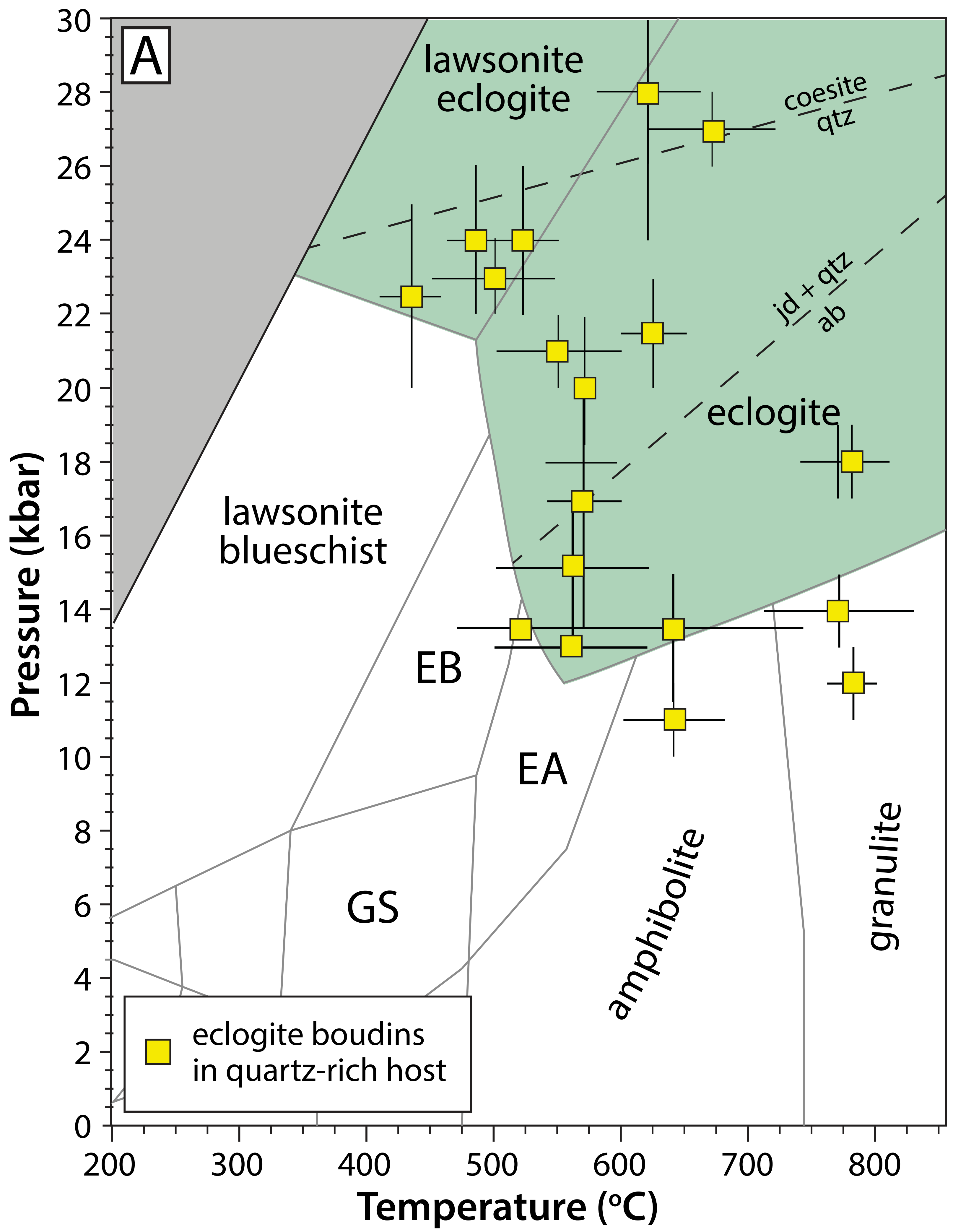


Viscosities for Quartzite & Eclogite Constrained by Field Data

Eclogite forms boudins within metasediments over a wide range of PT conditions

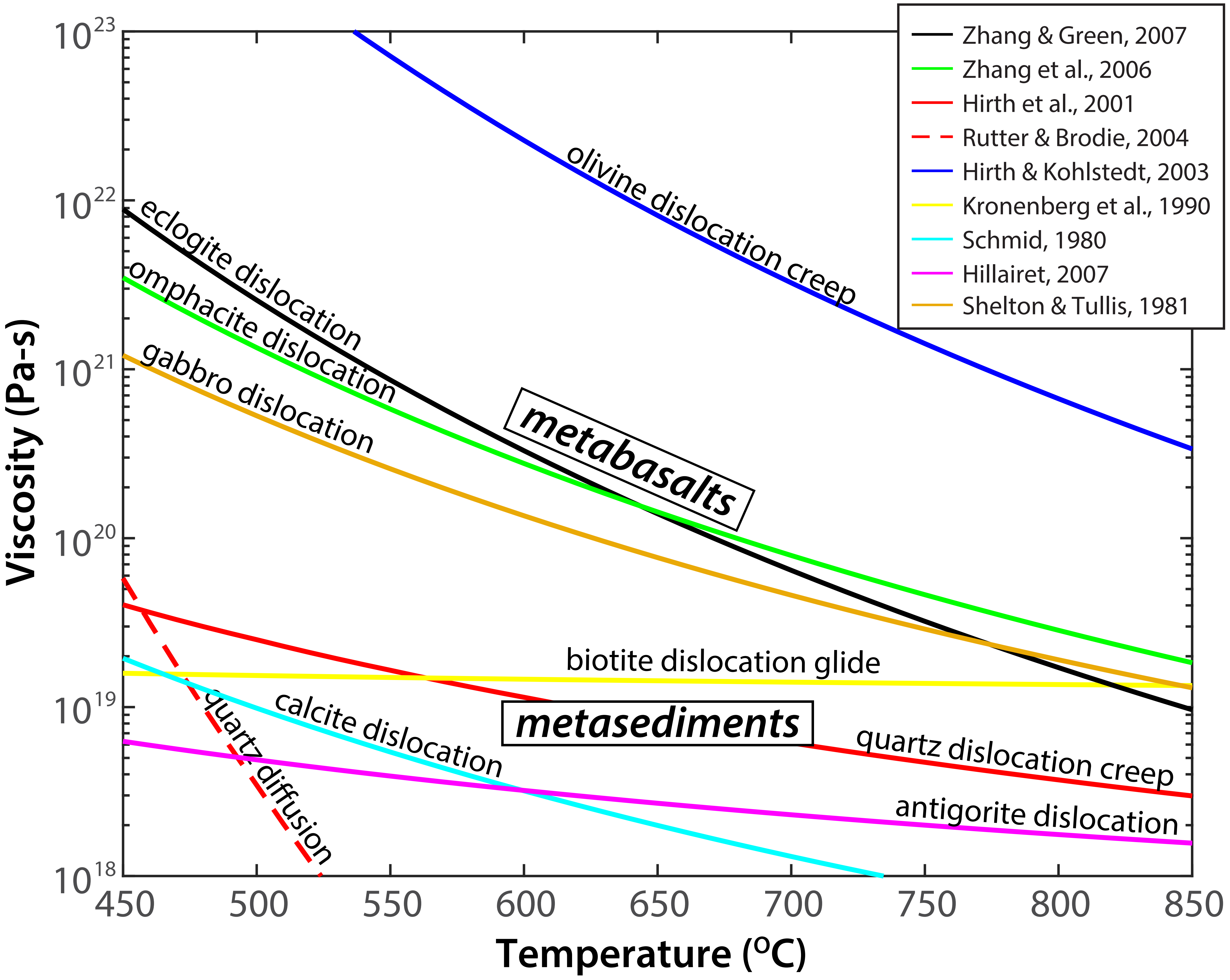






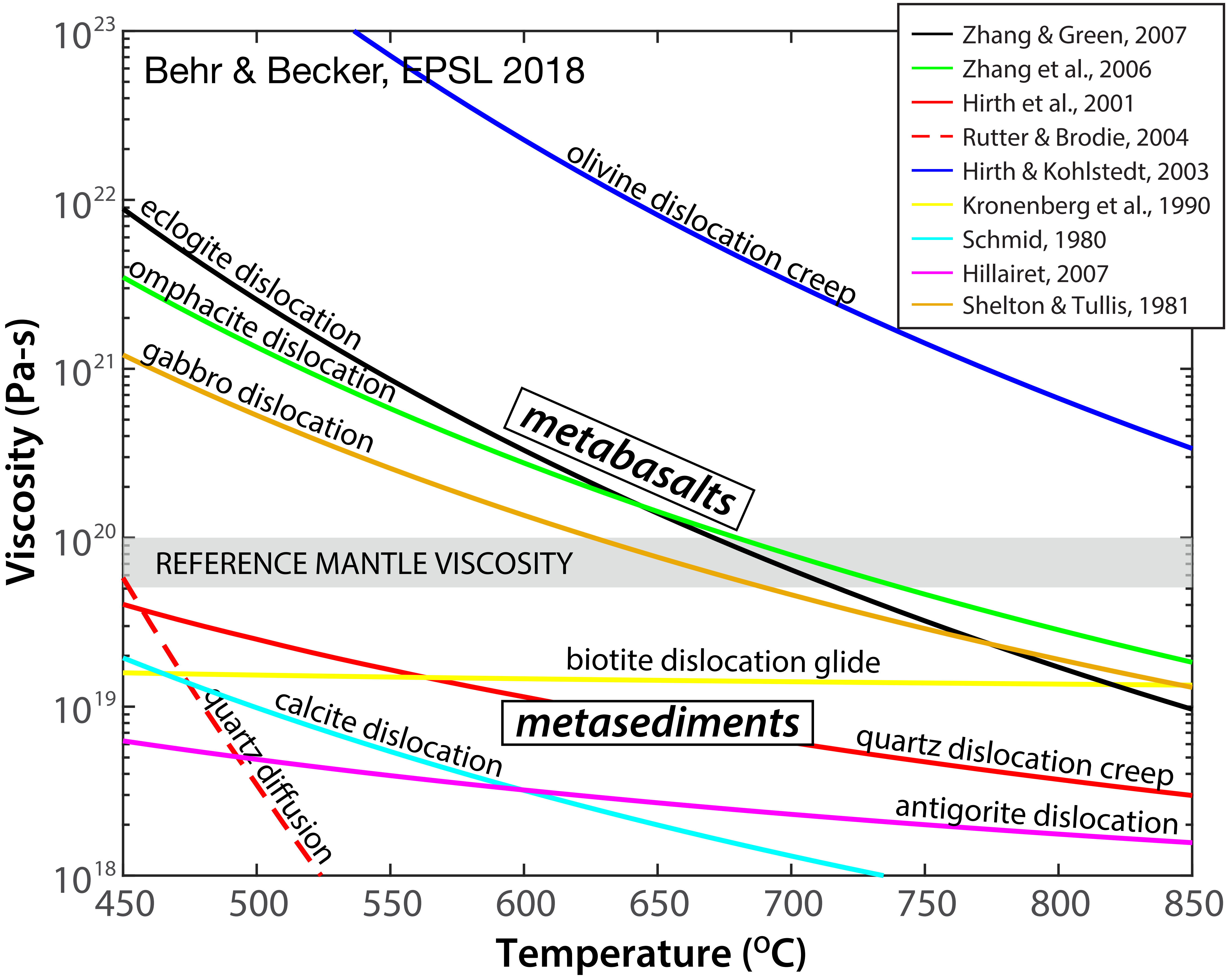
Viscosities for Quartzite & Eclogite Constrained by Experiment

Similar viscosity hierarchy quantified by experimental flow laws

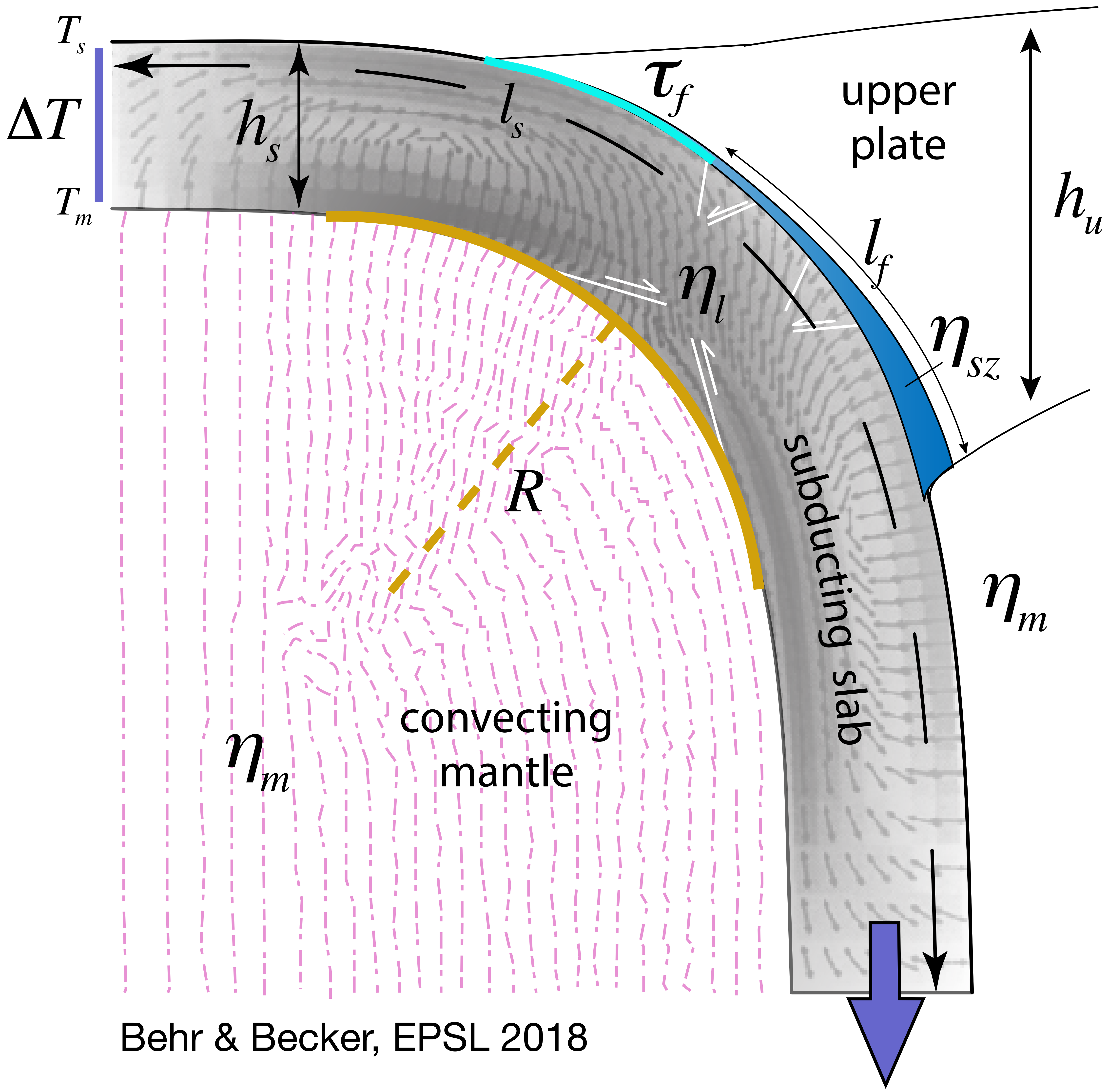


Viscosities for Quartzite & Eclogite Constrained by Experiment

Eclogite is strong relative to reference mantle between 450-700°C



