the surface, favouring lava eruptions; if subsidence is slow, the volcanic edifice may accumulate to such a height that ultimately only the lowest-density magmas can erupt. □

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Deep seismic reflection evidence for continental underthrusting beneath southern Tibet

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THE Himalaya and adjacent Tibetan plateau, constituting Earth's largest region of elevated topography and anomalously thick crust, formed as a consequence of Cenozoic collision between India and Asia—itself considered the archetypal continent–continent collision[1–3]. Here we report the first results from an attempt to image the structure of the crust beneath this region using deep seismic reflection profiling. Our ~100-km-long profile, acquired in the Tethyan Himalaya, shows a mid-crustal reflection that probably marks the active thrust fault along which the Indian plate is underthrusting southern Tibet; upper-crustal reflections with geometries suggestive of large-scale structural imbrication of the upper crust; and Moho reflections from the base of the double-normal-thickness crust underlying the region. These results lend substantial support to the view that crustal thickening beneath southernmost Tibet was accomplished by wholesale underthrusting of Indian continental crust beneath the structurally imbricated upper crust comprising the Tethyan Himalaya.

The deep seismic reflection data were collected by Project INDEPTH (International Deep Profiling of Tibet and the Himalaya), which is a cooperative programme between the Chinese Academy of Geological Sciences of the Ministry of Geology and Mineral Resources of China (MGMR) and Earth scientists from several universities in the United States. The profile was sited within the southern part of the Yadong–Gulu rift in southern Tibet (Fig. 1). The Yadong–Gulu rift is one of a series of north–south trending Quaternary grabens that transect the Himalaya and southern portion of the Tibetan Plateau[4]. The portion of the Yadong–Gulu rift containing the INDEPTH survey lies within the Tethyan Himalaya, largely comprising Palaeozoic and Mesozoic miogeoclinal strata that were deposited on the north-facing continental margin of India and subsequently folded and thrust southward during Neogene collision between India and Asia[5,6]. Collision-related compressive deformation within the Tethyan Himalaya was apparently followed by an episode of north–south extension, manifest principally by the development of the South Tibetan Detachment (STD), a major low-angle north-dipping ductile normal fault that now forms the boundary

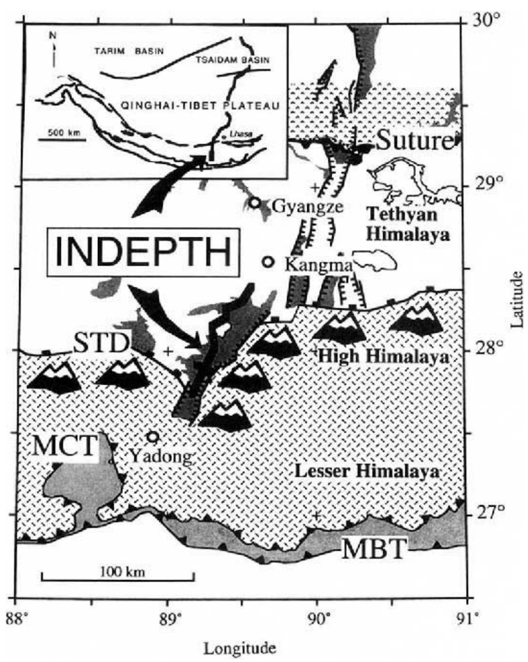

FIG. 1 Generalized geological map showing location of INDEPTH pilot deep seismic profile. MBT, Main Boundary Thrust; MCT, Main Central Thrust; STD, South Tibetan Detachment; Suture, Indus/Tsangpo suture; schematic mountains, crest of High Himalaya.

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between the Tethyan Himalayan sedimentary strata and High Himalayan crystalline sheet to the south[7]. Other extensional structures presumed to have formed during the same episode include brittle normal faults that cut and/or reactivate thrust faults within the Tethyan Himalaya, and a major top-to-the-north ductile shear zone that frames the crystalline Kangmar Dome, which lies within the Tethyan Himalaya immediately north of the INDEPTH profile[8]. Geochronological data demonstrate that the STD formed during convergence between India and Asia, and while active thrust faulting was occurring at lower altitude on the south flank of the Himalaya[7]. Intracrustal earthquakes with thrust-type first motions, occurring beneath the south flank of the Himalaya, indicate continuing convergence between India and southern Tibet[9].

