Multi-Scale Dynamics and Rheology of Mantle Convection with Plates

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Key Points

- Global dynamic models of mantle convection with plates, using Rhea with adaptive mesh refinement allowing for local resolution of 1 km
- Composite viscosity with diffusion creep (linear), dislocation creep (nonlinear), and yield stress
- Models have narrow plate boundaries, sharply defined slabs in the upper mantle, and tomography structure in the lower mantle
- Yield stress and stress exponent are varied: Strength and nonlinearity
- Models are tested with suite of constraints: Plate motions, plateness, minimum shallow slab strain rate from seismic moment release, state of stress from CMT stress axes
- We study regional dynamics: Microplate motions and trench rollback as function of yield stress and strain rate
- Stress exponent strongly affects model results
- Emerging pattern: Yield stress important when low (< 200MPa). When yield stress is high, convective stress becomes more important and yield stress has no impact anymore

Global Plate Motions and Plateness

Model 104
yield stress = 100 MPa
stress exponent = 3.0

Model 107
yield stress = 800 MPa
stress exponent = 3.0

Model 109
yield stress = 1200 MPa
stress exponent = 3.75

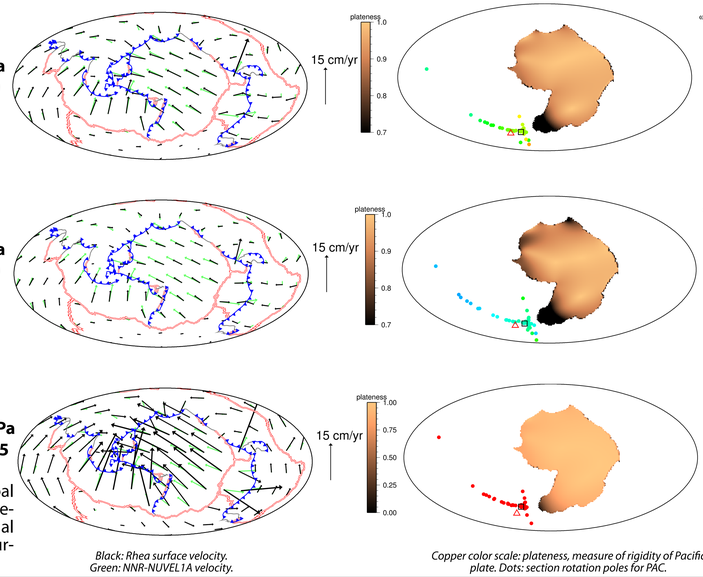


Figure 2: Left: Global plate motions and plateness. **Right:** Regional plate motions and surface strain rate.

Black: Rhea surface velocity. Green: NNR-NUVEL1A velocity.

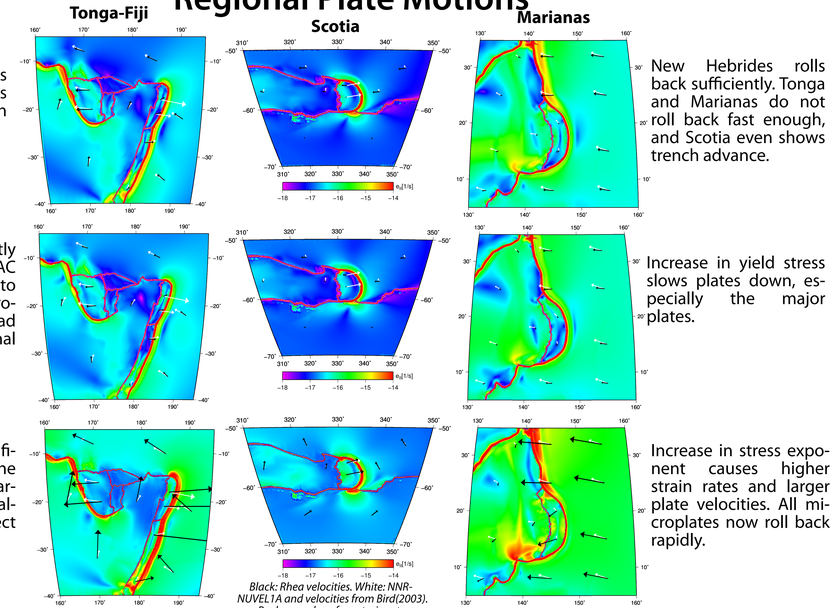
Copper color scale: plateness, measure of rigidity of Pacific plate. Dots: section rotation poles for PAC.

Plate motions fit observations reasonably well. PAC plateness is lowest at boundaries and in southwest corner.

Plate motions are significantly slower, plateness worse. PAC plate is more stuck due to higher yield stress. Section rotation poles are more spread out, indicating more internal deformation.

All plates speed up significantly, plateness improves. The effect of increase in nonlinearity (and therefore strain localization) is larger than the effect of increase in yield stress.

Regional Plate Motions



Black: Rhea velocities. White: NNR-NUVEL1A and velocities from Bird(2003). Background: surface strain rate.

New Hebrides rolls back sufficiently. Tonga and Marianas do not roll back fast enough, and Scotia even shows trench advance.

Increase in yield stress slows plates down, especially the major plates.

Increase in stress exponent causes higher strain rates and larger plate velocities. All microplates now roll back rapidly.

