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LETTERS

Imaging the Indian subcontinent beneath the Himalaya

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The rocks of the Indian subcontinent are last seen south of the Ganges before they plunge beneath the Himalaya and the Tibetan plateau. They are next glimpsed in seismic reflection profiles deep beneath southern Tibet[1], yet the surface seen there has been modified by processes within the Himalaya that have consumed parts of the upper Indian crust and converted them into Himalayan rocks[2,3]. The geometry of the partly dismantled Indian plate as it passes through the Himalayan process zone has hitherto eluded imaging. Here we report seismic images both of the decollement at the base of the Himalaya and of the Moho (the boundary between crust and mantle) at the base of the Indian crust. A significant finding is that strong seismic anisotropy develops above the decollement in response to shear processes that are taken up as slip in great earthquakes at shallower depths. North of the Himalaya, the lower Indian crust is characterized by a high-velocity region consistent with the formation of eclogite, a high-density material whose presence affects the dynamics of the Tibetan plateau.

In 2001–03, we operated 29 broadband seismometers in Nepal and Tibet for 18 months (Fig. 1), during which time we located ~1,700 earthquakes within the region. All distant earthquakes recorded were subjected to an automated selection process for receiver function calculation (by magnitude, distance, signal-to-noise ratio of the P arrival, and variance reduction of the receiver function). Removal of a handful of remaining outliers during visual inspection left ~40–250 high-quality receiver functions per station. Receiver function analysis allows determination of the time delay between near-vertically travelling direct P waves, and converted S waves that travel to the seismometer from subsurface interfaces with velocity contrast. Delays between the direct and converted wave are proportional to the depth of the interface and depend on the transmission velocities along their paths, while the amplitude of the converted arrival depends on the magnitude and sign of the velocity contrast. The delay times can be converted to interface depths assuming a velocity model. In Fig. 2b, we present a subsurface profile produced by migration and geographical stacking of the receiver functions using methods[4,5] similar to those developed for reflection seismology. Tests show that the structure is sufficiently uniform along the Himalayan arc for a single arc-normal projection within the area studied to be valid (see Supplementary Information).

The clearest feature on the processed image is the Moho, the surface separating the high velocities of the mantle from the slower ones in the Indian continental crust. The Moho appears as a near-horizontal surface beneath India (at ~45 km depth) and Tibet (at ~75 km depth), and is offset smoothly downward beneath the Himalaya over a distance of 120 km. The base of the Indian crust is thus well determined by the receiver function imagery, and confirms

