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Geodynamic constraints on stress and strength of the continental lithosphere during India-Asia collision.

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There has been quite some debate in recent years on what the long-term strength of the continental lithosphere is and how it is related to the occurrence of earthquakes. One of the best studied areas in this respect is the India-Asia collision zone, where -in some profiles- the Moho depth is known to within a few km's. A relocation of earthquake source locations revealed that in India earthquakes occur throughout the whole lithosphere whereas in Tibet, earthquakes are restricted to the upper 10-15 km of the crust with few exceptions slightly above or below the Moho. The lack of substantial earthquake activity in the sub-Moho mantle lithosphere seems puzzling since (1D) strength envelop models for the continental lithosphere predict large differential stresses (and brittle failure) in these locations.

A way out of this paradox is to assume that the rheology of the mantle lithosphere (i.e. the effective viscosity) is significantly smaller than usually assumed, either because of the effects of hydration, or because of increased Moho temperatures. As a consequence, the strength of the lithosphere resides in the crust and not in the upper mantle as previously assumed. This conclusion gets some support from spectral-based inverse models of the effective elastic thickness (using topography and gravity as input data), which is typically smaller than the seismogenic thickness.

Even though this explanation might appear appealing at first, there are at least two major problems with it:

(1) Estimations of the effective elastic thickness (EET) of the lithosphere are non-unique and model-dependent. Others, using a direct (non-spectral) modelling approach, find significantly larger values of the EET in the same locations (again using gravity & topography as constraints).

(2) Long term geodynamic models indicate that if the mantle lithosphere would indeed be as weak as suggested, it would be very difficult to generate plate-tectonics like behavior: Subducting slabs behave more like vertical drips; and topography cannot be sustained for geologically relevant timescales.

Yet, despite those problems, the relative lack of earthquakes underneath the Moho remains an intriguing fact, which is also found in other mountain belts such as the Swiss Alps.

The two modelling approaches that are used to interpret the data, however, are based on highly simplified assumptions. The 1D Christmas-tree approach assumes that strain rates are homogeneous throughout a vertical section of the lithosphere. EET-based estimations assume that the lithosphere is an elastic layer over an infinite half space. In reality, however, the lithosphere is expected to have depth- and temperature-dependent material properties, and it is unclear whether strain rates in such a lithosphere are indeed constant with depth.

For this reason, we here use a 2D modelling approach that takes geometrical complexities as well as mantle-lithosphere interaction into account.

Rather than modelling the evolution of the India-Asia collision over a million-year timescale, as would typically be done with such an approach, we here restrict ourselves to the present-day rheological stratification of the lithosphere. The advantage of such quasi-instantaneous lithospheric models is that they require only a few time steps per simulations and can therefore cover a wide parameter space. As input we use relatively well-constrained datasets such as surface topography, Moho depth (where available), and far field convergence velocity. From this, the state-of-stress of the lithosphere, its surface velocity, gravity anomalies and mantle flow fields are computed as a function of lithospheric geometry and rheological stratification.

Model results show that the response of the lithosphere and flow in the underlying mantle are significantly influenced by the rheology of the lithosphere, in particular by the effective viscosity of the mantle lithosphere. Models, in which the mantle lithosphere and lower crust are ‘weak’ become unstable and result in a Tibetan

plateau that disappears in geologically small times. Models with a ‘strong’ Indian mantle lithosphere, on the other hand, are capable of supporting the topography. Moreover, they generate mantle flow fields that are consistent with surface GPS velocities as well as Bouguer anomalies that are in agreement with observational constraints.

In contrast to predictions by 1D strength envelop constructions, the stresses in a strong mantle lithosphere underneath Tibet are actually small rather than large. An analysis of model results reveals that this is caused by a significant variation of strain rate with depth. If, in addition, the temperature-dependence of rheology is taken into account, the largest differential stresses are found around the Moho, close to regions with observed earthquake activity. Stress magnitudes, however, remain well below the dry Byerlee criteria in most cases, suggesting that sub Moho earthquakes would have to be facilitated by failure on preexisting faults, by the presence of fluids, or possibly by a shear-heating instability.

On the basis of our 2D quasi-instantaneous geodynamic models, which simultaneously fit gravity anomalies, surface topography, surface velocities and mantle flow directions, we conclude that there is no need to invoke a weak mantle lithosphere to fit observations. A simpler, geodynamically consistent, explanation is thus that the mantle lithosphere is relatively strong (as indicated by experimental constraints), but has small differential stresses (due to small strain rates).