Quantifying the Effect of Interface Viscosity on Plate Velocity



Behr & Becker, EPSL 2018

slab sinking due to thermal density contrasts

shear resistance along slab interface

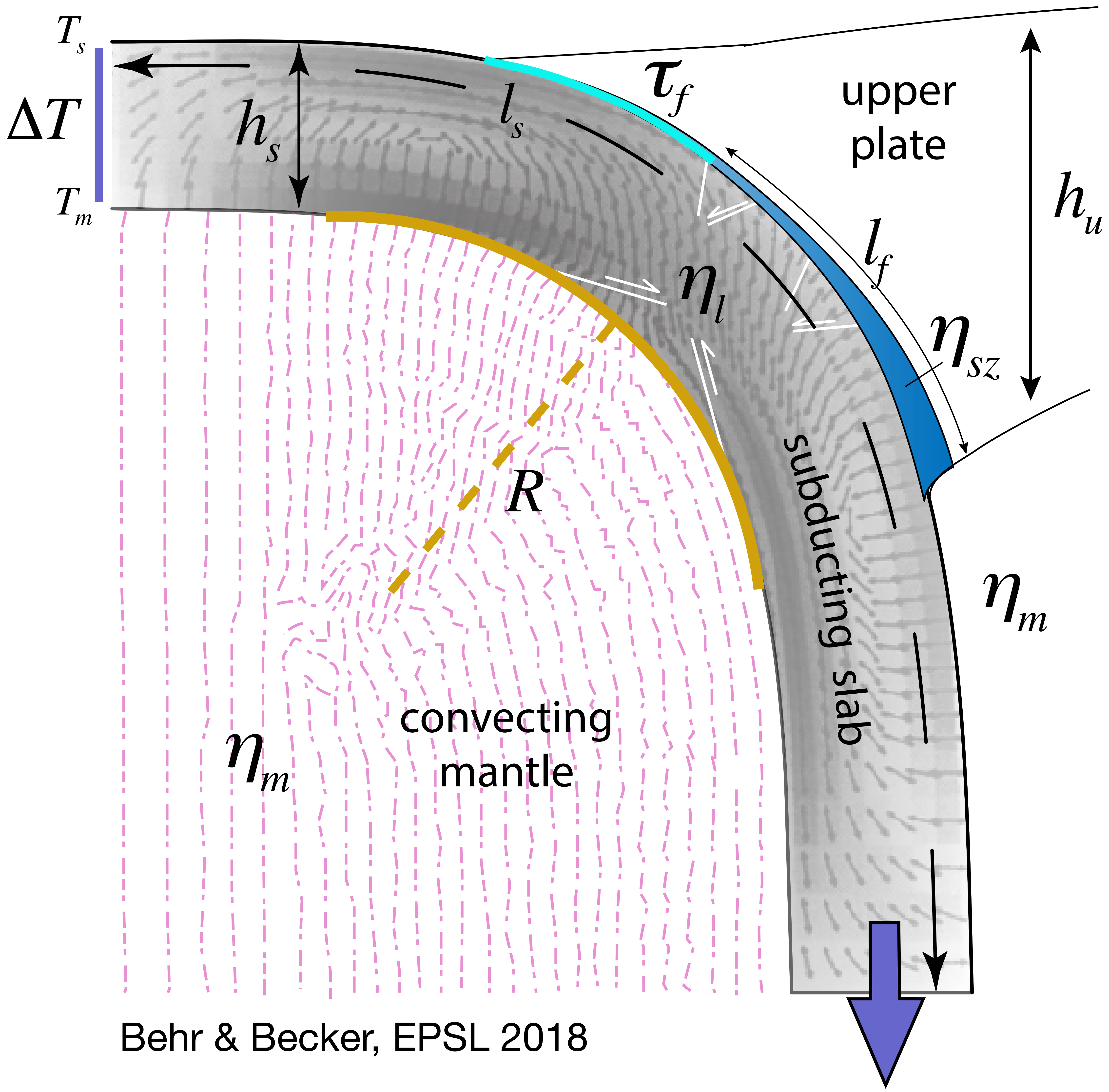
$$V_p = \frac{C_s \rho g \alpha \Delta T l_s h_s - C_f \tau_f l_f}{3\eta_m (A + C_m) + C_l \eta_l (h_l / R)^3}$$

dissipation into convecting mantle

dissipation into slab due to bending

formulation from Conrad & Hager, 1999

Quantifying the Effect of Interface Viscosity on Plate Velocity



Behr & Becker, EPSL 2018

Assumptions:

