How Mantle Slabs Drive Plate Tectonics: Supporting Online Material

Clinton P. Conrad and Carolina Lithgow-Bertelloni
Department of Geological Sciences, University of Michigan

Materials and Methods

Determination of Slab Locations

Slab locations are calculated by advecting oceanic plates downward into the mantle from regions of plate convergence at the surface into 20 equally-spaced depth intervals that span the depth of the mantle (*1*,*2*). Slab material moves downward at the speed of plate convergence in the upper mantle and slows by a factor of 4 in the lower mantle to account for the increased viscosity there. Lateral advection of slabs by mantle flow is not included in these calculations. The excess mass of each piece of slab material is determined from the age of this material at the time of subduction and is recorded with its location. The slab heterogeneity model that is produced by this method compares favorably with constraints from seismic tomography, the geoid, and dynamic topography (*1*). We chose this method to determine slab locations because it provides a natural history for subducted slabs in which the name of the subducting plate and time at which it subducted can also be recorded for each portion of slab material. We use this information to trace the continuity of each slab for the calculation of the slab pull force.

Calculation of Slab Pull Forces

The maximum slab pull force is the excess weight of all slab material that is physically attached to the surface plates. To define the material in the slab location model that is attached, we first examine the history of subduction since the Mesozoic and determine which slabs represent continuous subduction at each of nine present-day subduction zones since that time. The slab pull force is applied normal to the midpoint of each line segment that defines the surface trace of these subduction zones, where segment locations are taken from (*1*). The pull force is calculated by summing the excess mass of all the slab material within a specified radial distance of each segment's midpoint, and multiplying by the acceleration due to gravity. This radial distance is chosen to represent a maximum allowable rate of trench migration at the surface, which may affect the vertical coherency of the slab (*3*). We choose rollback rate cutoffs of 10% and 25% for different slab pull models, which means that slab material is included if the distance between the surface projection of the slab location and the midpoint of the subduction zone segment is less than 10% or 25% of the depth of that material. When tallying the slab mass that is connected to each subduction zone segment, slab mass that is connected to multiple segments is partitioned between them, so as not to double-count slab mass. Because the slab pull force may not be effectively transmitted across the 660 km phase transition (*3*), we also defined an upper mantle slab pull model in which only slab material above 660 km is included in the calculation of the slab pull force.

Calculation of Slab Suction Forces

Torques generated by slab suction are calculated using a degree 20 spherical harmonic expansion of the entire mantle slab heterogeneity model (*1*,*2*) and a propagator matrix solution for mantle flow that includes no-slip surface boundary conditions (*4*). The basal shear tractions that result depend on the mantle viscosity structure, which we take to be the one that gives the best fit to the geoid for the slab heterogeneity model (*1*). This calculation is identical to (*1*). The mantle density heterogeneity model used in (*1*) and in this study includes mass variations within the oceanic lithosphere. As a result, the slab suction force calculated here includes the force associated with thermal thickening of oceanic lithosphere. This force, also known as "ridge-push," accounts for at most only 5-10% of the forces on plates (*1*). Other possible plate forces are not included here, but are thought to be even less important (*1*,*5*).

Determination of Observed Plate Velocities

Observed plate velocities (Fig. 2B) are obtained using compiled rotation poles for all plates (*6*), with the exception of the African and South American plates, whose motion has recently been revised due to redating of South Atlantic seamounts (*7*). We recalculate new rotation poles for Africa and South America relative to the hotspots (*7*). We subtract the net rotation of the lithosphere to present results in a no-net-rotation reference frame.

Measurement of the Dot Product

The average dot product is calculated by taking the area-weighted average of local dot products between predicted and observed plate velocities on a 1 by 1 degree grid. To ensure a result of unity for a perfect correlation, the result is normalized by the square root of the area-weighted average dot product of both the predicted and observed fields dotted into themselves. This measurement of the dot product is more sensitive to the relative directions of predicted and observed plate motions than it is to variations in plate speed. It also implicitly gives more weight to faster moving plates.

Determination of Slab Pull Strength

We determine the average pull force per unit length for each subduction zone and divide by the average subducting thickness of those plates to obtain the average tensional stress applied to the side of each plate by slab pull. For the upper mantle slab model, the maximum stresses are between 200 and 500 MPa if 40-100% of slab weight is transmitted as slab pull.

Supporting References

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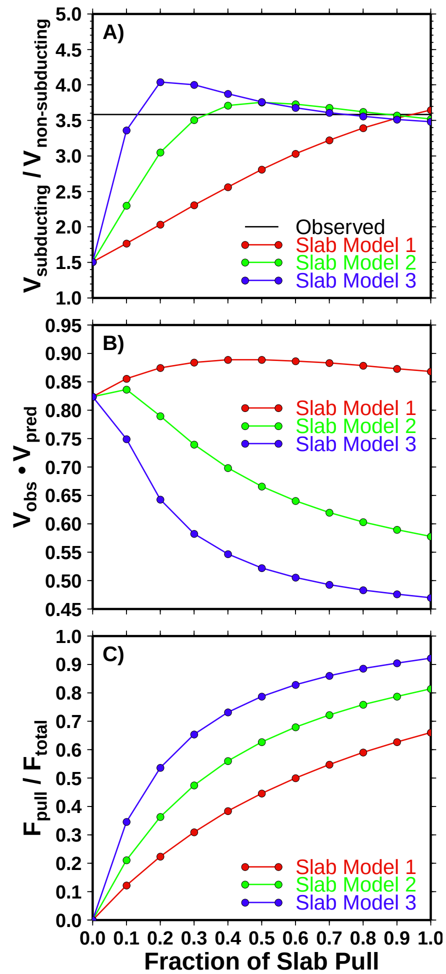

Supplementary Figure S1. Diagnostics of forcing models that combine the slab pull and slab suction mechanisms. In each case, slab material that is unconnected to the surface plates drives plate motions by slab suction. Material that is mechanically attached to the subducting plates, as defined here for Slab Models 1-3 (red, green, and blue, as in Fig. 1), drives plate motions through a combination of slab pull and slab suction. Here the slab suction force is gradually replaced by the slab pull force along the x-axis. Shown in (A) is the (area-weighted) average speed of the subducting plates (Cocos, Nazca, Pacific, Indian-Australian, and Philippine plates) relative to that of the non-subducting plates (African, Antarctic, Arabian, Caribbean, Eurasian, North American, and South American plates). For comparison, this ratio is shown in black for the observed plate velocity field (Fig. 2B). Shown in (B) is the (area-weighted) dot product of the observed (Fig. 2B) and predicted velocity fields. Finally, (C) shows the fraction of the total driving forces on all plates that is caused by the slab pull mechanism.