Multi-Scale Dynamics and Rheology of Mantle Convection with Plates

Thesis by

Laura Alisic

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"I do not know what I may appear to the world,

but to myself I seem to have been only like a boy playing on the sea-shore,

and diverting myself in now and then finding a smoother pebble or a prettier shell

than ordinary, whilst the great ocean of truth lay all undiscovered before me."

— *Sir Isaac Newton*

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16+ million compute hours. 122,880 compute cores. 7.2 terabytes of stored data. 6 notebooks. 5.5 years of work. These are some numbers to illustrate the effort that went into this thesis. But the real effort came from my PhD advisor, collaborators, and colleagues.

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Abstract

Fundamental issues in our understanding of plate and mantle dynamics remain unresolved, including the rheology and state of stress of plates and slabs; the coupling between plates, slabs and mantle; the small-scale dynamics in subduction zones; the flow around slabs; and the cause of rapid changes in plate motions. To address these questions, models of global mantle flow with plates are computed using adaptive finite elements, and compared to a variety of observational constraints. These dynamically consistent instantaneous models include a composite rheology with yielding, and incorporate details of the thermal buoyancy field. Around plate boundaries, the local mesh size is 1 km, which allows us to study highly detailed features in a globally consistent framework. Models that best fit plateness criteria and plate motion data have strong slabs with high viscosities around 10^{24} Pa s, and stresses of $\sim$ 100 MPa. We find a strong dependence of global plate motions, trench rollback, net rotation, plateness, and strain rate on the stress exponent in the nonlinear viscosity; the yield stress is found to be important only if it is smaller than the ambient convective stress. Due to strong coupling between plates, slabs, and the surrounding mantle, the presence of lower mantle anomalies affect plate motions. The flow in and around slabs, microplate motion, and trench rollback are intimately linked to the amount of yielding in the subducting slab hinge, slab morphology, and the presence of high viscosity structures in the lower mantle beneath the slab. The lateral flow around slabs is generally trench-perpendicular, induced by the strongly

coupled downward motion of the subducting slabs, and therefore our models do not account for the trench-parallel flow inferred from shear-wave splitting analysis. Flow models before and after the plate reorganization around 50 Ma are not able to reproduce the rapid change in Pacific plate motion from northwest to west that is associated with the bend in the Hawaiian-Emperor chain, despite a nonlinear rheology and the incorporation of detailed reconstructed paleo plate boundaries and age grids. In these models at 55 and 45 Ma, slab age is an important factor in the slab pull, determining the coupling between plates and slabs and between upper and lower mantle sections of slabs. The overall dynamics appear to be dominated by the characteristics of slab remnants in the lower mantle. Subducting slabs affect lateral flow in the upper mantle on a much smaller scale, and therefore we conclude that it is unlikely that the slabs in the western Pacific are responsible for the slowing of sub-Pacific flow after the initiation of their subduction around 50 Ma.

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