— *Slab thickness and interface geotherm scale with plate age (up to 100 km thick)*

— *Slab radius of curvature scales with upper plate thickness*

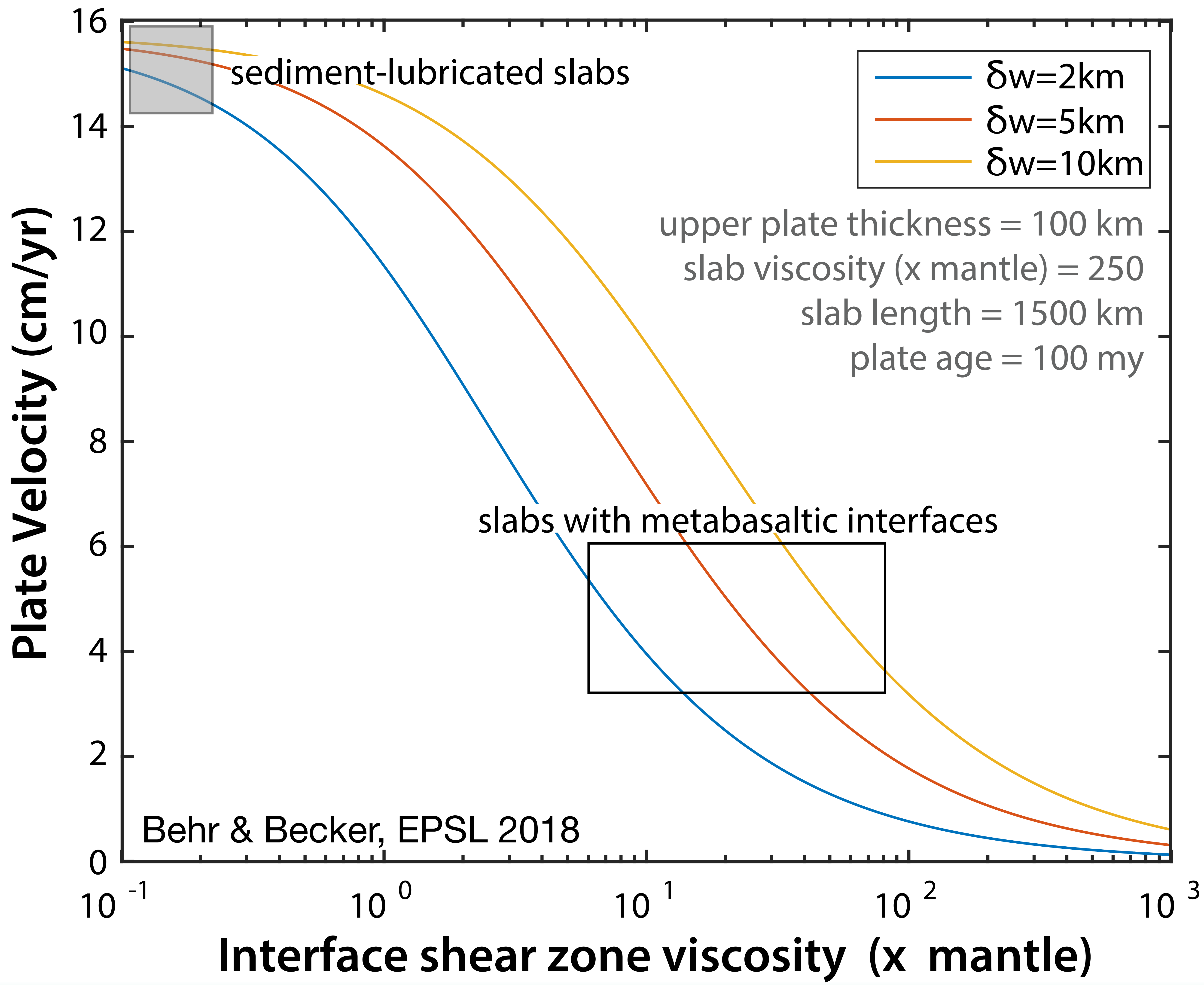
— *Contribution from frictional interface is negligible*

— *Upper plate viscosity is 100x convecting mantle*

— *Thermal/density parameters same as commonly assumed for oceanic lithosphere*

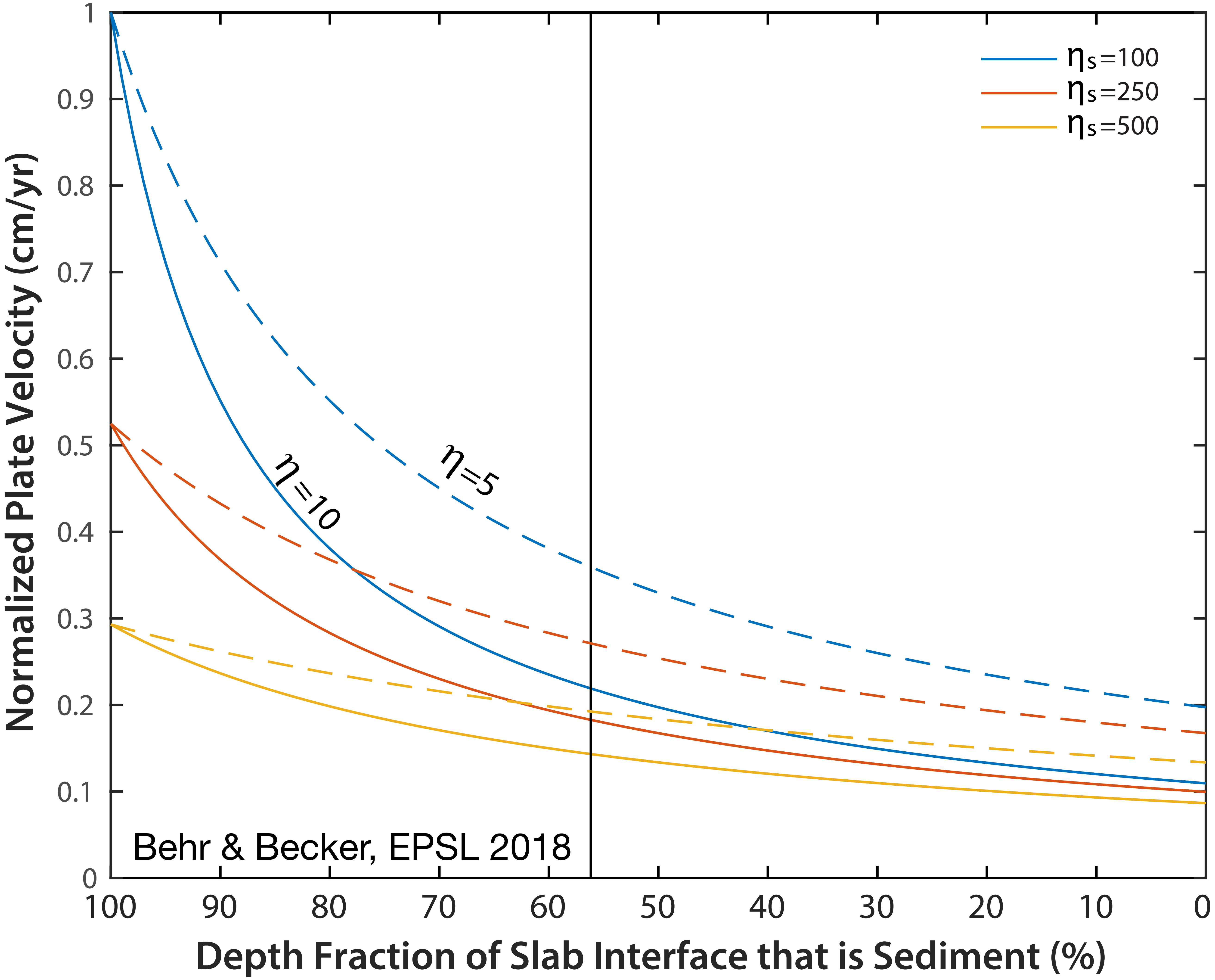
Quantifying the Effect of Interface Viscosity on Plate Velocity

Results: plate velocity as a function of interface viscosity and shear zone width



