The influence of rheology, phase changes and equation of state on subduction

S. D. King

Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA

Mantle convection models have evolved from idealized fluid layers with constant material properties to fluids that include more realistic geometries and physical properties. While mantle convection models have moved into three-dimensional spherical geometries and are capable of calculations in the correct thermal regime (i.e. at or near the Rayleigh number appropriate for Earth's mantle), resolving melt migration, dehydration reactions and their effect on rheology and heat transport, grain-size dependence of rheology, and possible non-equilibrium effects of phase changes, all of which are important in some aspects of subduction, limits most investigations to two-dimensional regions in the vicinity of a subduction zone.

As our understanding of the equations of state and deformation mechanisms of relevant mantle mineralogies improves, we are able to include increasingly complex rheologies and thermodynamic formulations to numerical calculations of mantle convection. Concurrent with this, the continuing improvements in the computational power makes it possible to explore complex rheologies and equations of state with a level of detail that was not possible even four or five years ago. More importantly, we are able to consider a series of calculations that allow us to systematically observe the effect of a thermodynamic variable or rheology formulation.

The results of global seismic tomography clearly indicate that slabs descend into the lower mantle. Acting on this, we can test various assumptions and predictions of equations of state, deformation mechanisms and chemical composition. With the degree of complexity now possible, we can use mantle convection calculations to test the sensitivity of the fluid system to specific physical and thermodynamical quantities. In this talk I will illustrate how calculations demonstrate that the assumptions about the pressure and temperature effects of the coefficient of thermal expansion have a large impact on the evolution of a subducting slab when all other factors are held constant. On the other hand, the effect of the strength of the slab has a much smaller effect on the evolution of a subducting slab.

Coefficient of thermal expansion

Bousinessq models of mantle convection, and indeed most early work, assumed that the coefficient of thermal expansion was constant. As models became more sophisticated and phase changes were added, many investigators included a depth dependent coefficient of thermal expansion based on the work of Chopelas and Boehler (1989). It is now possible to consider, without any additional computational work a fluid where density and coefficient of thermal expansion that have the temperature, pressure and phase dependence of olivine described by a thermodynamic model based on laboratory data (e.g. Ita and Stixrude, 1992).

We find that a depth-dependent coefficient of thermal expansion formulation leads to calculations strongly layered flows with little or no slab penetration. Models that assume that assume either a constant coefficient of thermal expansion or the depth, temperature and phase dependent coefficients of thermal expansion both result in flows where slabs can become distorted, deformed and temporarily stagnated, but penetrate the phase boundary after a reasonably short period of time (Fig. 1). More importantly, there are significant variations in the history of flow between calculations that entail relatively minor changes in thermodynamic properties of a single component (perovskite) in the upper part of the lower mantle. This illustrates that uncertainties in the mineral physical properties must be taken into account before quantitative postdictions of the convective state of planetary interiors can be made. Furthermore, we have identified that the flow pattern in our subduction/ phase change calculation is sensitive to reasonably small variations in, the coefficient of thermal expansion of perovskite.

Strength of the slab

The rheology of slab material is a function of temperature, pressure, deformation-rate and grain size. While an idealized thermal profile of a slab might suggest that because of the cold temperatures the interior is highly viscous, the grain-size reduction at phase boundaries will weaken the cold slab interior in places (Riedel and Karato, 1997).

By systematically studying various temperature-dependent rheologies and phase changes in a convecting fluid, we can demonstrate that there is minimal influence of slab rheology on the evolution of the slab/phase change system. We use a temperature-dependent rheology in the mantle and a temperature- and stress-dependent rheology in the lithosphere; however we do not consider grain size effects on rheology. While perhaps simplified compared to the complexities observed in the laboratory, our rheological formulation is typical of that used in many mantle convection studies.

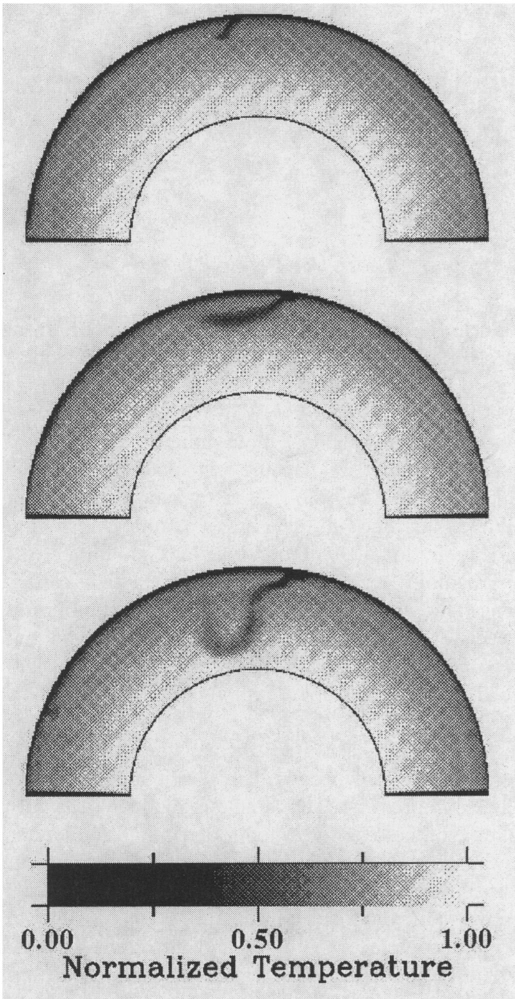

FIG. 1. Three snapshots of the temperature field from a calculation with a temperature, pressure and composition dependent coefficient of thermal expansion illustrating the interaction of the subducting slab and the phase change (not visible).

References

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