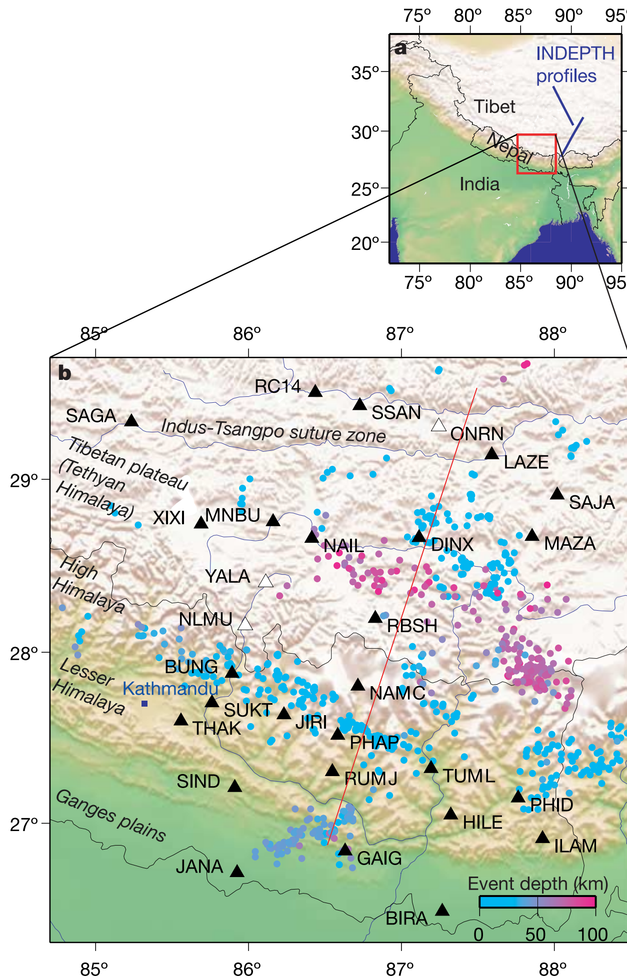

Figure 1 | Location map. a, Overview map with topography. The extent of the study area map in **b** is outlined in red. The location of INDEPTH profiles[1] is indicated in blue. **b**, Topography map of the study area. Stations deployed for this study are shown in black (three stations with little to no data owing to equipment problems or vandalism are shown in white). Hypocentres relocated with our network are colour coded by depth (scale in km). The red line is the location of the profile in Fig. 2 with end points 26.873° N, 86.517° E, and 29.525° N, 87.495°E, orientation N18E. Southern stations BIRA, JANA and GAIG are situated on thick sediments whose multiples dominate their receiver functions and are therefore not used for stacks shown in Fig. 2.

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widely-held views that the lower Indian crust underplates the southernmost Tibetan plateau.

Stations south of the High Himalaya delineate a shallow layer, whose seismic velocity is strongly dependent on incoming wave direction (Fig. 3a, c; see also Supplementary Information). Azimuthal variations in receiver functions can be caused by lateral variations, but several features of these early arrivals—the polarity reversal on the radial component, the strong transverse component energy without a preceding arrival at zero time, and repetition of the pattern at stations distributed over an extended area—require the presence of an anisotropic layer. Waves emerging steeply from the north experience an increase in velocity entering this layer, creating a negative polarity conversion, whereas waves emerging from the south experience a velocity decrease and show a positive polarity arrival. Their sum renders the layer invisible in the standard stack in Fig. 2b. In order to allow detection of interfaces with azimuthal polarity reversals, we calculated an azimuthal contrast stack of the difference between southern and northern azimuth arrivals (Fig. 2c), which shows clearly the base of the anisotropic layer in Nepal and a hint of its continuation under Tibet.

We can reproduce the azimuthal pattern in the receiver functions (Fig. 3b) with a strongly (~20%) anisotropic layer with foliation planes of fast seismic velocity dipping steeply down (~50°) towards a strike of north-northeast, the direction of plate convergence. The layer has a thickness of ~6 km, and its base dips from 8 km depth at the southern margin of the Nepal foothills to 20 km depth just south of the High Himalaya, coinciding with the location of the decollement separating the Himalaya and the Indian plate inferred from structural geology[6–8]. Limitations of depth resolution and unknown subsurface velocity variations place an uncertainty of 2 km on these depths. The anisotropic fabric in the hanging wall of the Himalaya is caused by shear on the decollement, which induces development of foliation planes that concentrate minerals such as micas and amphiboles (Fig. 3d). Shear-induced foliation planes tilt steeply downward in the direction of shear[9], consistent with our observations. Mineral alignment occurs under ductile conditions above temperatures of ~250 °C, conditions that can only prevail in the deeper, northern portion of the imaged shear zone, below the transition from locked to stable sliding that has been inferred on the decollement from geodetic evidence[10]. A concentration of small earthquakes at the depth of the