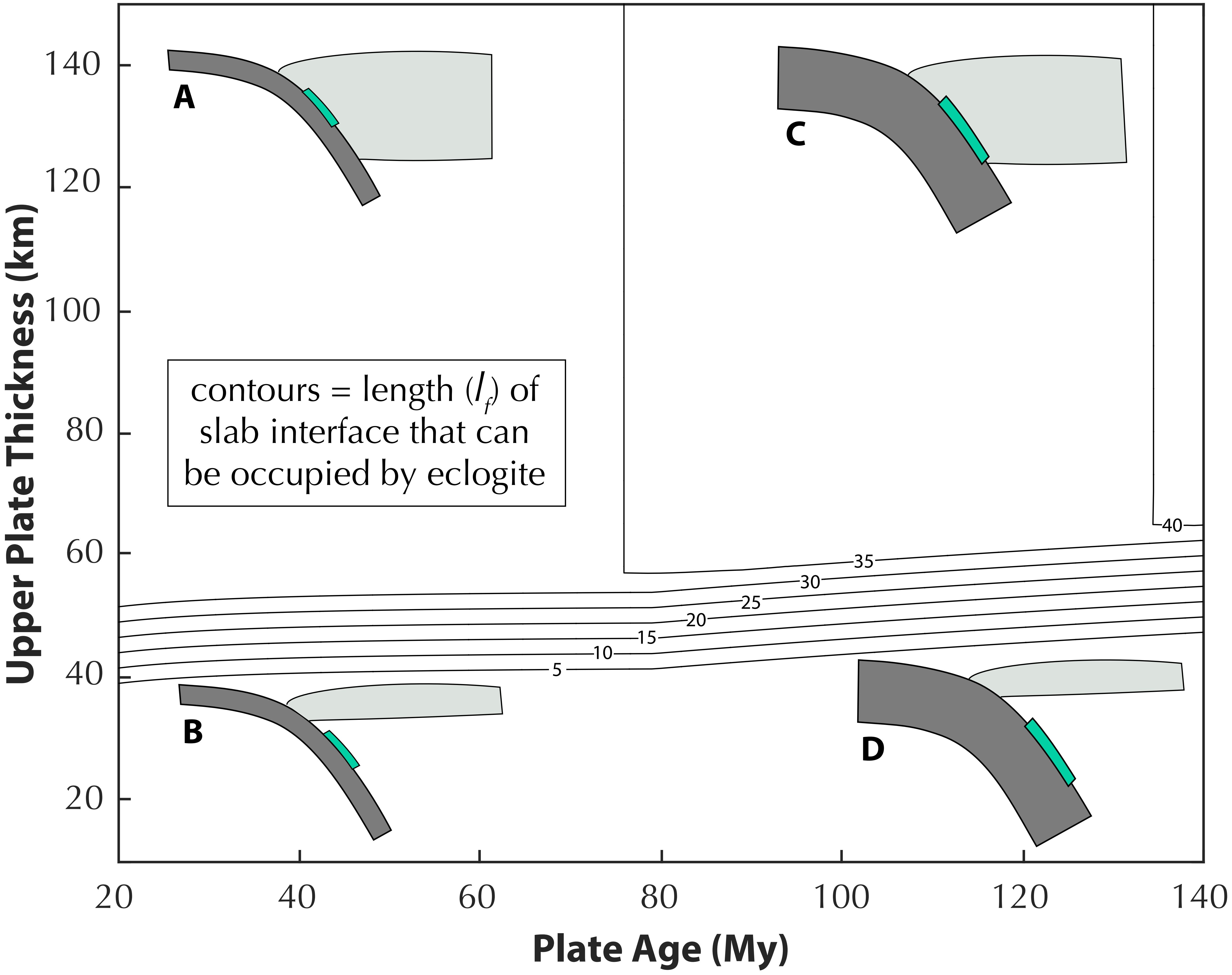
Quantifying the Effect of Interface Viscosity on Plate Velocity

Results: plate velocity as a function of interface viscosity, slab strength and % sediment

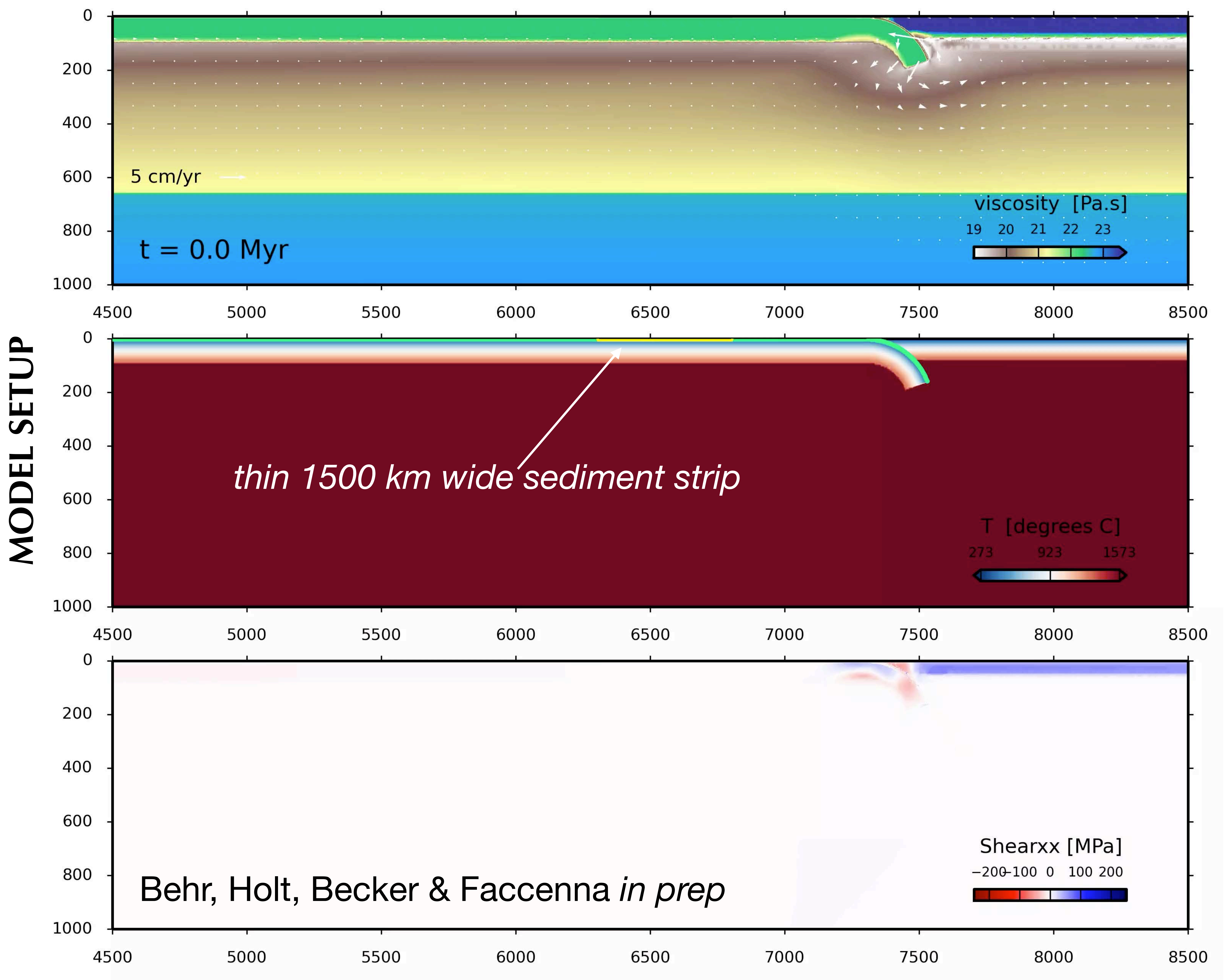


Results: Velocity as a Function of Interface Viscosity

***Results*: cold, old slabs with thick upper plates are most affected by sediment:mafic rock ratio**



Results: New Numerical Models Using ASPECT



Fully dynamic 2D subduction models built with the code ASPECT exploring how subduction interface viscosity influences:

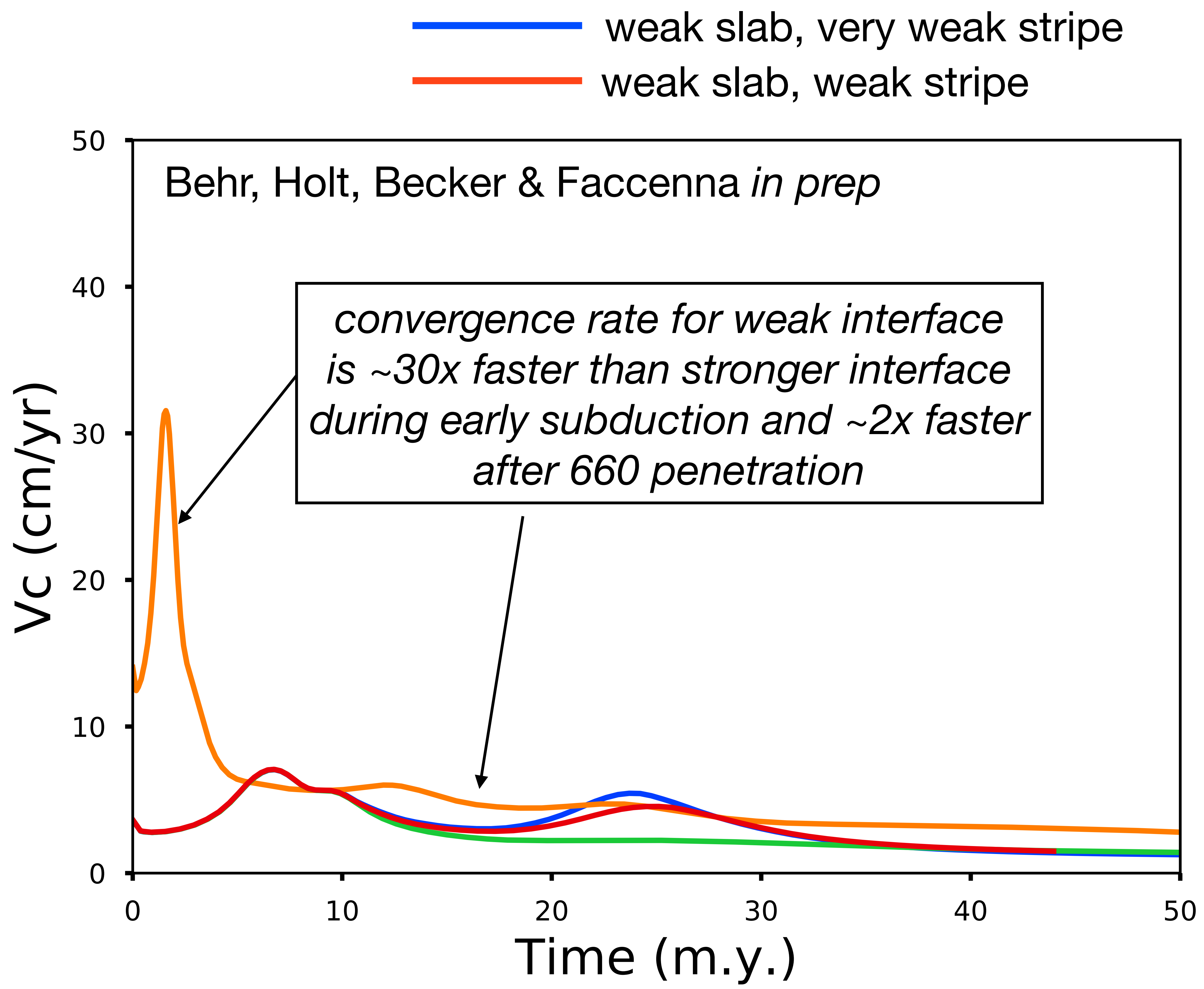
a) subducting plate sinking velocities
b) trench migration rates
c) convergence velocities
d) upper plate strain regimes
e) dynamic topography
f) interactions with the 660 km mantle transition zone.

