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State of stress in slabs as a function of large-scale plate kinematics: an approach with 2D and 3D numerical models

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The state of stress of slabs subducting worldwide, as revealed by seismicity, is extremely variable both with depth and between different subduction zones. Shallow seismic events in the trench-outer-rise generally indicate a transition from extension to compression with depth, consistent with the bending of the plate prior to subduction.
The reconstructed stress fields for intermediate depths (between 100 and 300 km) range from down-dip compression to down-dip extension. The occurrence of down-dip compression at intermediate depths is enigmatic, since slab pull should generate extension in the slab. A review of available data (e.g., Doglioni et al., 2007) indicates that dominant down-dip extension occurs, at intermediate depths, along E- or NE-directed subduction zones (e.g., the Nazca plate in the Chile subduction zone and the Cocos plate in the Mexican subduction zone) and down-dip compression along west-directed subductions (e.g., Tonga). This polarity-related pattern of the stress in slabs cannot be simply explained with the different age of subducting plates.
At depths deeper than 300 km, down-dip compression is typical in Wadati-Benioff zones that reach the 670 km transition, and it has been suggested to reflect the increasing resistance encountered by the subducting lithosphere.
In this work we focus on the origin of stress within subducting slabs at intermediate depths and investigate the correlation between subduction polarity, the nature of down-dip stresses in slabs, and plate kinematics. Hotspot tracks indicate that a relative motion occurs between the lithosphere and the underlying deep, high-viscosity mantle, with the asthenosphere acting as a detachment layer owing to its low viscosity. Several researchers proposed a global or net westward drift of the lithosphere relative to the mantle. The amplitudes of westward drift strongly depend on inversion choices. In the literature, velocities of westward drift ranging between 2 cm/yr and 13 cm/yr have been proposed. In summary, a wide consensus has been reached in the literature about the existence of a westward drift but not about its magnitude.
Using 2D and 3D viscoelastic plane strain models (including the crust, lithospheric mantle, and upper and lower mantle) we investigate the dependency of the stress field of slabs on geometry (dip of the slab) and kinematics (velocity of convergence between upper and lower plates and their “absolute” velocity with respect to the underlying mantle) of subduction zones.
We conclude that, although the state of stress in slabs is controlled also by other processes, down-dip compression in the subducting slab is enhanced by mantle flow opposing the direction of the dip of the slab, whereas down-dip extension is favored by mantle flow in the same direction of the slab dip (i.e. sustaining it). These predictions are in agreement with available geophysical observations, although exceptions to this simple pattern are observed worldwide. In addition, if the slab is decoupled from the upper plate, convergence between upper and lower plates induces a down-dip compressional component of stress within the slab, decreasing the magnitude of extension in models characterized by mantle flow sustaining the slab and increasing compression in models with mantle flow opposing subduction. However, these are second-order variations when compared to the control exerted by absolute plate kinematics and by the magnitude of slab pull. Sensitivity analysis of rheological parameters allows us to conclude that these results are generally consistent, although low values of viscosity of the lithospheric mantle render this prediction less stable.