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

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How surface deformation within mountain ranges relates to tectonic processes at depth is not well understood. The upper crust of the Tibetan Plateau is generally thought to be poorly coupled to the underthrusting Indian crust because of an intervening low-viscosity channel[1]. Here, however, we show that the contrast in tectonic regime between primarily strike-slip faulting in northern Tibet and dominantly normal faulting in southern Tibet requires mechanical coupling between the upper crust of southern Tibet and the underthrusting Indian crust. Such coupling is inconsistent with the presence of active 'channel flow' beneath southern Tibet, and suggests that the Indian crust retains its strength as it underthrusts the plateau. These results shed new light on the debates regarding the mechanical properties of the continental lithosphere[2–4], and the deformation of Tibet[1,5–10].

The processes governing continental deformation, and the formation of mountain ranges and plateaus, are hotly debated[2,3,8,10]. Because it is the largest mountain range on the Earth, and has been formed by processes that are still active, the Tibetan Plateau has been central in this debate and has inspired a wide range of tectonic models. In 1924 Argand[11] proposed that Indian crust underthrusts most of Tibet, and that the resulting doubling of crustal thickness is responsible for the high elevation of the plateau; a view which has to some extent been confirmed by recent geophysical observations that suggest that the Indian crust underlies the southern half of the plateau[12]. This view is also consistent with the large amount of underthrusting implied by kinematic models of the orogen derived from structural geology[13] and the metamorphic and exhumation history of the range[14].

However, how the underthrusting of India influences the tectonics of Tibet is unclear. High temperatures (over 600 °C) must exist in the deep crust of Tibet, as suggested by heatflow measurements[15] and thermokinematic models[14]. Various geophysical observations[16] have been interpreted as evidence for a 'channel' of weak, possibly partially molten, middle crust beneath southern Tibet. The middle crust of Tibet may therefore have a low enough viscosity to result in mechanical decoupling between the Tibetan upper crust and the underthrusting Indian lithosphere. A popular extension of this view is that the middle crust might actually be extruded from below the high topography, both southwards towards the Himalaya[1,17] and eastwards towards southeast Asia[10]. On the other hand, some authors have argued that the whole Tibetan lithosphere might actually be deforming as a coherent unit, with little depth variation of strain[7].

The deformation of Tibet arises from the forces driving the India–Asia collision: essentially the buoyancy of the Indian ridge and the sinking of subducting slabs beneath southeast Asia[18]. In addition, forces are induced within the plateau and bounding mountain ranges by the lateral variations of crustal thickness[7,8]. The Tibetan crust is approximately 75 km thick, about twice the thickness of the relatively undeforming continental crust in the surrounding areas[19]. This contrast is certainly one key factor in determining the state of stress within the plateau, as demonstrated by the correlation between elevation and tectonic regime[6]: thrust faulting is dominant at low elevations around the edge of the mountain range, whereas the high interior of the plateau deforms by a combination of normal and strike-slip faulting[20–22] (Fig. 1). Mantle dynamics could also play a part, but the