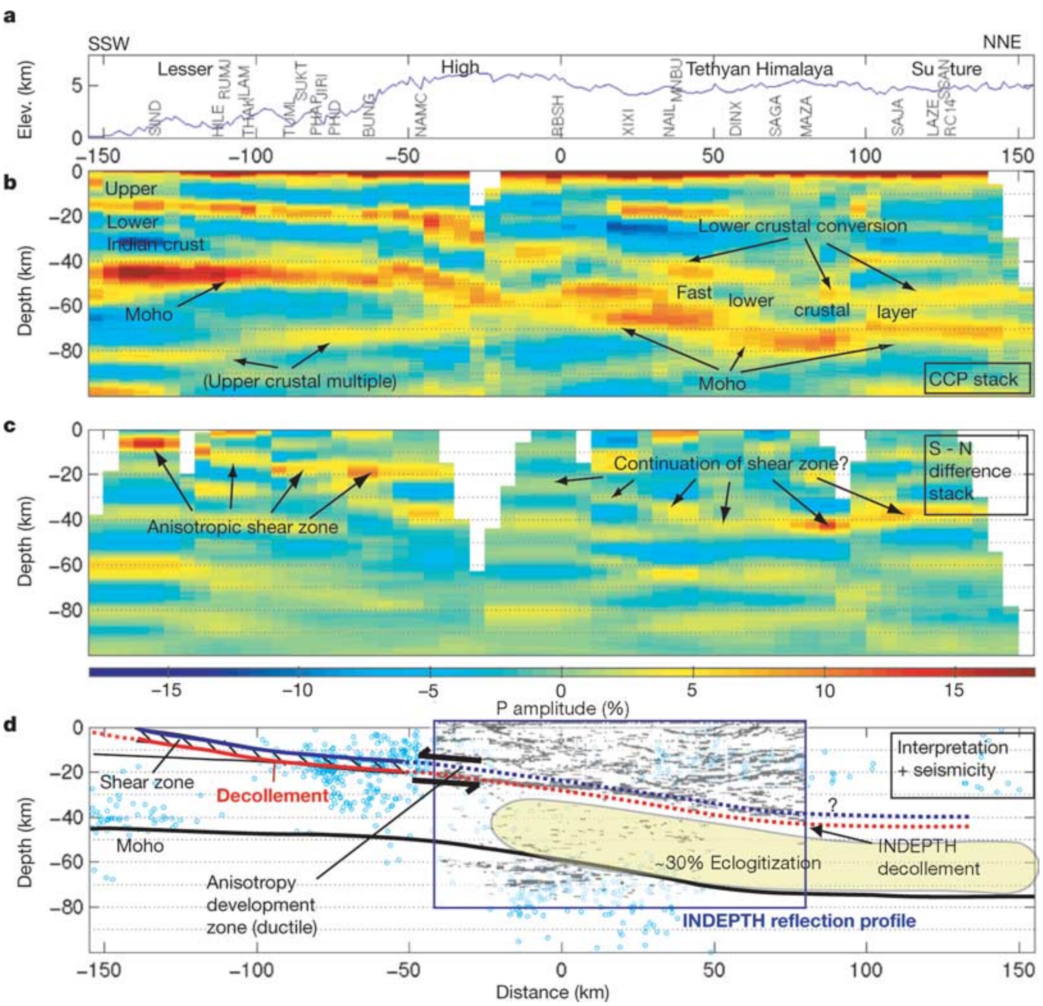

Figure 2 | **Receiver function analysis along profile and interpretation.** **a**, Topography and station locations along the N18E profile indicated in Fig. 1. Elev., elevation. **b**, Common conversion point (CCP) stack of radial receiver functions along the same profile, migrated from time to depth with a simple three-dimensional velocity model from tomographic inversion (one one-dimensional model for Nepal, with station corrections for SIND and BUNG, and one one-dimensional model for Tibet; Supplementary Table 2). White gaps are areas with no data coverage. Bin width is 5 km, with lateral smoothing over 30 km. Colour scale for **b** and **c** is stacked receiver function amplitude expressed as a percentage of the direct P arrival. (See Supplementary Information for discussion of the upper crustal multiple.) **c**, South–north azimuthal difference common conversion point stack: the amplitudes of receiver functions from southern versus northern azimuths are differenced before stacking to allow imaging of arrivals that change polarity over back-azimuth (see also Supplementary Information). Lateral smoothing is now limited to 10 km to allow more precise differencing of receiver functions from opposite azimuths. Scale as in **b**. **d**, Interpretation of **b** and **c**, with INDEPTH reflection profile[1,8] and seismicity located with our network superimposed. Scale as in **b** and **c**.

decollement occurs just south and upslope of the presumed brittle-to-ductile transition, and north and downslope of the locked portion of the decollement (Fig. 2d).

The anisotropy that we observe at depths above the brittle–ductile transition is presumably conveyed upwards along the decollement from deeper levels by tectonism and exhumation, as demonstrated by surface exposures of the Main Central thrust that have been mapped locally and shown to possess similar several-kilometres-thick shear zones[11]. Strong anisotropy from ductile deformation indicates that significant local strain and pure shear exist in the lower part of the Himalayan wedge, which may encourage structural geologists to further investigate the role of finite strain in balanced cross-sections.