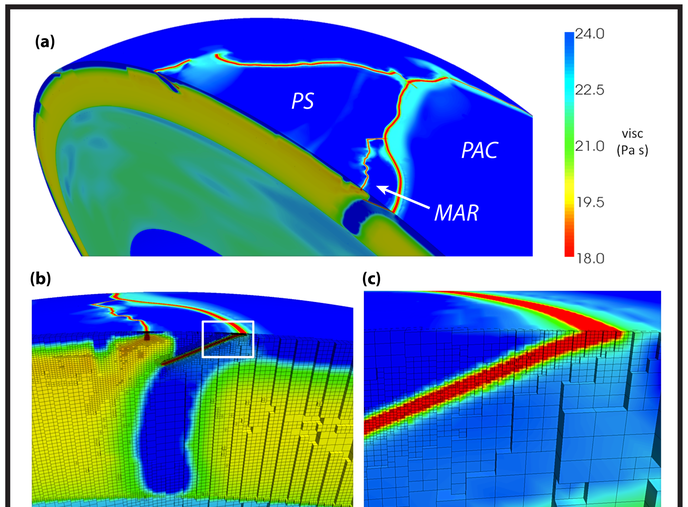


Figure 1. Typical global viscosity field. **(a)** Cut through the Pacific (PAC), Marianas (MAR) and Philippine (PS) plates. **(b)** Zoom-in on the Marianas slab, with nonlinear effects visible in the mantle wedge and slab hinge. **(c)** Further zoom-in on the mesh around the weak zone at the Marianas trench, as indicated by the white box in (b), with a highest resolution of ~1 km.

Model Constraints

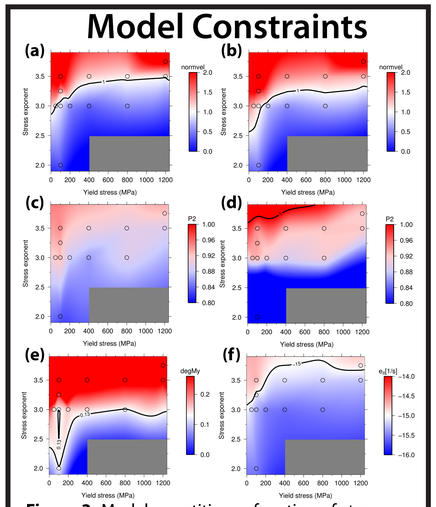


Figure 3: Model quantities as function of stress exponent and yield stress, with contours denoting constraints. **(a)** PAC normalized velocity; **(b)** Global average normalized plate velocity; **(c)** PAC plateness; **(d)** Global average plateness; **(e)** Net surface rotation; **(f)** Global average shallow strain rate.

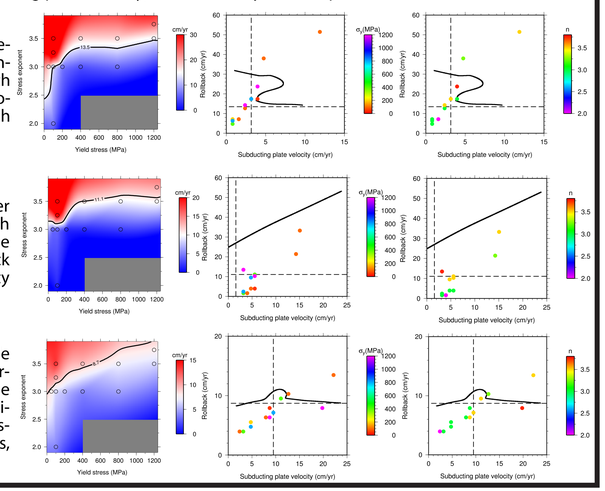
Microplates and Trench Rollback

Figure 4: Left: Trench rollback as function of stress exponent and yield stress, contour denotes constraint. **Center**: Trench rollback as function of subducting plate velocity, color coded by yield stress; dotted lines denote plate velocity constraints, shallow slab strain rate constraint shown as solid contour. **Right**: Trench rollback as function of subducting plate velocity, color coded by stress exponent.

New Hebrides
Rollback, subducting plate velocity and strain rate constraints lie close. Models with moderate to high stress exponents and yield stress match the constraints.

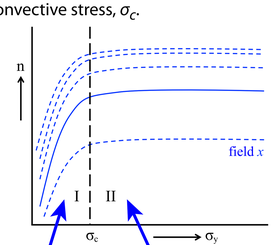
Sandwich
Strain rate constraint is never reached. Only models with high stress exponent come close to matching rollback and subducting plate velocity constraints.

Marianas
The three constraints coincide well, and models with moderate stress exponent fit the constraints. The Marianas microplate shows unusually sustained effect of yield stress, even for high yield stresses.



Convective Stresses

Figure 5: Schematic of the behaviour of a resulting quantity, e.g. plate velocity, as function of stress exponent (n) and yield stress (σ_y). Dotted lines show contours, which are closer together for higher stress exponent. The transition stress between domains I and II is denoted as the convective stress, σ_c.



Domain I:
Yield stress and stress exponent both have strong influence on the quantity.

$\sigma_{max} = \sigma_y < \sigma_c$

Yield stress limits strength of material.

Domain II:
Yield stress has no bearing on the result, only the stress exponent has effect.

$\sigma_{max} = \sigma_c < \sigma_y$

Convective stress determines bulk ambient stresses, yield stress affects only localized areas with high ambient stress.