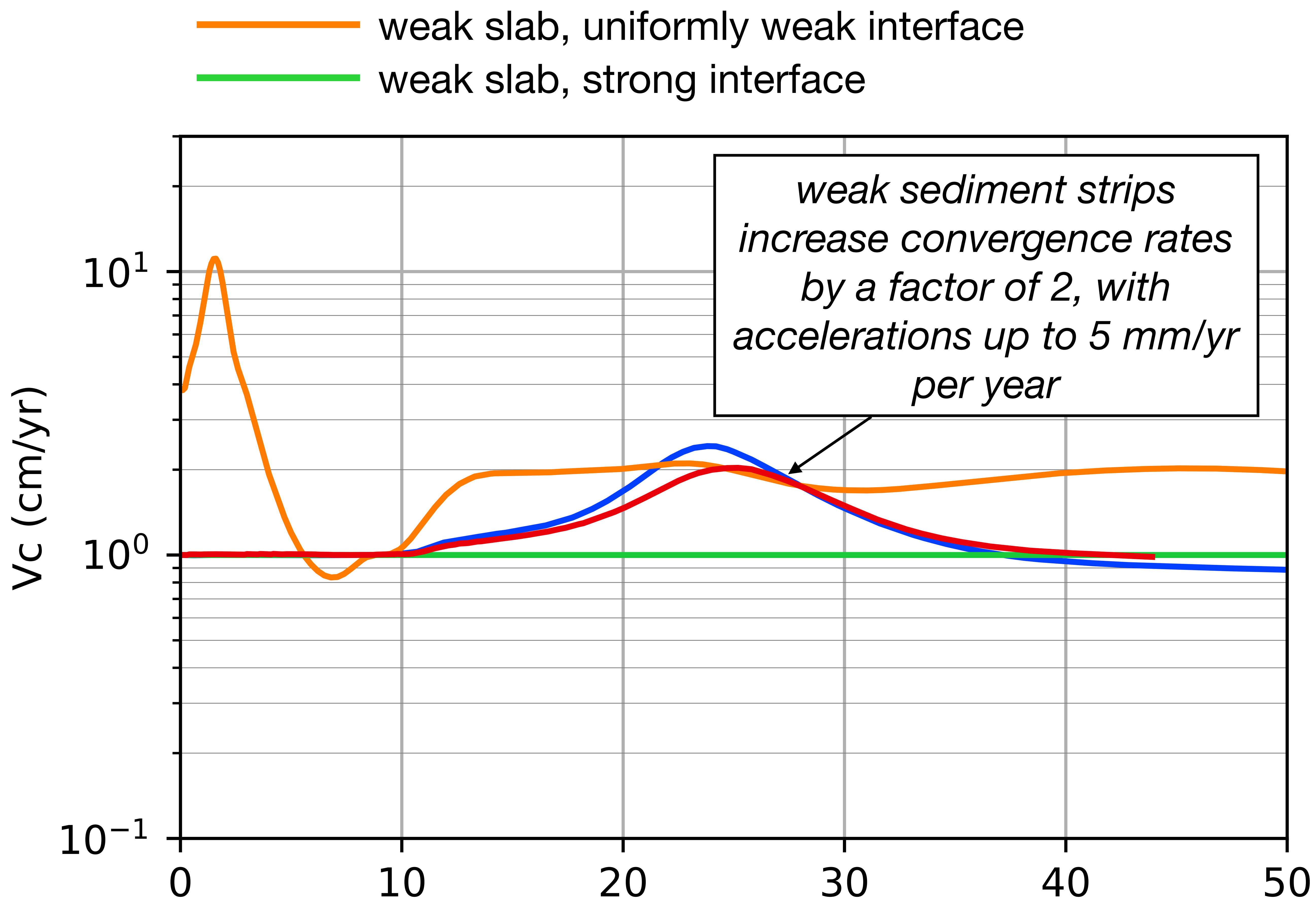
Implemented two main types of models:

1) uniform interface models where interface viscosity and slab strength are systematically varied
2) varying interface models where a low viscosity sediment strip of finite width is embedded within a higher viscosity interface.

Results: New Numerical Models Using ASPECT

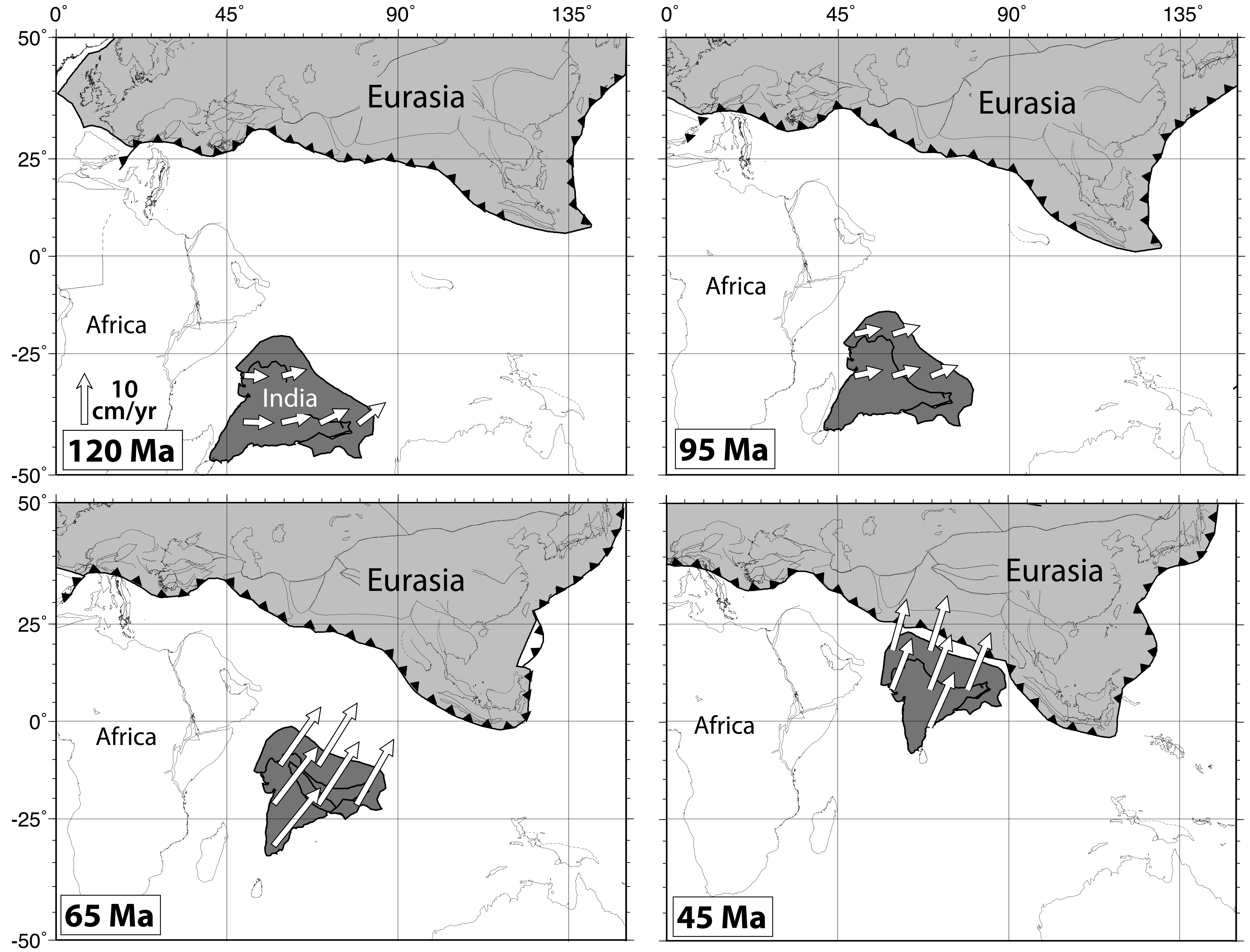
Dynamic models support the importance of sediments in influencing convergence velocities



