Ultra-High Resolution and Composite Rheology in Global Mantle Flow

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Introduction

A full understanding of the dynamics of plate motions requires numerical models with a realistic, nonlinear rheology and a mesh resolution sufficiently high to resolve large variations in viscosity over short length scales. We suspect that resolutions as fine as 1 km locally in global models of the whole mantle and lithosphere are necessary. But to have this resolution on a uniform mesh on the globe is computationally extremely costly. Therefore we need to use local mesh refinement which adapts to local physics in the model.

Rhea

We use the adaptive mesh mantle convection code Rhea *(Burstedde et al, 2008)* to model convection in the mantle with plates in both regional and global domains. Rhea is a new generation parallel finite element mantle convection code designed to scale to hundreds of thousands of compute cores. It uses forest-of-octree-based adaptive meshes via the p4est library. With Rhea's adaptive capabilities we can create local resolution down to ~ 1 km around plate boundaries, while keeping the mesh at a much coarser resolution away from small features. The global models in this study have approximately 160 million elements, a reduction of ~2000x compared to a uniform mesh of the same high resolution.

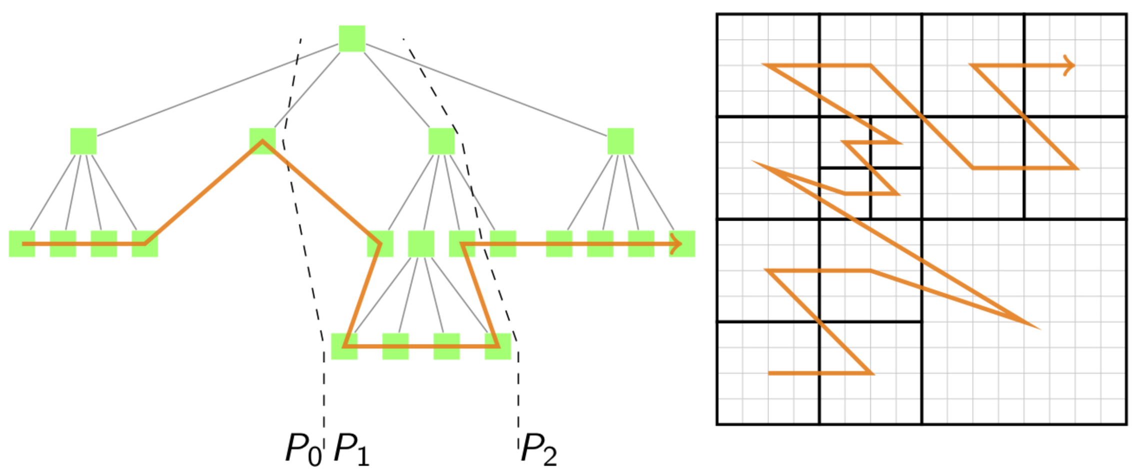


Figure 1. Example of a 2-D quadtree with refined and coarsened elements. The space-filling curve uniquely determines the ordering of all elements.

Rheology

$$\eta = \left(\frac{d^p}{A\,{C_{OH}}^r}\right)^{\frac{1}{n}} \dot{\epsilon}_{II}^{\frac{1-n}{n}} \exp\left(\frac{E_a + pV_a}{nRT}\right)$$

A composite formulation of Newtonian (diffusion creep) and non-Newtonian (dislocation creep) rheology along with yielding is implemented *(Billen and Hirth, 2007)*. Plate boundaries are modeled as very narrow weak zones with a defined viscosity reduction.

$$\eta_{comp} = \frac{\eta_{df}\eta_{ds}}{\eta_{df} + \eta_{ds}}$$

$$\sigma_y = \min\left(\sigma_0 + \frac{\delta\sigma}{\delta z} z\ ,\ \sigma_{y_{\max}}\right)$$

$$\eta_{eff} = \min\left(\frac{\sigma_y}{\dot{\epsilon}_{II}}\ ,\ \eta_{comp}\right)$$

Regional models

In the regional models, the thermal model consists of plates following a halfspace cooling model, and a slab for which buoyancy is conserved at every depth.

