Evidence for strong mechanical coupling and strong Indian lower crust beneath southern Tibet

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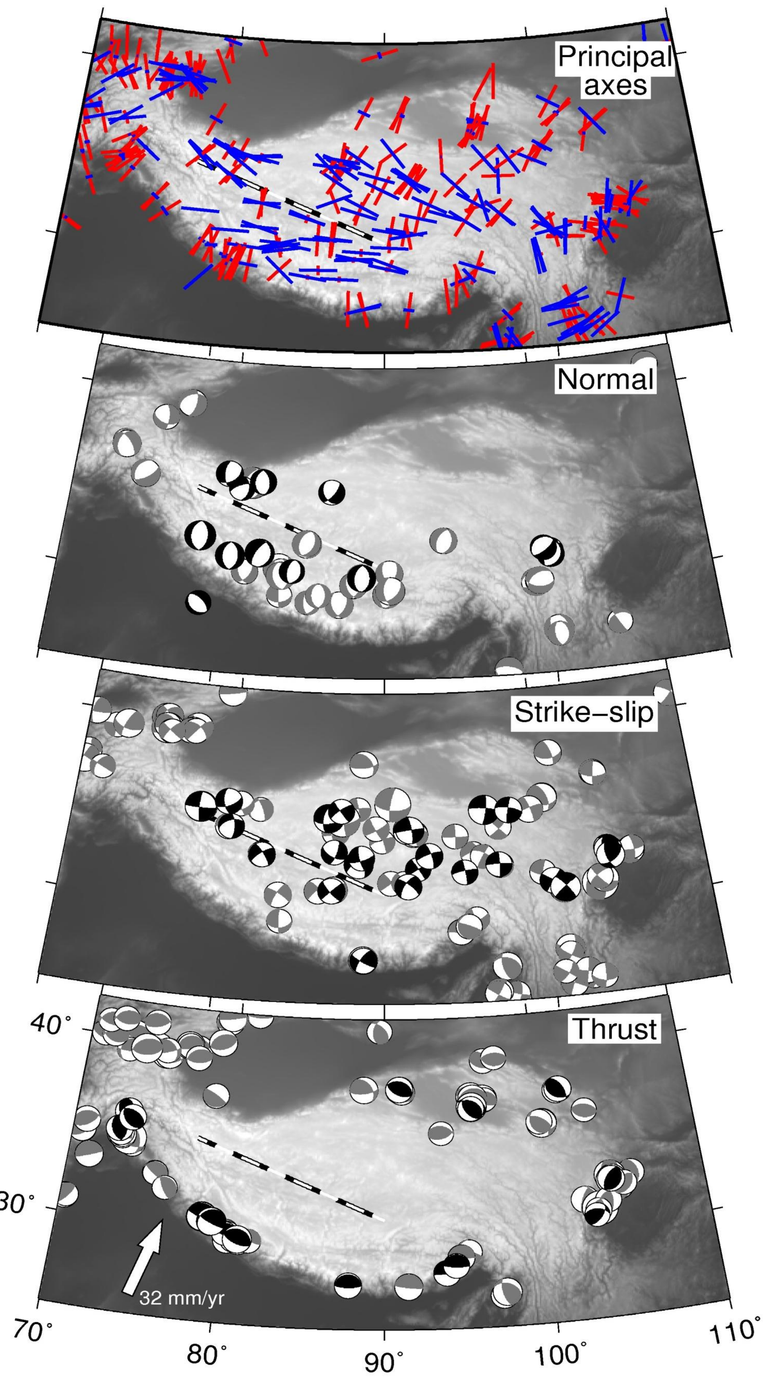
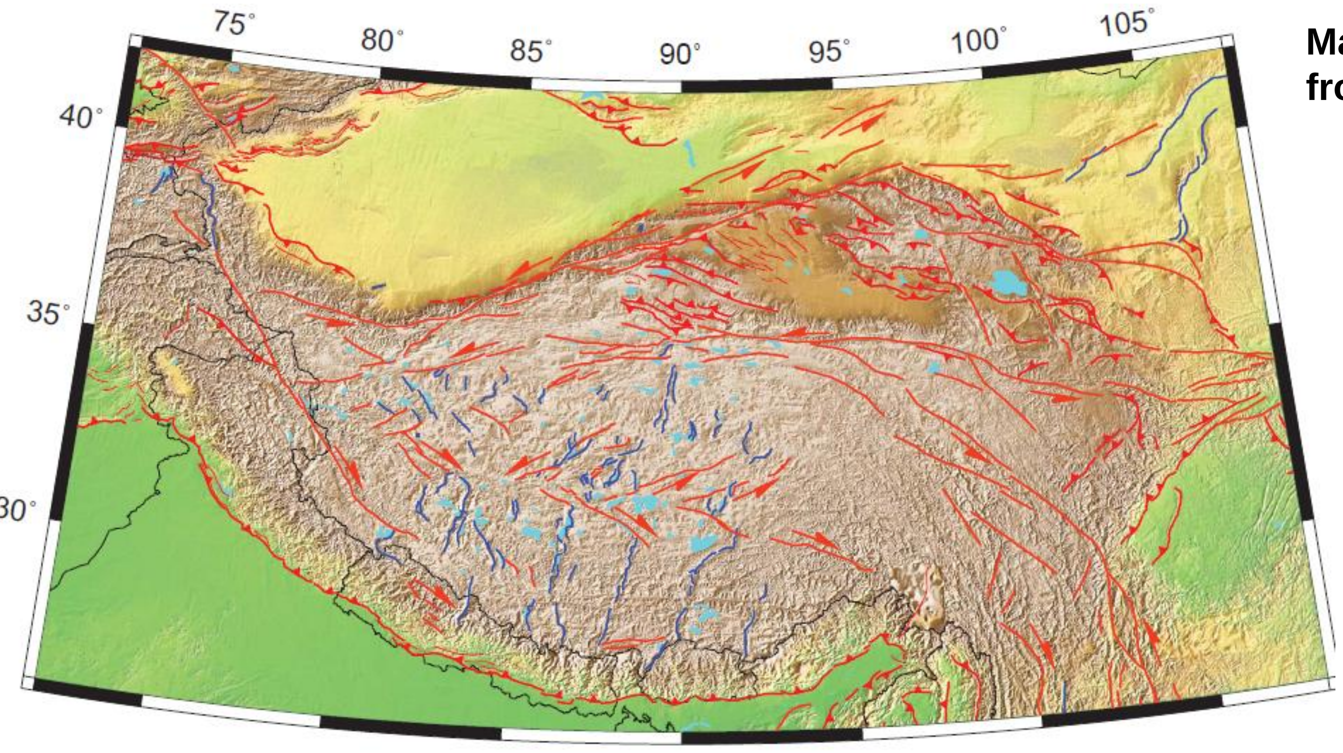
Abstract

