Chapter 7

Conclusions

The analyses of the preceding chapters are designed to investigate styles of convection that may arise in the Earth's mantle because low surface temperatures create a lithosphere that is dense, allowing it to drive convection, but also strong, causing it resist convective flow. Chapters 2 and 3 show that convective instability at short wavelengths should be capable of removing the basal portion of the mantle lithosphere, but that the amount and rate of removal depends on the details of how viscosity and density vary with depth. This type of convection is often described as occurring beneath a "stagnant lid" because it does not involve the cold, dense, material at the surface that is too stiff to flow. For the entire thickness of the mantle lithosphere to participate in convection, it must subduct into the mantle interior, a process that requires the entire lithosphere to experience a bending deformation. Chapter 4 examines the bending of a viscous subducting lithosphere and shows that subducting plates need not be particularly weak for subduction to occur. In fact, it is possible to demonstrate mantle-scale flow with mobile surface plates even if this flow is primarily resisted by the bending of plates in subduction zones (Chapter 6). For the Earth, this style of convection requires an effective viscosity for the bending lithosphere of about 10^{23} Pa s (Chapters 5 and 6), a value that is only about two orders of magnitude stiffer than estimates for the average viscosity of the underlying mantle. Lithospheric viscosity of this magnitude is certainly possible given the extreme temperature-dependence of mantle viscosity.

The two types of convection studied here, convective instability beneath a "stagnant lid" and plate-like flow with subduction zones that are "strong," are controlled largely by the strength of the mantle lithosphere. As a result, lithospheric strength may be a fundamental property of convection in the mantle, controlling not only the style of convection, but also the rate at which it occurs. Yet, the mechanical properties that apply for lithosphere deformation, either at the lithospheric base or within a subduction zone, are difficult to determine. For example, the extreme temperature dependence of mantle viscosity observed in the laboratory suggests that the lithosphere's cold temperatures should force convection to occur beneath a stagnant lid, but mobile plates are observed on Earth. Thus, some process must cause subduction zones to be weaker than plate interiors. Obvious candidates include brittle fracture, which is observed within subducting plates by the seismicity it produces, the weakening effects of water or other volatiles, and various other non-linear constitutive relations that cause rock strength to decrease as strain-rates increase. Although these weakening effects can be observed experimentally, it is difficult to extrapolate laboratory results to the length scales, stresses, and strain-rates appropriate for subduction.

In determining an expression for the energy dissipated by a bending subducting plate, the analysis of Chapter 4 uses a viscous rheology for the plate and assumes that any weakening effects of nonlinear behavior can be grouped into an "effective" value for this viscosity (Chapter 4). Even if such weakening mechanisms are important, this assumption should be valid for a plate with a given thickness because the effective value for viscosity can be defined as the one that would produce the proper amount of viscous dissipation if a Newtonian flow law were applicable. This assumption may break down, however, when this analysis is applied to plates of varying thickness, as it is in Chapters 5 and 6. In particular, the various weakening mechanisms might be expected to become more important for thicker plates, because the stresses and strain-rates associated with bending are larger for a thicker plate. Thus, a flow law with a maximum yield stress or some other weakening mechanism could cause the total amount of energy that a bending subducting plate can dissipate to be limited. Because an excessively large amount of bending dissipation is shown here to cause convection beneath a stagnant lid, such mechanisms could be essential for generating subduction and plate tectonics. As a result, it would be useful to include such rheological laws in future models of subduction zone deformation. Such an effort would require the determination of more appropriate expressions for the amount of energy dissipated by a bending slab. This should require not only a better understanding of the rheology that applies for large, rapidly deforming regions such as subduction zones, but also a better understanding of the "details" of how subducting plates deform. This understanding can be partially achieved in the laboratory, but probably also requires the development of new ways of using surface observations to constrain numerical models.

The analysis of Chapter 4 shows that for a plate with Newtonian viscosity, the bending resistance depends on the cube of a plate's thickness as it subducts. Thus, this thickness could also be an essential quantity that determines whether the bending resistance at subduction zones is unimportant, controls plate velocities, or stops them altogether in the case "stagnant lid" convection. As shown in Chapter 6, small-scale convection, possibility facilitated by the presence of a low-viscosity asthenosphere, may remove material at the base of the oceanic lithosphere, and thus could limit the subducting plate thickness. In addition, because plates thicken as they cool, the processes that determine the age of plates at the time of subduction should also affect their thickness. If, for example, plates were limited to the size of the Cocos plate, the subduction zone resistance would be small because plates would not have time to grow thick. Thus, small-scale processes such as subduction initiation or convective instability, which should be important for local deformation such as mountain building, could also profoundly influence mantle-scale convective processes associated with plate motions and the thermal evolution of the Earth.

In addition to plate bending at subduction zones and small-scale instability beneath plates, the lithosphere may deform in other ways that influence mantle-scale convection. For example, although the effects of transform faults are not studied here, such faults involve potentially strong parts of the oceanic plate, are comparable in length to subduction zones, and accommodate significant motion along their length.

As a result, the energy dissipated by transform faults may, like subduction zones, be important to the mantle's energy budget. If this is the case, transform faults could exert a significant resisting influence on plate motions, and thus may be as important as subduction zones in influencing mantle convection. Other regions, such as ridges and continental lithosphere, also exhibit interesting and important styles of localized deformation that should also dissipate energy, and thus exert a potentially important influence on convection in the mantle as a whole.

Because convection in the Earth's mantle may depend on small-scale processes associated with the "details" of how the lithosphere deforms, it is important to obtain a better understanding of these deformation processes. This thesis demonstrates that one way to assess the global importance of local-scale processes is to study them in a local model, as is done here for subduction and convective instability beneath continental lithosphere. Such studies can provide insight into the relevancy of these processes to larger-scale convection, and could help constrain lithospheric properties, particularly if they yield predictions that can be tested by geological or seismological observables. Even if they are important globally, small-scale processes need not be adequately resolved in large-scale convection models. Instead, methods of parameterizing the effect of these process in large-scale models can provide an efficient method for testing their effects on convection. An energy-balance method for including the bending deformation of a subducting plate within a large-scale model of convection is demonstrated here, as is a method for parameterizing the effects small-scale convection beneath the oceanic lithosphere (Chapter 6). In summary, an efficient way of studying the global-scale effects of small-scale processes of lithosphere deformation is to use local models to gain insight into these processes, and then to develop methods for including their essential aspects within the framework of a larger-scale convection model.

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