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Thermomechanical modelling of stability of Large Low Shear Velocity Provinces

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The thermomechanical evolution of the Earth remains a highly disputed subject. There are, however, some seemingly robust observations. A few are the focus in this study: (1) Tomographic studies, reconstruction of continental motion and rotation, and geodynamic modeling infer that the antipodally located Large Low Shear Velocity Provinces (LLSVPs) at the base of the mantle are stable, long-lived and impose the planform of flow in the mantle and of plate tectonics at the surface [Dziewonski, 2010]. (2) Studies of post-glacial rebound data, geoid highs and lows and geochemical mixing suggest that the average lower mantle viscosity is between one or two orders of magnitude greater than that of the upper mantle.
In this study, the geometry of the mantle is approximated by a hollow cylinder. The inner and outer mechanical boundary conditions are free slip and free surface, respectively. The importance of free surface boundary condition has been emphasized for correctly capturing the interactions between dynamics of the lithosphere and deep tectonic processes, e.g. Kaus [2010]. Fixed temperatures are prescribed for the thermal boundary conditions. The mantle flow is in the Stokes regime and the Boussinesq approximation applies. Newtonian rheological behavior is employed with a viscosity that depends exponentially on temperature. The large-scale heterogeneities at the base of the mantle are introduced as material of an anomalous viscosity and density.
The viscosity-temperature relation and the conservation laws governing the thermomechanical processes are simplified based on the above assumptions and non-dimensionalized. Both structured and unstructured FEM codes are developed for solving the conservation equations of energy and momentum together with the incompressibility constraint. Some of the utmost challenges in geodynamic modelling include accurate representation of complex geometries, such as topography of the deformed lithosphere, and capturing of sharp interfaces, such as the outline of the LLSVPs. Various techniques have earlier been developed to address these, out of which unstructured body-fitted computational meshes combined with adaptive remeshing proved to be highly successful. Devising an automatic grid refinement strategy for the unstructured code is one of the objectives of this study.
Another objective is to develop a robust non-diffusive advection solver. A Lagrangian advection algorithm is conventionally used to minimize numerical diffusion. In 'marker-in-cell' technique (Gerya, 2010), temperature is advected by tracer particles and then interpolated from the tracers to the Eulerian grid. The quality of this approach depends on extrapolation and interpolation, and a subgrid diffusion step must be introduced. To avoid these issues, the diffusion step is in this study performed on a separate computational grid, with tracer particles comprising computational nodes. This approach compared to the Eulerian and 'marker-in-cell' techniques.
Both structured and unstructured codes are benchmarked by reproducing critical Rayleigh number and Nusselt-Rayleigh scaling for rectangular geometry, provided by linear stability analysis and the thermal boundary layer theory, respectively. Methods are tested based on convergence of measures, such as Nusselt number, with successive grid and time-step refinement. The convection pattern and Nusselt-Rayleigh relation are compared to Christensen [1984]. Analytical solutions are derived where possible and used for benchmarking.