The INDEPTH seismic reflection profile is a nominal 15-fold common-midpoint (CMP) stacked section acquired with explosive sources, 50-m receiver-group spacing and 50-s listening time (Fig. 2). Processing includes elevation statics, pre-stack gain balance, bandpass filter, deconvolution, normal-moveout (NMO) correction, CMP stack, post-NMO mute, post-stack gain balance and display. Long-offset and off-line seismic data were also acquired during the field program with portable REFTEK seismographs.

The most prominent laterally extensive feature visible on the INDEPTH seismic profile is a 'mid-crustal' reflection that extends across the entire section, dipping gently to the north (~9–13 s two-way travel time, TWTT, Fig. 2). Sino-French refraction data collected in the Tethyan Himalaya, in the early 1980s, indicate that the mean crustal velocity above this horizon is in the range 6.0–6.4 km s^{-1} (ref. 10). Using this range of velocities to convert echo-time to depth, and projecting the reflection profile onto a north–south section, yields an average northward dip for this feature of $\sim 9 \pm 2°$. At the southern end of the profile the reflection is at $\sim 28 \pm 1$ km depth and at the northern end $\sim 40 \pm 2$ km depth. Wide-angle reflections recorded by REFTEKs deployed north of the CMP profile indicate that this horizon extends in the subsurface at least 30 km beyond the north end of the profile.

Comparison with existing earthquake and geological data suggests that this reflection marks the thrust fault along which India is presently underthrusting southern Tibet—termed here the Main Himalayan Thrust (MHT). Figure 3 shows the spatial relationship of the INDEPTH profile to existing seismological constraints on the position of the MHT[9]; the reflection data have been projected onto a north–south profile, and positioned at the appropriate distance north of the reference position for the earthquake data. Although the positioning of the reflection profile is approximate, a straightforward interpretation is that the midcrustal horizon imaged on the profile is the northern continuation of the active India–Asia thrust (MHT). Balanced cross sections across the eastern Nepal Himalaya, constructed from surface geological data, also imply a depth to the MHT beneath the High Himalaya of ~30 km[11,12]—in essential agreement with the depth to the interpreted MHT reflection at the south end of the INDEPTH profile. The reflection data imply that Indian continental crust in the footwall of the MHT dips gently to the north beneath southern Tibet, and extends at least as far north as the middle of the Tethyan Himalaya—some 200 km north of the Himalayan thrust front (MBT, Fig. 1). This is substantially north of its last seismologically constrained position, but well within the ~440 km of total convergence between India and southern Tibet that has been estimated from palaeomagnetic data to have occurred since the initiation of