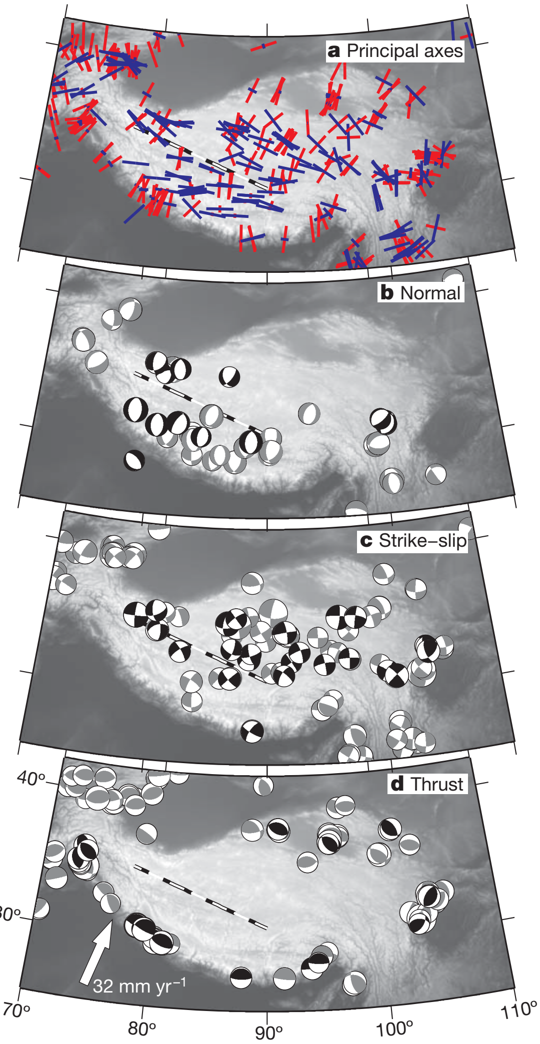

Figure 1 | Tectonic regime within and around the Tibetan Plateau. **a**, Principal axes of the horizontal components of the earthquake moment tensors, normalized to the length of the largest axis (red is compression, blue is extension). **b**, **c** and **d**, Focal mechanisms of upper crustal (depth less than 50 km) earthquakes of moment magnitude exceeding 5.5, subdivided on the basis of rake. Black focal mechanisms are from the studies listed in the Supplementary Information; grey focal mechanisms are well-constrained CMT solutions (http://www.globalcmt.org/; over 50% double couple; ref. 30). **d** also shows the India–Asia convergence velocity[23]. The dashed line in the central plateau on each panel shows the estimated location of the northern limit of underthrust Indian lithosphere[12,19].

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hypothesis that thickened mantle lithosphere has been convectively removed from beneath the range[6] can now be ruled out because of the observation that Tibet is still underlain by a continuous mantle lid visible to surface wave tomography[19].

Some previous attempts at modelling Tibetan tectonics as a result of crustal buoyancy, and of north–south compression induced by the collision, have yielded good agreement with the distribution of present-day strain around Tibet[8]. Such studies reproduce the contrast between thrust faulting around the edge of the plateau and east–west extension within the range, but a close look at the active deformation within the plateau indicates a clear contrast between southern and northern Tibet that is not explained by existing models. Earthquake focal mechanisms (Fig. 1) and mapped active faults show that the deformation of southern Tibet is dominated by east–west extension across north–south-trending rifts[20], whereas northern Tibet is characterized by conjugate strike-slip faulting (with some minor normal faulting also occurring at fault bends and junctions[21]). It should be noted that the north–south shortening observed in Global Positioning System (GPS) data within the southern plateau represents recoverable elastic strain build-up around the thrust faults beneath the Himalayas[23], and not the permanent deformation with which we are concerned here. Any shortening within the southern plateau that cannot be explained by elastic strain around the Himalayan thrust faults is lower in magnitude than is resolvable with the currently available GPS data, and so is minor compared with the east–west extension that is geodetically visible and is accommodated by the observed normal faulting (see Supplementary Information).

The contrast between north and south Tibet is not likely to be due to lateral variations in topographically induced stresses, given the uniform elevation of the plateau. We observe that the change in tectonic regime, which occurs at the Karakoram–Jiali fault zone that runs between the eastern and western Himalayan syntaxes[21], coincides approximately with the proposed location of the northern edge of the underthrust Indian crust and upper mantle[12,19,24]. We therefore investigate whether mechanical coupling between the Tibetan upper crust and underthrust Indian crust could actually explain the contrast in present-day tectonic regime between southern and northern Tibet. Such an idea is plausible because the underthrusting Indian crust will exert considerable northward-directed shear stresses upon the overlying material, which are not likely to be present in northern Tibet, thereby leading to a fundamental difference in stress state between the two regions. To test this hypothesis we have modelled the active deformation of Tibet, resulting from approximately north–south compression induced by the collision, and lateral variations in crustal thickness. We have assumed either coupling to, or decoupling from, the underthrusting Indian crust, which is modelled as either rigid or viscously deforming.