On the basis of our observed geometry and receiver function studies from India[12], we assume a midcrustal interface imaged at 17 to 20 km depth in the southern third of the profile to be an inherited feature of the Indian crust, unrelated to the collision to the north. In Fig. 2, the Moho and midcrustal interface in the Nepal foothills in the southern part of the profile are parallel to each other, with a gentle northward dip. In contrast, the decollement, indicated by the base of the anisotropic shear zone, slices down northward at a steeper angle from near the top of the upper crust down into the midcrustal interface. This geometry suggests that the upper part of the Indian crust detaches along the base of the shear zone from the deeper portion and is incorporated into the Himalaya, while the lower crust continues its descent under Tibet. The position of the decollement as we observe it under Nepal, and the hint of its possible continuation that we see under Tibet (Fig. 2c), correspond well with the decollement imaged by INDEPTH reflection data ~200–300 km east of our study area (Fig. 2d). The accumulation of only upper-crustal Indian rocks into the Himalaya is consistent with geological findings[2,13]. The descending lower part of the crust, under increasing pressures and temperatures, appears to undergo changes in material properties.

A crustal positive amplitude arrival, seen at all Tibetan stations at depths of 45–55 km, implies a high-velocity layer in the lower crust. At the same stations, conversions from the Moho are weaker than we observe in Nepal, which is expected for a reduced velocity contrast at the Moho due to a fast lower crust. We estimate crustal velocities using arrival times of local and regional earthquakes recorded at our network[14]. Minimizing travel time residuals in earthquake locations, as well as tomographic inversions, require a fast lower crust under the Tibetan plateau, with P velocities of over ~7.0 km s^{-1} (Supplementary Figs 3, 4). In contrast, the same procedures applied to events in Nepal return a crustal velocity model with normal wave speeds very similar to published values[15], with a P velocity in the lower crust of 6.4–6.5 km s^{-1}. Some increase in velocity would be expected as the Indian lower crust is subjected to higher pressures and initially cold temperatures at increasing depths. However, an increase in P velocity as large as ~0.5 km s^{-1} in lower-crustal materials as a result of a 30 km burial is unlikely without the additional influence of phase transitions, on the basis of laboratory measurements[16].

A much more likely explanation for the anomalous velocity increase is partial eclogitization of the lower Indian crust under Tibet. Eclogite is seismically fast, and our observed velocities suggest that ~30% of the lower Indian crust undergoes this phase transition. As the density of the converted material increases by up to ~21% (ref. 17), the total lower-crustal volume would be reduced, and its density increased, by up to 6%. Although large-scale, pervasive