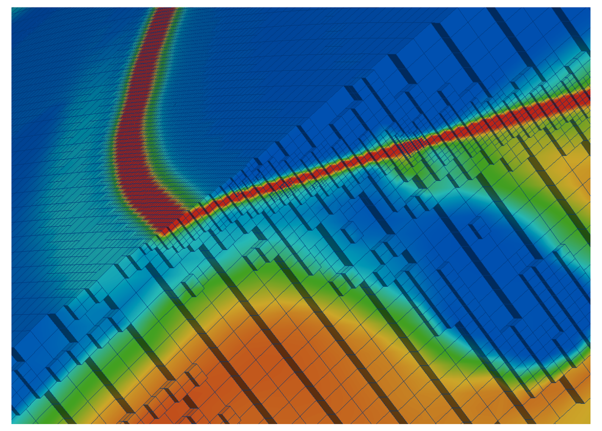


Figure 2. An example of mesh refinement around a plate boundary, shown on the viscosity field.

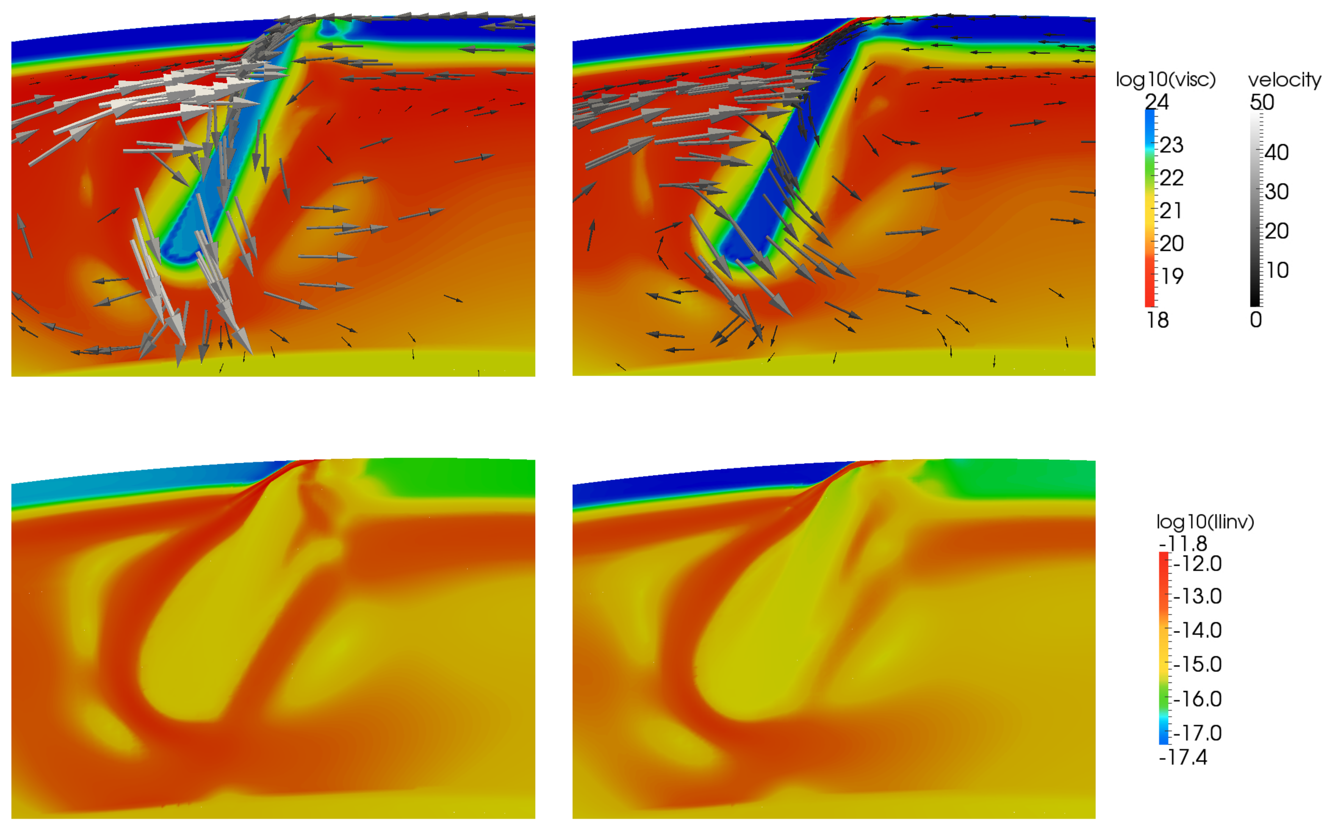


Figure 3. Two models with different maximum yield stress. **Left:** 150 MPa. **Right:** 300 MPa. The **top** shows viscosity and velocity, the **bottom** shows the second invariant of the strain rate.