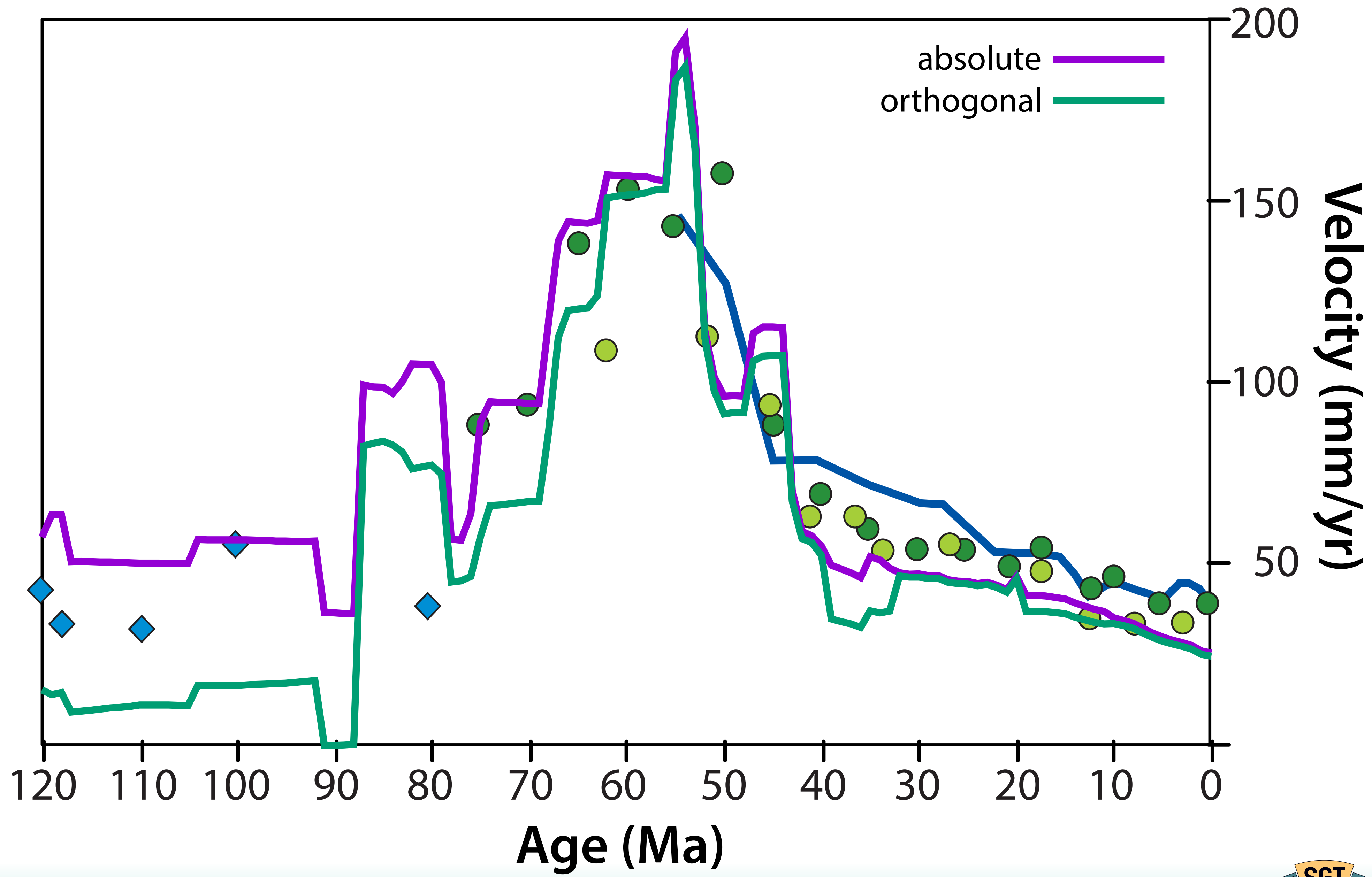


Cenozoic Acceleration of India Related to Sediment Subduction?

An acceleration of Indian motion relative to Eurasia documented for Cretaceous

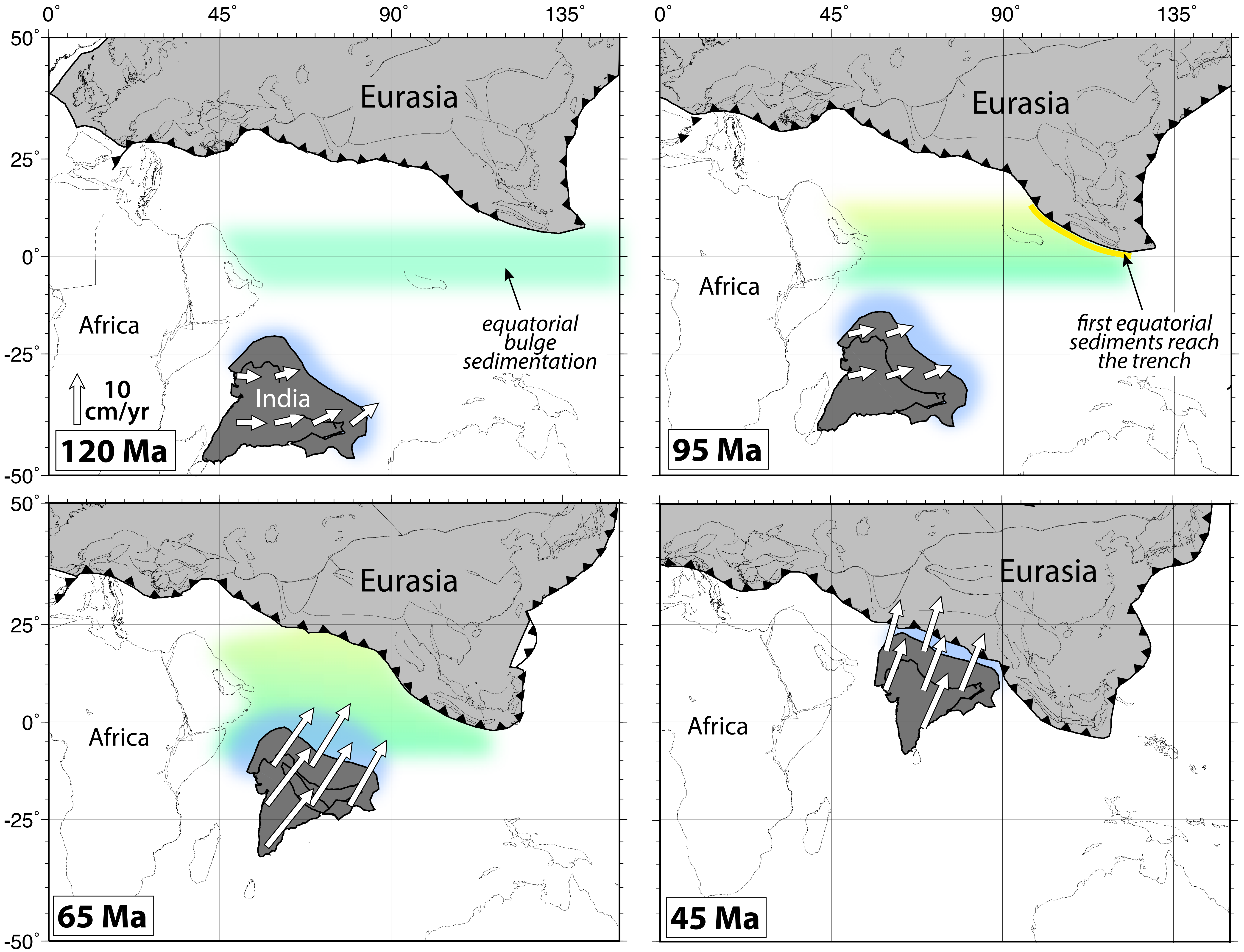


Data compiled from: Seton et al. (2012), Kent & Muttoni (2013), Jagoutz et al. (2015), Molnar & Stock (2009), Copley et al. (2010), Cande et al. (2010), Cande & Stegman (2011), van Hinsbergen et al. (2012) (see Behr & Becker, 2018 for full references)



Cenozoic Acceleration of India Related to Sediment Subduction?