How surface deformation within mountain ranges relates to tectonic processes at depth is poorly understood. This paper discusses the Tibetan Plateau, where the upper crust is generally thought to be poorly coupled to the underthrusting Indian crust because of an intervening low viscosity channel. However, here we show that the contrast in tectonic regime between northern Tibet, where strike-slip faulting predominates, and southern Tibet, which is characterized by normal faulting, requires mechanical coupling between the upper crust of southern Tibet and the underlying Indian crust. Comparison between the heterogeneous deformation within the Tibetan Plateau (Figure 1) and the results of our numerical experiments (Figure 2) suggests that the Indian lower crust acts in a rigid manner where it underlies southern Tibet, and that the surface is mechanically coupled to the lower crust. For the lower crust to act rigidly in numerical experiment A requires a viscosity ≥ 5×10^{23} Pa s. Such a high viscosity at lower crustal temperatures would require an anhydrous rheology, such as metastable granulite. This mechanical coupling is inconsistent with the presence of an active 'channel flow' beneath central Tibet, and suggests that the Indian crust retains its strength as it underthrusts the plateau. These results represent important additions to the current debate surrounding the material properties of the continental lithosphere, and have implications not only for the tectonics of Tibet, but also for the formation and evolution of other past and present mountain ranges.



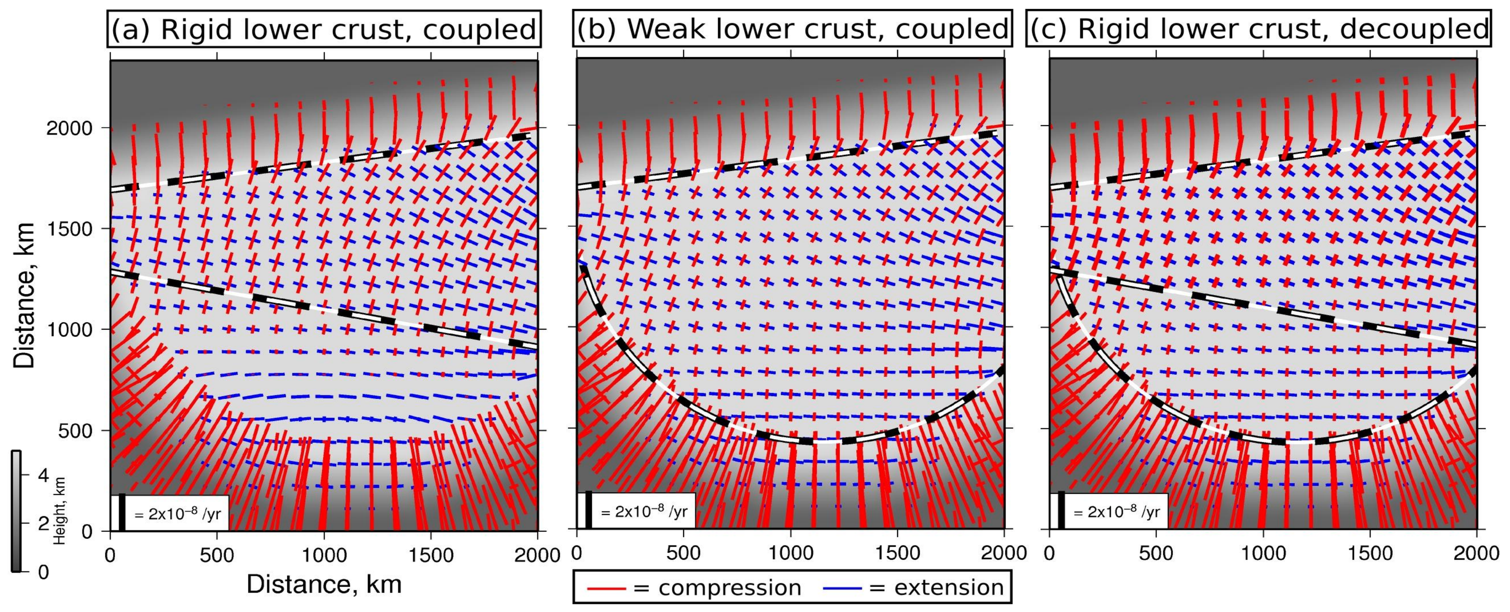


Map of active faults within Tibet from Styron et al [2010]

Blue: Normal faults
Red: Strike-slip and Thrust faults

1. Key Observations *The tectonic regime varies within the Tibetan Plateau. NE plateau = strike-slip faulting, SW plateau = normal faulting.*

The upper panel shows the principal axes of the horizontal components of the earthquake moment tensors, normalized to the length of the largest axis (red is compression, blue is extension). The other three panels show focal mechanisms of Mw> 5.5 upper crustal earthquakes (depth < 50 km), subdivided based on rake (from top to bottom, those with one or both planes with rakes within 45o of pure normal, strike-slip, and thrust motion). Black focal mechanisms were obtained by the studies listed in the supplemental material, and those shown in grey are well-constrained CMT solutions (% double couple > 50). The lower panel also shows the India-Asia convergence velocity. The dashed line in the central plateau on each panel shows the estimated location of the northern limit of underthrust Indian lithosphere.