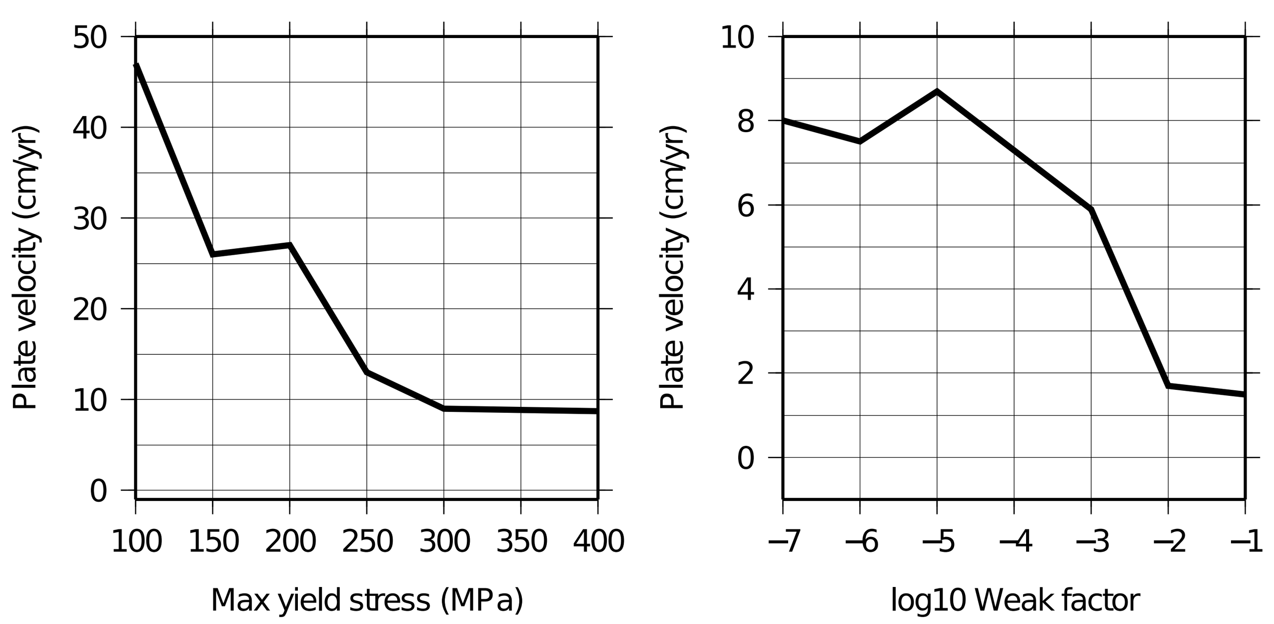
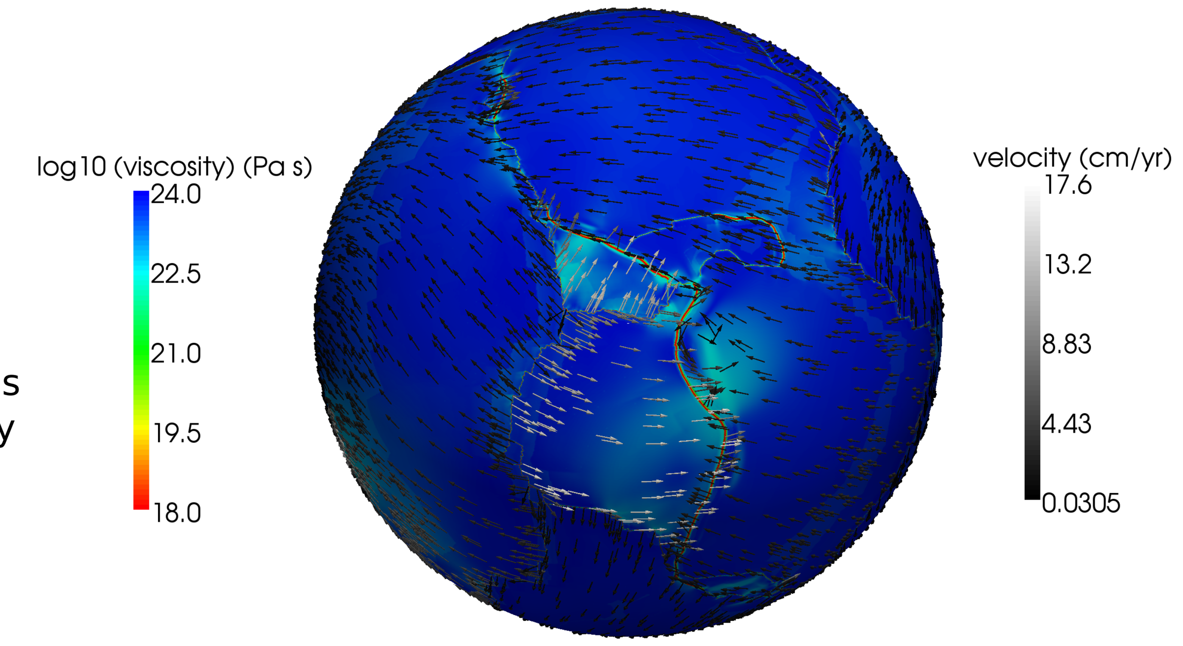