The subducting Tethyan lithosphere had a carpet of equatorial pelagic sediments



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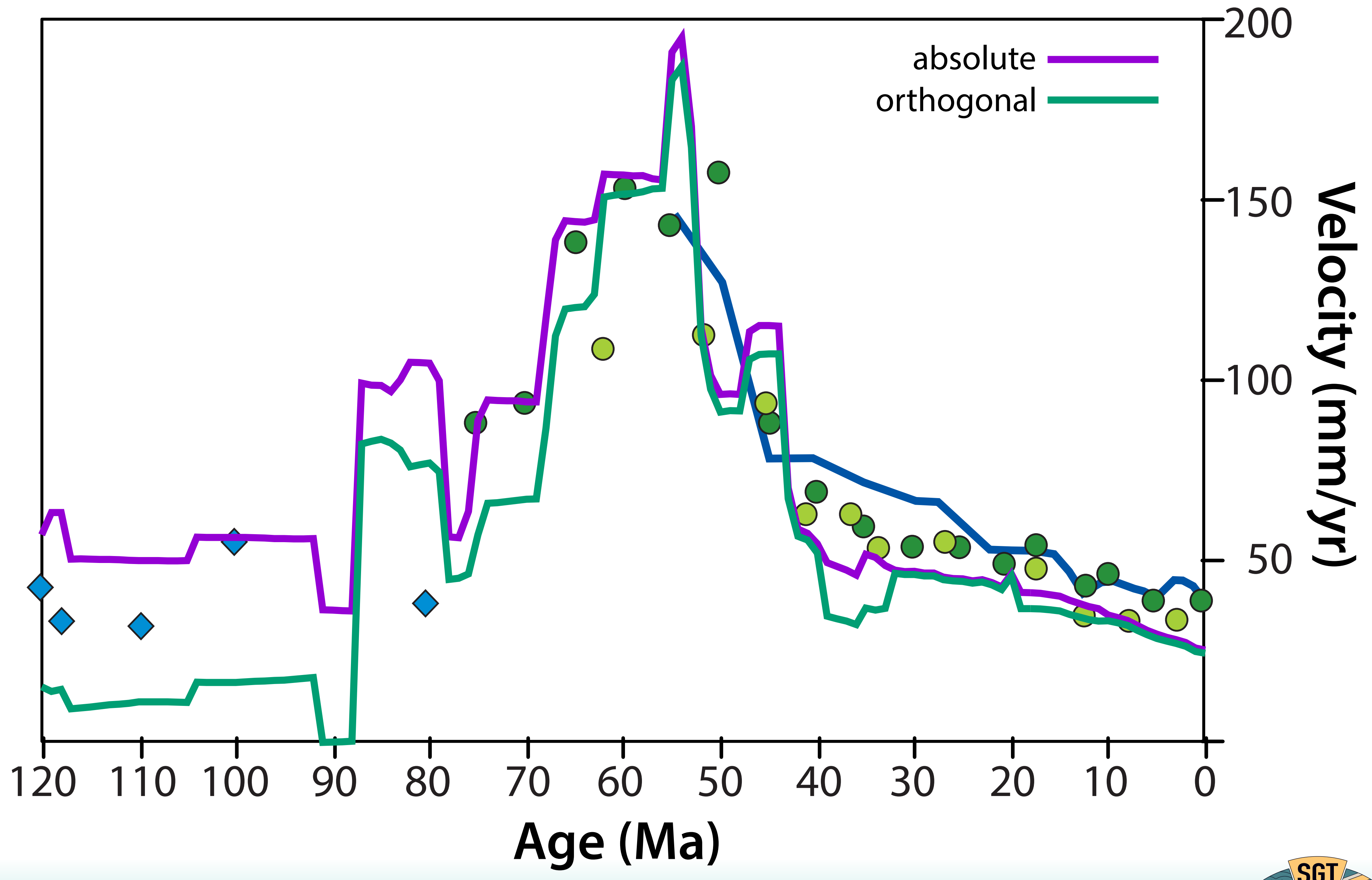
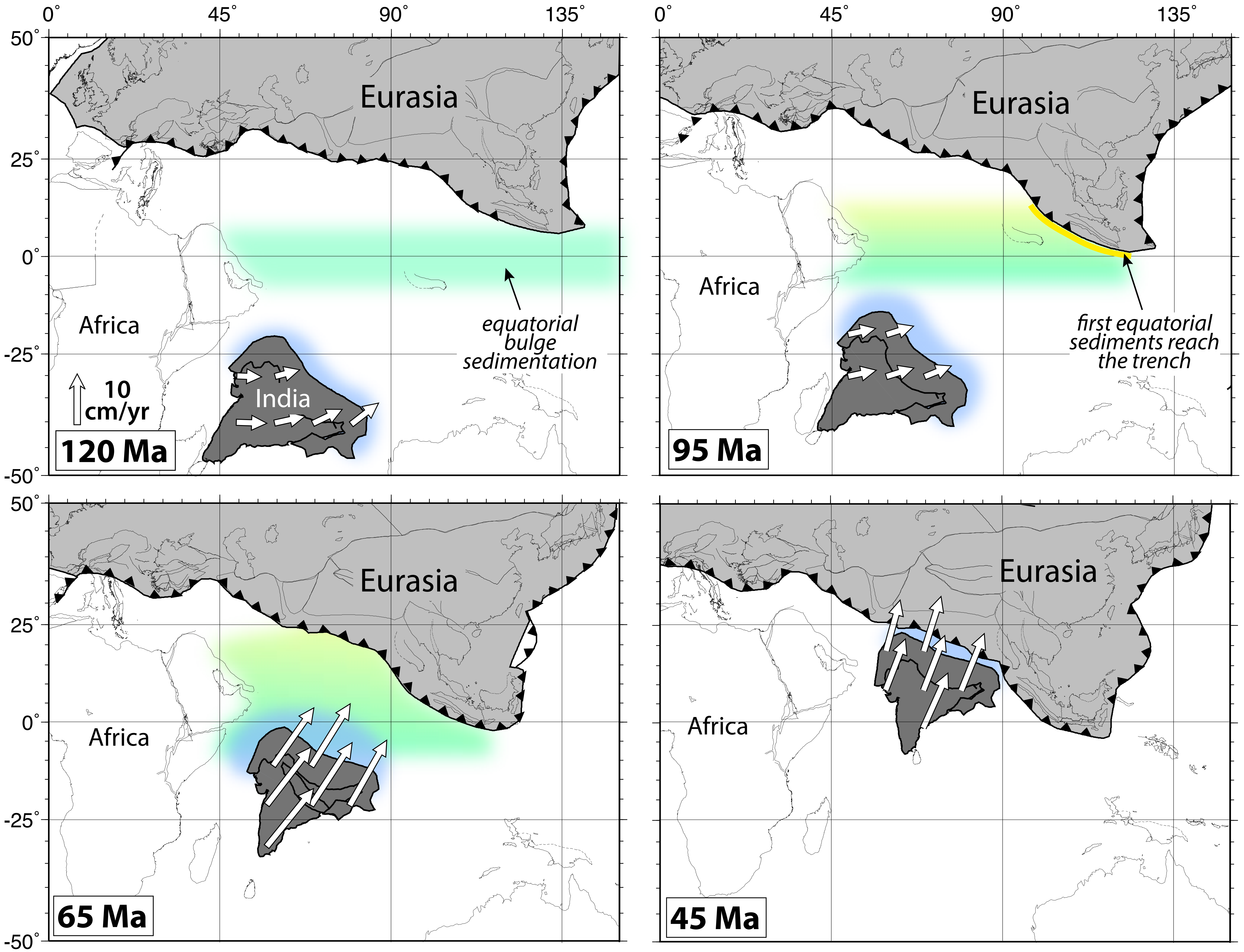
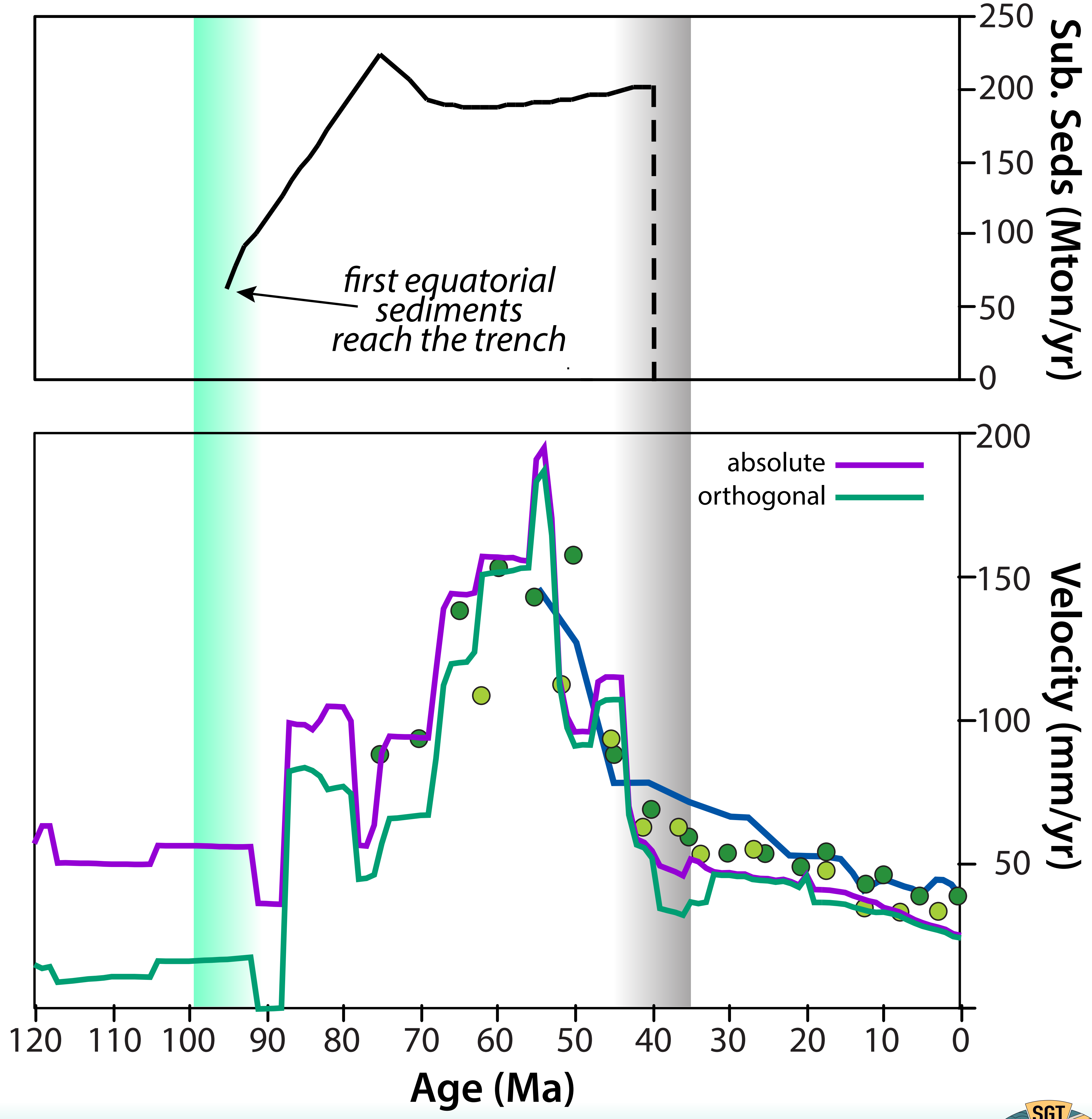


Cenozoic Acceleration of India Related to Sediment Subduction?