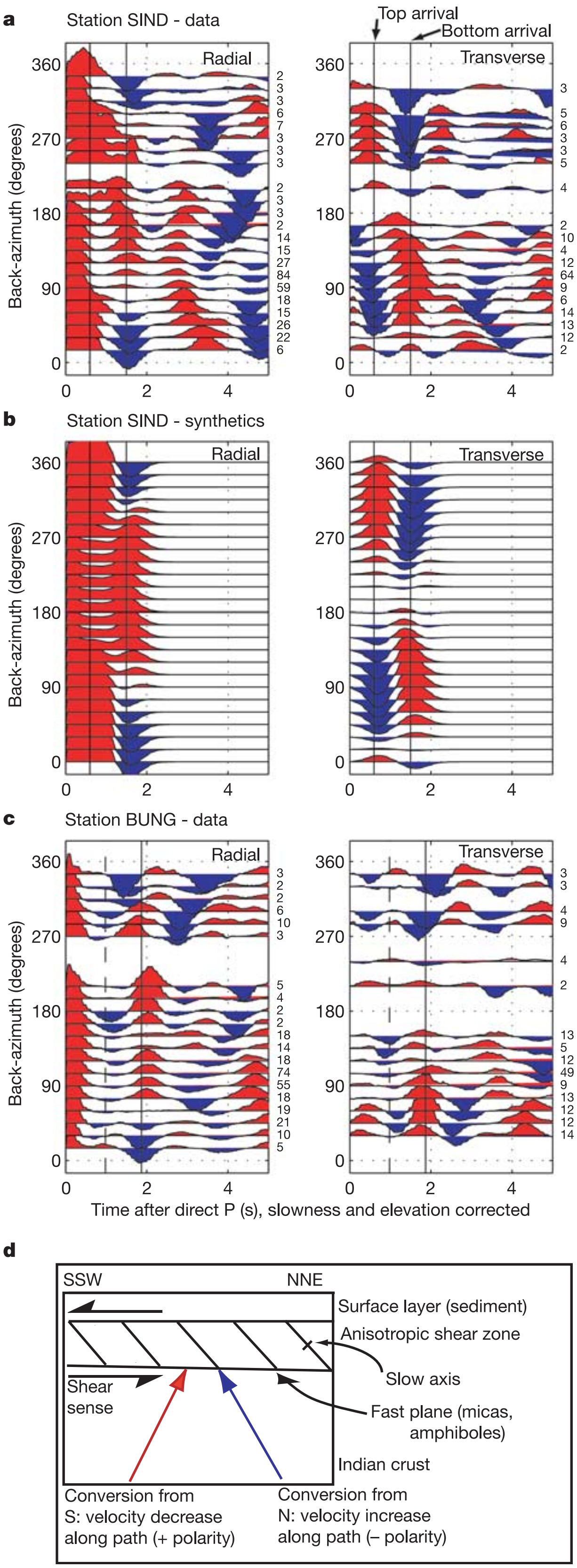

Figure 3 | Observed and synthetic data showing the anisotropic shear zone, and explanation. **a**, Radial (left) and transverse (right) receiver functions observed at southern Nepal station SIND, with number of receiver functions per 15° bin average indicated. Slight azimuthal smoothing is applied (5° overlap between bins, no duplication in count on right). Positive arrivals are shown in red, negative in blue. Arrivals with polarity reversal are indicated. **b**, Synthetic receiver functions[32] (see Supplementary Information) calculated for a shallow, strongly (20%) anisotropic layer to match the polarity reversal arrivals observed at SIND. **c**, The northern Nepal station BUNG shows similar arrivals later than at SIND, indicating that the depth of the layer increases to the north. Although SIND and BUNG are the best examples, similar arrivals are seen at all Nepal stations. **d**, Model used for synthetics at SIND with explanation of the anisotropy development and the mechanism of polarity reversal in radial receiver function amplitudes.

conversion to eclogite can result in delamination of the denser material into the mantle, we see no evidence of such a process in the seismic image. The timing and amplitude of both Moho and lower-crustal interface in Tibet vary from station to station and with back-azimuth at the same station, making for a diffuse appearance in the stack compared to the Moho under Nepal (Fig. 2). This appearance suggests that eclogitization is incomplete and distributed, presumably influenced by water availability[18]. The lower Indian crust appears to underplate Tibet at least as far north as the Indus-Tsangpo suture. Further support for the presence of a layer containing eclogite is provided by INDEPTH results to the north and east of our study area, with findings of a Moho 'doublet'[7] (corresponding to our lower-crustal high-velocity layer) just north of the Indus-Tsangpo suture that vanishes further north[5].

Our seismic profile allows us to answer several outstanding questions in Himalayan mountain building. Gravity measurements predicted an increase in Moho depth under the High Himalaya[19,20], but whether this occurred along a steepened continuous Moho, as we confirmed in this study, or on a stepped Moho in an imbricated crust, was a matter of debate[21–23]. We provide seismic evidence for a single decollement south of the High Himalaya, and show that strong deformation of the upper Indian crust, and its incorporation into the Himalaya, may quantitatively reconcile inequities in previous estimates of crustal volume budgets within the collision zone[2].

Eclogitization and loss of the denser material into the mantle have been invoked as possible mechanisms to balance the crustal volume deficit[24,25]. However, several seismic studies have inferred abnormally low, rather than increased, velocities for the Tibetan lower crust[24,26,27], suggesting an absence of eclogite. Our Moho depths and the crustal velocities used to calculate depths are internally consistent owing to our joint use of receiver functions, hypocentre determination, and tomographic inversion, and we are able to confirm the presence of fast material above the Tibetan Moho, with velocities and geographical distribution that suggest partial and diffuse eclogitization. Although eclogitization has recently been proposed as an explanation[28] for deep earthquakes under Tibet, our internally consistent event locations and Moho depths confirm previously held views[29] that the deep events occur in the mantle. Eclogitization can therefore only be an indirect cause of the deep seismicity. Our observation of a fast lower crust under Tibet is the first seismic confirmation of a previously postulated zone of eclogite between the High Himalaya and the Indus-Tsangpo suture, where cold temperatures due to fast underthrusting initially inhibit the eclogite transition and allow the High Himalaya to reach its unusual elevation before eclogite forms north of the High Himalaya[30]. As the lower crust subsequently heats up to reach temperature equilibrium, the eclogite probably converts to low-density granulite north of the Indus-Tsangpo suture (suggested also by the disappearance of the INDEPTH Moho 'doublet'[5]), which would help buoy up the Tibetan plateau[31].

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

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