Figure 4. Plots of subducting plate velocity as a function of maximum yield stress (**left**), and viscosity reduction in the weak zone (**right**). An increase in the maximum yield stress causes the subducting plate velocity to decrease. Decreasing the strength of the weak zone between the plates increases the decoupling of the plates and hence the subducting plate velocity.

Global models

Since plate velocities and 'plateness' are dynamic outcomes of numerical modeling, we must carefully incorporate both the full buoyancy field and the details of all plate boundaries at a fine scale. The global models are constructed with detailed maps of the age of the plates *(Müller et al, 2008)* and a thermal model of the seismicity-defined slabs which grades into the more diffuse buoyancy resolved with tomography *(Li et al, 2008)*. They are tested by assessing the plateness of the surface velocity field, and its misfit with measured surface velocities.

Figure 5. A global model with viscosity and velocity, centered just west of the Americas. This model has a maximum yield stress of 50 MPa and a reduction in viscosity of 1e5 in the weak zones.



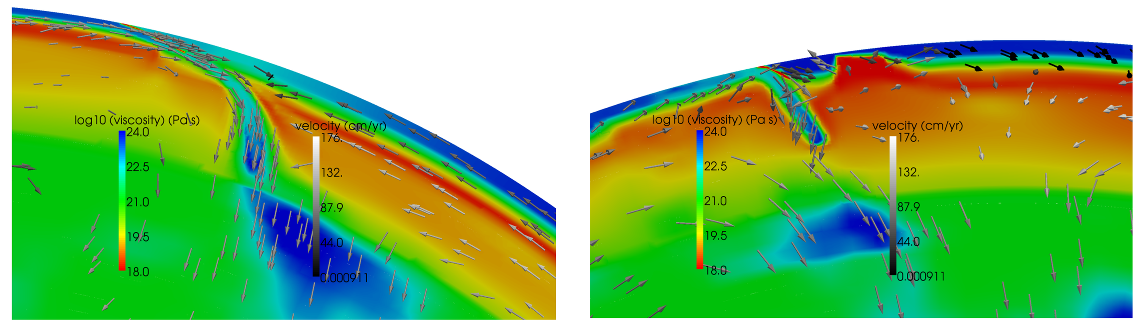


Figure 6. Cross-sections with viscosity and velocity. **Left:** Chile. **Right:** New Hebrides.

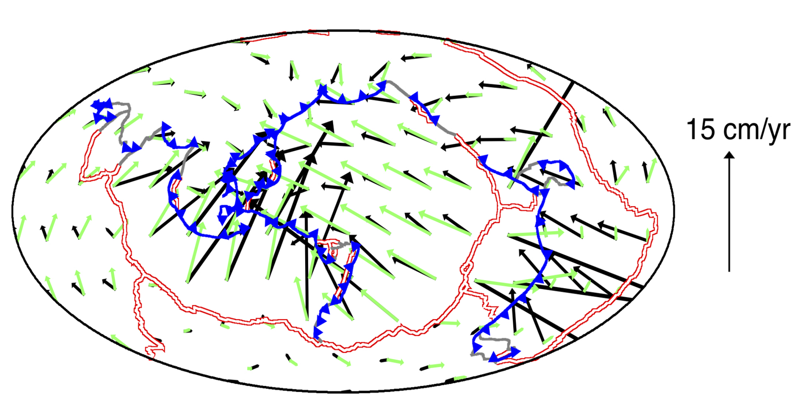


Figure 7. Global plate motions computed by Rhea (black arrows) and from Nuvel1a with no net rotation (green arrows).