Following many previous investigations of continental tectonics, we assume that the crust obeys a viscous rheology[5,6,25]. We acknowledge that this modelling cannot reproduce the details of surface tectonics, which are locally characterized by deformation on discrete faults. However, the model is appropriate for estimating how large-scale lateral variations of tectonic regime within Tibet depend upon the boundary conditions around the edge of the plateau (which we impose on the basis of GPS measurements), and those at the base of the deforming crust (which is the effect we study here). A previous study analysed the decoupling effect of a weak middle crust in two dimensions[9], but did not address the effect of such a weak horizon on the spatial variations of tectonic regime within Tibet. This question, which we pursue here, requires a three-dimensional model. We therefore use the approach of Copley[25], assuming a two-layered viscosity structure based upon previous studies[5,25] (see Methods).

We compare three numerical experiments. In experiment A (Fig. 2a), the lower 20 km of the underthrusting crust beneath the southern half of the plateau is assumed to be rigid. In the southern plateau the surface motions are accommodated by the shearing of the upper crust over this rigid lower crust, leading to significant shear stresses on horizontal planes. Where the topography slopes steeply on the southern margin of the range, topographically induced stresses dominate the deformation and lead to arc-normal compression. East–west extension of the upper crust within the southern plateau is caused by the combination of the shear stresses on horizontal planes, the topographically induced stresses that are transmitted to the interior of the range, and the approximately north–south compression imposed by the applied motions of the bounding plates. In models with topographic forces and convergence across the range, the effect of the horizontal shear stresses related to the underthrust rigid lower crust is to make the southern plateau interior move more slowly southwards than it otherwise would (equivalent to the overlying crust feeling a pull northwards by the underthrust crust). The resulting north–south extensional stresses between this region and the southern margin balance the compression resulting from the plate convergence. The relative contributions of these causes of deformation are shown in the Supplementary Information. In this model, the weak middle crust of the southern plateau does not flow southwards as a high-velocity channel, but rather acts as a horizontal simple shear zone, transmitting to the upper crust the shear that is induced by the relative motion between the surface and

