Chapter 5

Summary and Outlook

5.1 Summary

In this thesis, I have addressed the modeling of mantle convection with plates, utilizing adaptive mesh refinement techniques so that small-scale features such as plate boundaries and localized deformation in plates and slabs can be resolved. In this chapter, the main findings are summarized and put into context of our current understanding of mantle dynamics.

The rheology of plates, slabs, and the surrounding mantle The models presented in this thesis indicate that model constraints such as plate motions and plateness are best met when plates and slabs are strong, with a viscosity of $\sim 10^{24}$ Pa s. Localized strain-rate weakening reduces the viscosity to $\sim 10^{22}$ Pa s or less in plate hinges. The spatial extent and amount of this weakening depends on slab morphology and motion, and on the rheology (specifically the yield stress and stress exponent). Plate boundaries have a low viscosity of $\sim 10^{18}$ Pa s, so that they effectively decouple plates from one another. The (de)coupling between plates is an important aspect of these models: local changes in plate boundary strength significantly affect the plate motions and surface state of stress in a much larger area. For example, increasing the plate boundary strength in Peru affects stress orientations in the entire South America and Nazca plates. This behavior illustrates the highly nonlinear nature of the models, and demonstrates that the spatial variation of plate boundary strength is an important future avenue of research.

The debate in literature of weak versus strong slabs is partly the result of differences between linear and nonlinear rheology: studies using a linear rheology effectively only assess the average viscosity of slabs, whereas nonlinear rheology allows for localized weakening in otherwise strong slabs.

Coupling between plates, slabs, and the surrounding mantle The strong plates and slabs in the convection models are able to act as highly effective stress guides. Coupling between surrounding mantle and slabs is high, given that the velocity field is continuous from the slabs to the surrounding mantle. Changes in yield stress and stress exponent directly affect the velocity magnitude in plates, slabs, and asthenosphere, but these in turn affect the entire mantle flow. The distribution of energy dissipation in the mantle is also indicative of coupling between mantle, slabs, and plates. Pointwise, the dissipation is highest in bending plates, which is also indicated by the significant strain-rate weakening there. By volume, the majority of dissipation takes place in the lower mantle. This is in contrast to earlier studies where the bending dissipation was viewed as the dominant process.

The importance of lower mantle structure for plate tectonics Lateral viscosity variations in the lower mantle can affect plate motions, depending on whether high-viscosity structures are directly beneath (and connected with) subducting slabs. Generally, subducting slabs are slowed by the presence of broad, high-viscosity, lower mantle features which act as a "braking force". Stresses are transmitted upward from the lower mantle structures or the tip of the subducting slabs into the plates, and therefore these lower mantle structures affect surface velocities. In contrast, overriding slabs are sped up by increased lower mantle viscosity variation due to the added buoyancy in the convective system. This behavior fits the hypothesis of strong coupling throughout the convective domain. It is therefore essential to include lower mantle lateral viscosity variation in mantle convection models. Consequently the details of tomography models affect model results, especially for the mid-mantle, as the continuity between the slab and underlying anomaly is very important. For example, the tomography model used for the convection model does not contain a section of the Sandwich slab below ~ 300 km depth, resulting in trench rollback that is significantly slower than observations indicate.

Regional dynamics in globally consistent convection models In order to model regional dynamics, it is important to include the global mantle flow, especially when a nonlinear rheology is used. Depending on choices in rheology, the global models are able to reproduce observed details in surface motions, such as trench rollback and microplate motion. Flow around subducting slabs is mostly trench-perpendicular, indicating that it is mainly driven by the downgoing motion of the slab. The models do not display significant trench-parallel flow components and therefore do not match simple predictions from seismic anisotropy studies. The only trench-parallel flow in our models is around the edges of slabs, and in areas where the proximity of multiple slabs creates complex flow patterns. The velocity orientation and magnitude, as well as yielding in slabs, are linked to slab morphology and dip, plate motion, trench rollback, and the presence and continuity with lower mantle structure beneath the slab.

The effect of regional geometry versus rheology on modeled quantities Plate velocity is predominantly governed by the amount of negative buoyancy attached to the plate in the form of subducting slabs, modulated by the amount of deformation determined by the rheology. Microplates are more significantly affected by stress exponent as they require a very strong de-coupling from other plates. The state of stress and the direction of plate motions are primarily governed by plate and slab geometry; variation in rheology does not result in consistent trends in either quantity.

Causes of rapid plate reorganizations in the geologic past In light of the previous conclusions, it is to be expected that both mantle flow and temporal changes in plate tectonics play a part in reorganizations; they are necessarily strongly coupled phenomena. The model dynamics are dominated by the size, morphology, and strength of slab remnants in the lower mantle, such that rapid changes in surface motions have proven difficult to reproduce. The additional uncertainties in plate reconstructions and mantle structure make modeling in the geologic past even more challenging than for the present. For example, there are significant discrepancies in the net rotation among different paleo plate reconstructions, and details of the mantle structure in the past are virtually unknown.

5.2 Outlook

The advances in mantle convection modeling described in this thesis open up various avenues of future work. First of all, the problem of reproducing rapid changes in the motion of major plates in a dynamic flow model remains. Much could be learned from experimenting with various time-dependent models used to construct the mantle structure, especially ones with different slab lifespans. Additionally, the inclusion of active upwellings in both present-day models and in the historic models would allow for study of the effects of plumes and their interaction with ridges on plate motions. A major question still open is the effect of variation in plate boundary strength on plate motions, which could be studied in more detail in a systematic manner. This could be coupled with local tectonic indicators of plate boundary strength, for instance in areas where ridges are being subducted. Furthermore, time-dependent convection models would allow time evolution of weakening and would pose an additional constraint on rheology, given that plates and slabs must be able to retain their strength over significant intervals of time. Such time-dependent models would also provide a more realistic way to model plate reorganizations, including features such as temporal plume-ridge interaction.Because the paleo plate reconstructions are the only global means currently at hand to structurally verify these convection models, it is paramount that improvements to the reconstructions continue being made, especially with respect to the net rotation.