Methods

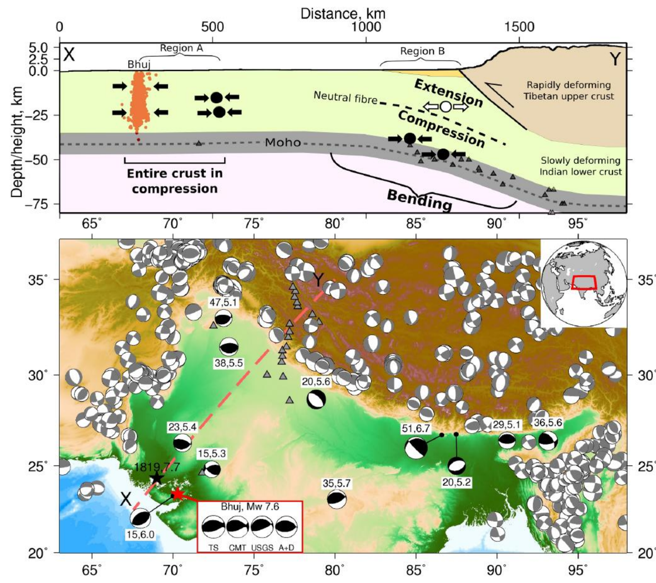
The model geometry and topography approximate what is currently seen in the Tibetan Plateau, and the topography is assumed to be isostatically compensated at the Moho. The perpendicular component of the velocity on the eastern and western boundaries is approximated and interpolated from GPS velocities. For simplicity, a Newtonian rheology is used throughout. The upper 15~km of the crust is given a viscosity of 1×10^{22} Pa s, the remainder of the crust 1×10^{20} Pa s, and the viscosity is vertically tapered for 5 km either side of the contrast. (see Copley&Mc Kenzie, 2007, and Copley, 2008 for details about the numerical implementation)

2. Model: *To match the heterogeneous surface strain, the shallow crust in southern Tibet must be mechanically coupled to relatively rigid Indian lithospheric material in the lower crust.*

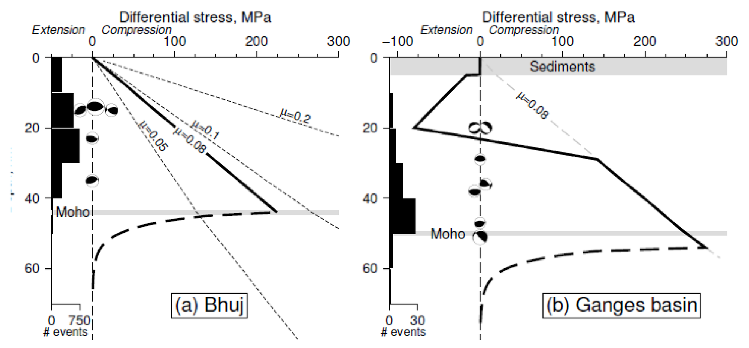
The principal axes of the horizontal strain-rate tensor at the surface, from our model calculations. Red bars represent compression, and blue bars extension. Equal length red and blue bars are equivalent to strike-slip deformation. In the region north of the northernmost dashed line, the lower 35 km of the crust is given the velocity of the Tarim Basin relative to India. For (a) and (b), in the region south of the southernmost dashed line the lower 20 km of the crust is forced to have zero velocity. In (c) the region of rigid lower crust is the same as (a), but in the region enclosed by the two southernmost dashed lines a horizontal decoupling horizon is inserted above the rigid lower crust. Background shading represents the model surface elevation.

3. Independent evidence for a strong granulitic Indian lower crust.

India suffers little deformation as it indents Eurasia (less than 2mm/yr over >1000km distance, hence a strain rate smaller than 10^{-17} s^{-1}). Given that the driving force is estiamte dto 5.5 10^{12}N/m [Copley et al, 2010], the effective viscosity of the Indian lithosphere is inferred to be higher than 10^{24} Pa.s. Seismicity throughout the Indian crust is consistent with little viscous deformation fo the lower crust, as well as the depth distribution of stress at the front of the Himalaya where the Indian lithosphere is bent due to overhrusting by the load of the range.



Seismicity of northern India and surroundings [Copley et al, submitted]. Grey focal mechanisms are from the CMT catalogue. Those shown in black are within Indian lithosphere, are labelled with the centroid depth in km and the moment magnitude. Focal mechanisms of the Bhuj earthquake (TS: Copley et al, submitted, A+D: Antolik and Dreger [2003]). The cross-section shows the aftershocks of the Bhuj earthquake (red circles, Bodin and Horton [2004]), and the locations of earthquakes shown on the map within 400 km of the section (black circles: reverse faulting, white circles: normal faulting).



Distribution of differential stress with depth (solid: brittle regime, dashed: ductile regime) at Bhuj and beneath the Ganges foreland basin (regions A and B on map). The histograms on the left of each graph show the depth distribution of aftershocks following the Bhuj earthquake (left graph, Mandal et al. [2006]), and of earthquakes in eastern Nepal, south of the Main Central Thrust (right graph, Monsalve et al. [2006]). The lower hemisphere focal mechanisms of earthquakes shown in black on map are shown on (b) for events within 500 km of the Himalaya, and otherwise on (a).