Plate Speeds Modulated by Sediment Subduction

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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
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 (-)
Corollary of sediment lubrication: subduction plate speeds?

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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. Čižková et al, EPSL, 2002)
   - Close correlation between slab radius of curvature and overriding plate thickness (e.g. Holt et al, GRL, 2015)

![Diagram showing weak and strong slabs with GW values](image)

Čižková et al, EPSL 2002

![Graph showing correlation between plate thickness and radius of curvature](image)

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

Weak due to lots of sediment and high fluid pressures?

Potential to be strong??
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

[Images of rock types: greywacke, metagreywacke, pillow basalts, blueschist + eclogite]
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)
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

![Graph showing viscosity vs. temperature for different materials and processes.](image-url)
Eclogite is strong relative to reference mantle between 450-700°C

Viscosities for Quartzite & Eclogite Constrained by Experiment

- Zhang & Green, 2007
- Zhang et al., 2006
- Hirth et al., 2001
- Rutter & Brodie, 2004
- Hirth & Kohlstedt, 2003
- Kronenberg et al., 1990
- Schmid, 1980
- Hillairet, 2007
- Shelton & Tullis, 1981

- Quartz dislocation creep
- Quartz diffusion
- Biotite dislocation glide
- Calcite dislocation
- Antigorite dislocation
- Metasediments
- Metasalts
- Omphacite dislocation
- Gabbro dislocation
- Eclogite dislocation
Quantifying the Effect of Interface Viscosity on Plate Velocity

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

slab sinking due to thermal density contrasts
shear resistance along slab interface
dissipation into convecting mantle
dissipation into slab due to bending

formulation from Conrad & Hager, 1999

Behr & Becker, EPSL 2018
Quantifying the Effect of Interface Viscosity on Plate Velocity

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

![Graph showing the relationship between plate velocity and interface viscosity and shear zone width.](image)

- **Upper plate thickness**: 100 km
- **Slab viscosity (x mantle)**: 250
- **Slab length**: 1500 km
- **Plate age**: 100 My

Sediment-lubricated slabs

Slabs with metabasaltic interfaces

Behr & Becker, EPSL 2018
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

 contours = length \( \ell_f \) of slab interface that can be occupied by eclogite
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*

Behr, Holt, Becker & Faccenna *in prep*

- weak slab, very weak stripe
- weak slab, weak stripe
- weak slab, strong interface
- weak slab, uniformly weak interface

Convergence rate for weak interface is ~30x faster than stronger interface during early subduction and ~2x faster after 660 penetration.

Weak sediment strips increase convergence rates by a factor of 2, with accelerations up to 5 mm/yr per year.
Cenozoic Acceleration of India Related to Sediment Subduction?

An acceleration of Indian motion relative to Eurasia documented for Cretaceous

(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

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

Modulation of Late Cretaceous and Cenozoic climate by variable drawdown of atmospheric $p$CO$_2$ from weathering of basaltic provinces on continents drifting through the equatorial humid belt

D. V. Kent\textsuperscript{1,2} and G. Muttoni\textsuperscript{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