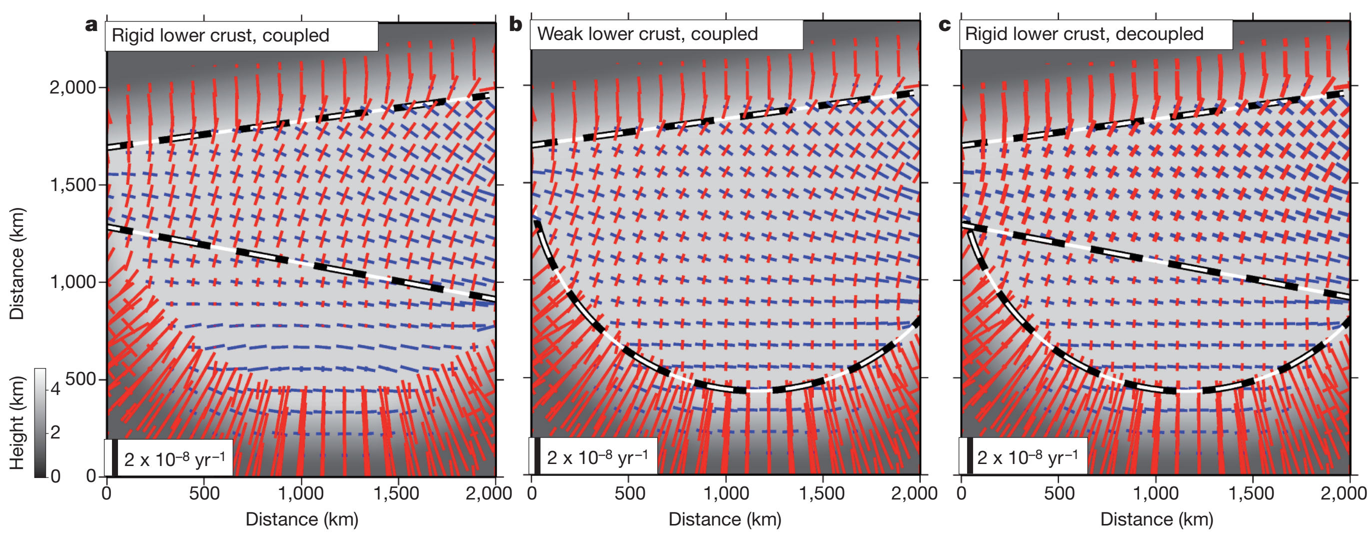

Figure 2 | Modelled principal axes of the horizontal strain-rate tensor at the surface. Red bars represent compression, and blue bars extension. Red and blue crosses (with bars of equal length) indicate strike–slip deformation. North of the northernmost dashed line, the lower 35 km of the crust is given the velocity of Tarim relative to India. For **a** and **b**, south of the southernmost dashed line the lower 20 km of the crust is forced to have zero velocity. **c** is the same as **a**, except that between the two southernmost dashed lines a horizontal decoupling horizon is inserted above the rigid lower crust. Background shading represents elevation. See Supplementary Information for the modelled velocities. Scale bars are strain rate, $2\times10^{-8}\ yr^{-1}$.

the underthrusting lower crust. The northern plateau is characterized by strike–slip deformation (assuming that the tectonic regime is related to the stress tensor according to Anderson's theory of faulting). The tectonic style differs from the southern plateau because in this northern region the shear stresses on horizontal planes are negligible.

In experiment B (Fig. 2b) we impose the condition that the rigid lower crust extends only a short distance beneath the southern margin of the plateau. The interior of the range in this case is everywhere characterized by strike–slip deformation. This is because shear stresses on horizontal planes are negligible throughout the interior of the range. In the southern plateau in experiment A, it was these shear stresses that had the effect of counteracting the compression imposed upon the range by the motions of the bounding plates, allowing pure east–west extension to occur.

Experiment C (Fig. 2c) is similar to experiment A, but with the addition of a decoupling horizon above the rigid lower crust, where shear stresses on horizontal planes are forced to be zero. This model behaves very similarly to that in experiment B, because they share the characteristic that no significant shear stresses on horizontal planes are present in the middle and upper crust.

Comparison between the results of our numerical experiments (Fig. 2) and the heterogeneous active deformation within the Tibetan Plateau (Fig. 1) suggests that at the present day 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 in this region. The deformation in the northern plateau is similar (except for slightly different strain rates) in all three numerical experiments, showing the tectonics in this region to be relatively insensitive to the rheology of the underthrust Indian crust beneath the southern plateau. For the lower crust to act rigidly in numerical experiment A requires a viscosity of more than 5×10^{23} Pa s. Such a high viscosity at lower crustal temperatures would require an anhydrous rheology, such as metastable granulite[3]. Evidence of a strong rheology for the Indian lower crust, and an absence of large-scale granulite-to-eclogite transformation, have independently been inferred from the modelling of gravity anomalies across the Himalaya[26]. Mechanical coupling between the surface and the rigid lower crust implies an absence of low-viscosity decoupling horizons within the crust, and is therefore inconsistent with 'channel flow' models of present-day tectonics in southern Tibet.

METHODS SUMMARY

The model geometry and topography approximate what is currently seen in the Tibetan Plateau, and deformation is driven by velocity boundary conditions and topographically induced stresses. We have used a crustal thickness of 40 km under the lowlands in the north and south of the model, 75 km in the region of underthrust Indian lithosphere, and 65 km in the northern plateau[27]. The crustal thickness is tapered between the values used in the mountains and the lowlands in proportion to the surface topography. The perpendicular component of the velocity on the eastern and western boundaries is approximated and interpolated from GPS velocities[28], and no constraints are imposed on the component parallel to the boundary. The model is constructed in a reference frame attached to the lowlands in the southern part of the model domain, which represent northern India. For simplicity, a newtonian rheology is used throughout. The viscosity of the upper 15 km of the crust is 10^{22} Pa s (ref. 25), and that of the lower crust is 10^{20} Pa s (ref. 5). The viscosity is vertically tapered for 5 km either side of the contrast. Northern Tibet is underthrust by the Tarim basin for about 200 km (ref. 29). As in southern Tibet, we model this as a region of rigid lower crust (the Tarim basin, like India, is underlain by Precambrian basement), which is given the velocity of the central Tarim basin relative to India[28]. We assume that the vertical normal stress at the base of the model balances the mass of the overlying rock. We also impose zero shear stress on the base of the model, because some models of southeastern Tibet[25] suggested that the hot and hydrated mantle in the region was too weak to provide a rigid lower boundary to deformation within the crust.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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