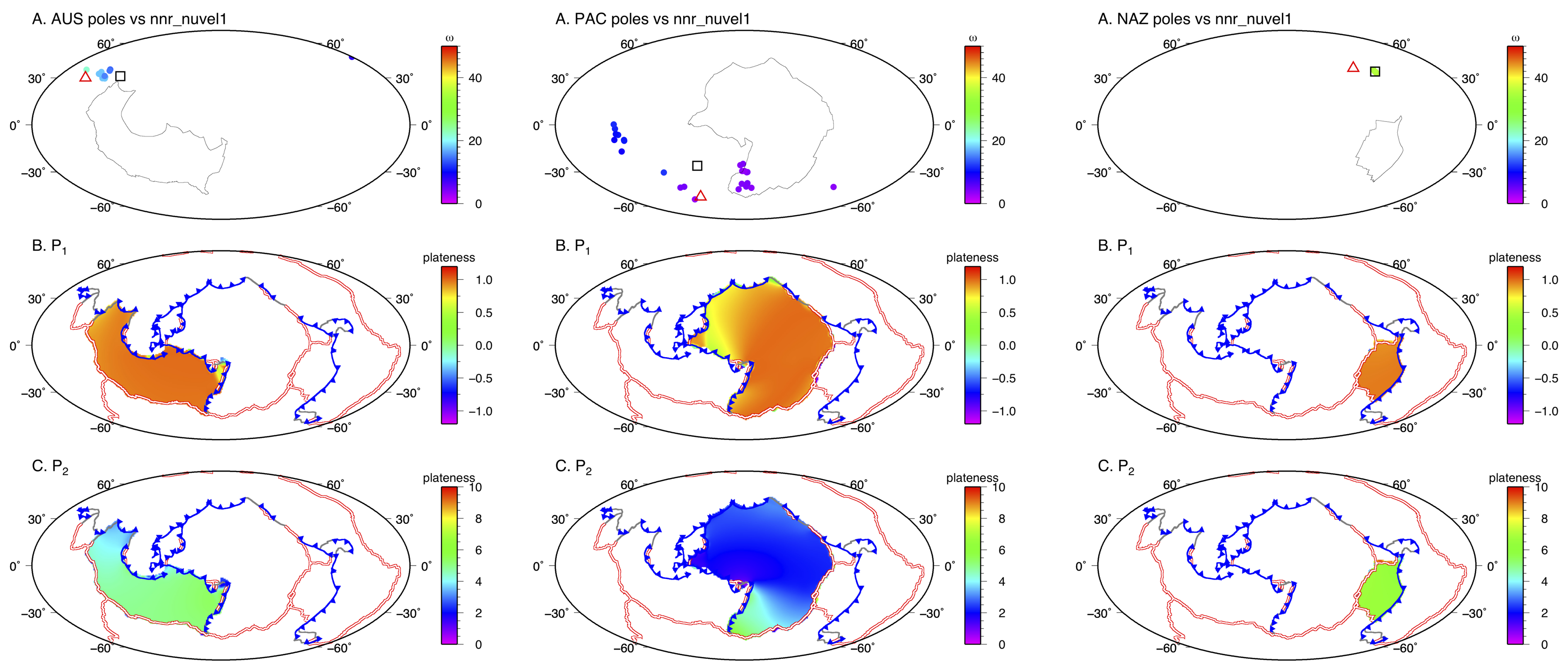


Figure 8. Euler poles and plateness for the Australian plate (**left**), Pacific plate (**center**) and the Nazca plate (**right**). Plateness (quantitative measures of how close the surface velocity field is to a plate) is computed in three ways. **A** (top): Within the polygons of each plate, we use an inverse procedure to find the Euler poles within many smaller domains with the plate. Each plotted dot refers to the inverted Euler pole within a 20 degree spherical cap. The spread of the poles is a measure of plateness. Red triangle is the Nuvel1 pole while the plate square is the average inverted pole. **B** (middle): Plateness defined as the dot product of the Nuvel1 pole and the Rhea velocities. **C** (bottom): Plateness defined as the vector difference between Rhea and Nuvel1 velocities.

Conclusions and Future

* Our current global dynamic model has unprecedented local resolution and a composite nonlinear rheology that includes yielding.

* Improvements to the plateness and fit of velocity to plate motion data can be made by locally varying the yielding and weak zone properties.

* The global mantle flow models will allow us to address the cause of changes in plate motions and the distribution of energy dissipation within the convective system.

Acknowledgements

This research was supported in part by the NSF through TeraGrid resources provided by TACC, by NSF's PetaApps program, and by the Caltech Tectonics Observatory.

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