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Techniques to achieve geodynamic self-consistency in data-assimilation models of mantle convection

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Recent models of mantle convection that incorporate data-assimilation such as paleogeography reconstructions of plate boundary locations, the history of global plate motions used as surface velocity boundary conditions and paleo-age of seafloor as a proxy for oceanic plate thickness, have been employed to generate mantle thermal structures that can be directly compared to present-day mantle structure as inferred from seismic tomography. However, previous models contained significant mismatch, particularly in areas with complex tectonic histories such as western North America. We present several techniques used in some recent models (Liu and Stegman, EPSL, 2011) that achieve an unprecedented level of agreement between modeled thermal mantle structure and several recent tomography models using EarthScope's USArray data. In particular, these models are able to forward predict a rupture in the subducting Farallon-Juan de Fuca slab that laterally tears open across the face of the slab and allows an asthenospheric upwelling to occur (Liu and Stegman, Nature, 2012). The surface projection of the tear's development agrees remarkably well with the temporal-spatial evolution of Steens-Columbia River Basalt volcansim.

To achieve this level of agreement, there are four major technical aspects, all of which work in concert and are critical for success: 1) a weak hinge is prescribed as the region behind the trench 2) a low-viscosity wedge that helps to reduce coupling to the surface 3) a pseudo-free surface boundary condition consisting of a layer of "sticky air" that allows for more natural plate bending and single-sided subduction 4) because the convective system (including the tectonic plates) are separated from the surface velocity boundary condition, we introduce a phase change that allows the "sticky air" to be viscous enough for the surface plate motions applied above to actually drive the plates below.

Since the bending of the plate is driven by the negative buoyancy of the slab (i.e. slab pull), the sinking velocity of the slab is also critical such that slab-plate continuity is maintained at all times. Only then will continuous slab bending and progressive subduction occur. Using previous studies (Stegman et al., 2010; Schellart et al., 2007, 2010) as a guide for the strength of the hinge, we eventually found a value that allows the plate to bend and enter the mantle at the exact same speed as the prescribed trench motion. We then ensure the subducted slab sinks at the appropriate speed, and this is sensitive to both the plate thickness as prescribed by the paleo-age of seafloor and the specific radial viscosity profile.

The seismic tomography provides an incredibly robust constraint on the mantle dynamics because it reflects the time-integrated history of subduction. In order to recover excellent agreement, the sinking of all slab material in the model must follow a very specific trajectory such that the final state matches observations. This can only be achieved if convective motions arising from driving forces (slab buoyancy) and resisting forces (viscosity structure including weak hinge, low-viscosity wedge, and radial viscosity profile) are all in perfect harmony with the imposed surface boundary conditions.