Insights on the strength of the continental lithosphere from quasi-instantaneous lithospheric models

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The processes that generate stress in the lithosphere are incompletely understood. Whereas it is obvious that lithospheric deformation (and topography) is ultimately caused by cooling of the Earth from the time of formation, it is less clear how lithospheric deformation is coupled to mantle flow and how this affect stresses. Part of this is due to the somewhat complicated rheology of the lithosphere, which varies from brittle (elastoplastic) to ductile (viscous). In addition, vertical layering of the lithosphere may give rise to instabilities which affect its dynamics and stress evolution in a non-trivial manner. Obtaining a better insight in these processes thus requires numerical tools that can model the mantle-lithosphere system in a self-consistent manner (i.e. in a single computational domain) including topographic effects (i.e. free surface) and visco-elasto-plastic rheologies.

Recently, a number of modelling techniques have been developed that have the above-mentioned features and that are useful to model long-term tectonic scenarios (on a Myrs) timescale. A problem, however, with many of these long-term tectonic simulations is that they are computationally expensive and that the parameter space is too wide to sample with brute-force forward simulations. For this reason, I take a different approach and use the numerical technique to obtain insight in the most likely present-day rheological stratification of the lithosphere. The advantage of such quasi-instantaneous lithospheric models is that they require only a few timesteps per simulations and can therefore cover a wider parameter space. Moreover, they take relatively well-constraint geophysical data such as Moho depth, topography, GPS velocity and earthquake locations as input.

Model results, applied to the India-Asia collision zone and to Taiwan demonstrate that the approach gives constraints on the effective viscosity and rheological stratification of the lithosphere. They also show that the distribution of high effective viscosities, representing the strength distribution in the ductilly and plastically deforming areas of the lithosphere, does not necessaily correspond to the distribution of high differential stresses, presumably representing the areas of high earthquake activity. The reason is that strain rates are not necessarily constant with depth in continental collision zones, as assumed in constructing yield strength envelopes (‚Christmas trees‘) and thin-sheet models. A direct transformation from stress to strength (i.e. effective viscosity) in the lithosphere is not possible without knowledge of the strain rate distribution. Consequently, the analogy of lithospheric areas with high earthquake activity and lithospheric areas with high mechanical strength is questionable for continental collision zones.

In the case of the India/Asia collision, results show that differential stresses in the mantle lithosphere underneath the Himalaya and Tibet are small even if it is strong (i.e. has a large effective viscosity). The scarcity of large earthquakes underneath the Moho in this region can thus not be used as evidence for a weak (or water-rich) mantle lithosphere.