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The importance of mineral physics and a free surface in large-scale numerical models of mantle convection and plate tectonics

Paul Tackley, Takashi Nakagawa, Fabio Crameri, James Connolly, Frédéric Deschamps, Boris Kaus, and Taras Gerya
Departement Erdwissenschaften, ETH Zurich, Zurich, Switzerland (ptackley@erdw.ethz.ch)

Here, our recent progress in understanding the large-scale dynamics of the mantle convection - plate tectonics system is summarised, with particular focus on the influence of realistic mineral physics and a free surface.

High pressure and temperature experiments and calculations of the properties of mantle minerals show that many different mineral phases exist as a function of pressure, temperature and composition [e.g. Irifune and Ringwood, EPSL 1987], and that these have a first-order influence on density (which has a large effect on the dynamics) and elastic moduli (which influence seismic velocity). Numerical models of global thermo-chemical mantle convection have typically used a simple approximation such as the extended Boussinesq approximation to treat these complex variations in material properties. Instead, we calculate composition-dependent mineral assemblages and their physical properties using the code Perple_X, which minimizes free energy for a given combination of oxides as a function of temperature and pressure [Connolly, EPSL 2005], and use this in a numerical model of thermo-chemical mantle convection in a three-dimensional spherical shell, to calculate three-dimensionally-varying physical proporties. In this presentation we compare the results obtained with this new, self-consistently-calculated treatment with results using our old, approximate treatment, focusing particularly on thermo-chemical-phase structures and seismic anomalies in the transition zone and core-mantle boundary (CMB) region [Nakagawa and Tackley, G3 2009], which are strongly influenced by the coupling between compositional variations and phase transitions. The numerical models treat the evolution of a planet over billions of years, including self-consistent plate tectonics arising from plastic yielding, melting-induced differentiation, and a parameterised model of core evolution based on heat extracted by mantle convection.

Self-consistent plate tectonics-like behaviour may be introduced into global mantle convection models by using visco-plastic rheology with a constant or depth (pressure)-dependent yield stress [Moresi et al., GJI 1998; van Heck and Tackley, GRL 2008]. Yet, these models fail to create Earth-like plate tectonics, because the "subduction" is two-sided and approximately symmetric, whereas terrestrial subduction is one-sided. Previous gobal models assumed a free-slip upper boundary, in which the shear stress is zero but the vertical position of the boundary is fixed. In contrast, subduction zones display some of the largest topographic variations on Earth. We thus study the effect of a free surface on the mode of subduction in 2D and 3D global, fully dynamic mantle convection models with self-consistent plate tectonics. We observe that indeed, a free surface leads to single-sided subduction, whereas identical models with a free slip upper boundary develop double-sided subduction. A free surface is thus an essential ingredient to obtain realistic subduction behaviour in numerical models, probably because it allows the slab to bend in a natural manner. Another ingredient for stable single-sided subduction is a low strength interface between the plates achieved by the presence of metamorphic fluids in the subduction channel. Such a lubrication layer consisting of weak hydrated sediments accommodates stable one-sided subduction by strain localization, while the absence of a weak shear zone leads to mechanically two-sided subduction since in this case the plastic strength of the entire plates needs to be sufficiently low to allow for subduction [Gerya et al, Geology 2008]. In conclusion, a free surface is the key ingredient to obtain thermally one-sided subduction, while additionally including a weak crust is essential to obtain subduction that is both mechanically and thermally one-sided.