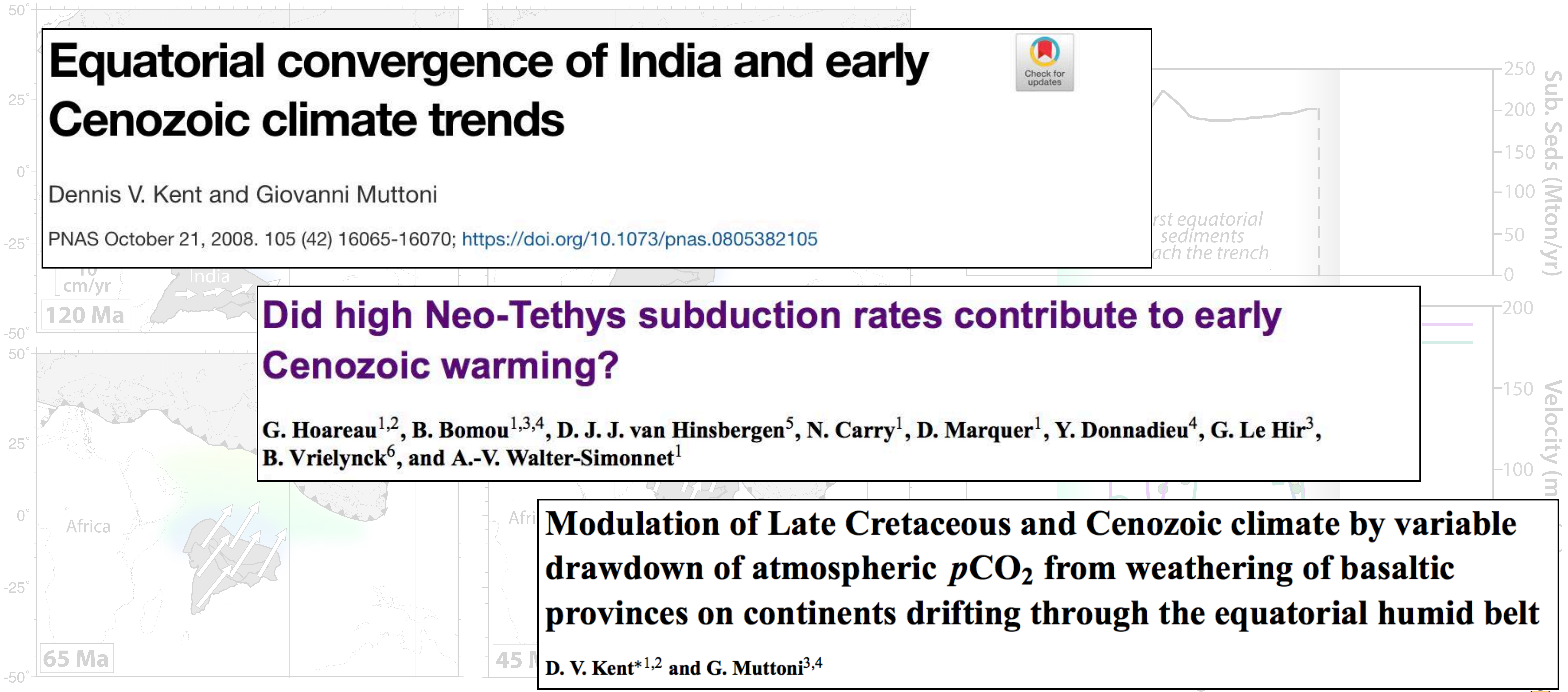
Sediment arrival at the trench roughly correlates with plate acceleration





Cenozoic Acceleration of India Related to Sediment Subduction?

Previous work has examined this for its role in Cenozoic global warming…



Equatorial convergence of India and early Cenozoic climate trends

Dennis V. Kent and Giovanni Muttoni

PNAS October 21, 2008. 105 (42) 16065-16070; https://doi.org/10.1073/pnas.0805382105

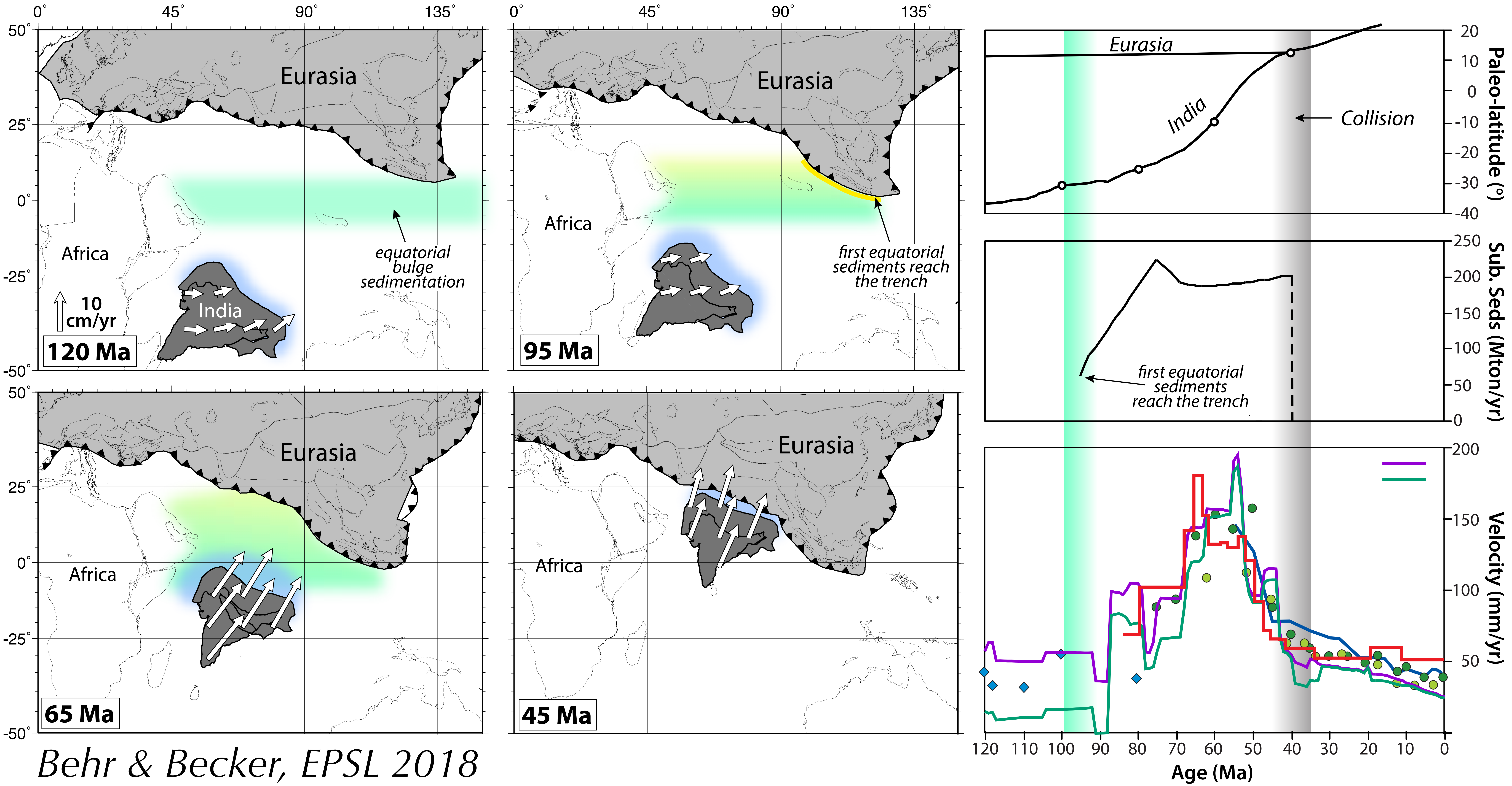
Did high Neo-Tethys subduction rates contribute to early Cenozoic warming?

G. Hoareau[1,2], B. Bomou[1,3,4], D. J. J. van Hinsbergen[5], N. Carry[1], D. Marquer[1], Y. Donnadieu[4], G. Le Hir[3], B. Vrielynck[6], and A.-V. Walter-Simonnet[1]

Modulation of Late Cretaceous and Cenozoic climate by variable drawdown of atmospheric pCO_2 from weathering of basaltic provinces on continents drifting through the equatorial humid belt

D. V. Kent*[1,2] and G. Muttoni[3,4]

Cenozoic Acceleration of India Related to Sediment Subduction?



Behr & Becker, EPSL 2018

Conclusions

- The viscous shear zone within subduction zones can affect plate speeds as a function of subducted sediment-to-mafic-rock ratio.

- Effects of sediments on plate velocities are most pronounced for:
  - oceanic-continental subduction where the upper plate is thick
  - for slabs with viscosities less than 250 times the ambient mantle

- mid-Cenozoic acceleration of India's motion during subduction of equatorial pelagic sediments on the Tethys seafloor may in part be due to the lubricating effect of sediment subduction

- Lithological control of plate boundary strength and hence plate speeds can potentially link plate tectonics, climate and life into one `Earth System'

Published References

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