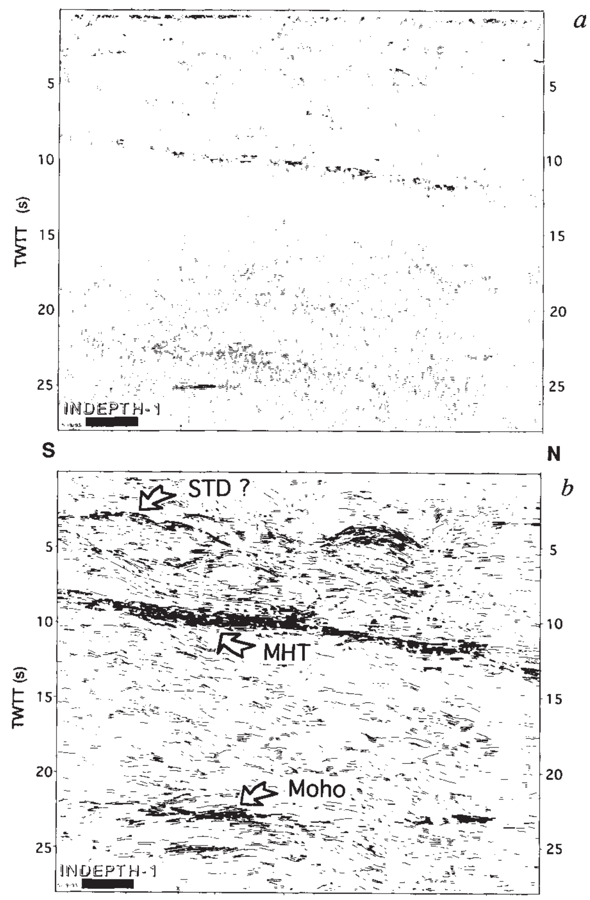

FIG. 2 *a*, upper 30 s of INDEPTH pilot deep seismic profile (unmigrated). Display is ~1:1 (that is, on the same distance scale horizontally and vertically) assuming an average crustal velocity of 6 km s^{-1}. *b*, Generalized line drawing showing interpretation of principal features. MHT, Main Himalayan Thrust; STD, South Tibetan Detachment; Moho, interpreted base of Indian continental crust underthrusting southern Tibet. Scale bar (lower left) is 10 km.

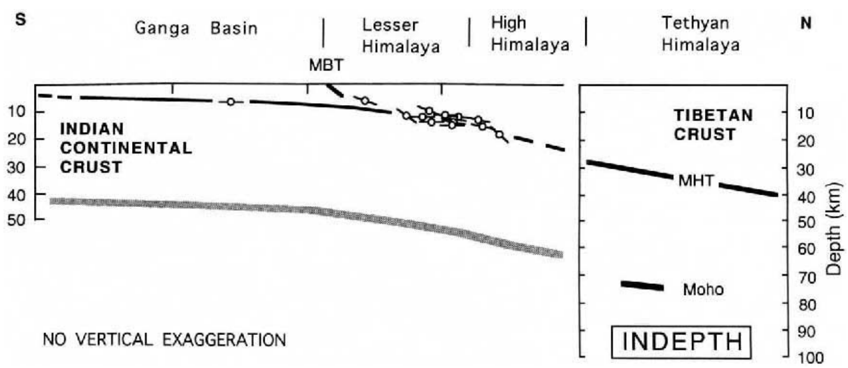

FIG. 3 Spatial relationship of INDEPTH seismic profile on the north side of the Himalaya to well located thrust-type earthquakes defining the active India–Asia decollement beneath the south side of the Himalaya (modified from Fig. 16 in ref. 6). MBT, MHT, Moho, same as in Figs 1 and 2. Grey line, approximate Moho beneath Himalaya interpreted from gravity data[15].

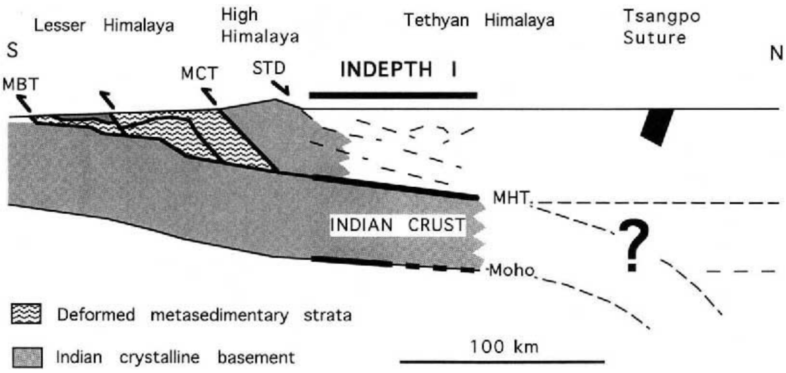

FIG. 4 Schematic crustal cross-section of the Himalaya and the southern Tibetan Plateau showing location of INDEPTH seismic profile and present limit of knowledge of large-scale crustal structure (~1:1). Upper-crustal structure south of the crest of the Himalaya is generalized from ref. 11. MBT, MCT, MHT, STD, same as in Figs 1 and 2.

Himalayan collision (~45 Myr ago)[13]. As the potential error in the palaeomagnetic estimate is comparable in magnitude to the estimate itself, a basic goal of deep profiling in the region is to determine the actual northward extent of Indian crust beneath the Plateau.

Large-scale displays of the INDEPTH profile show that the crust above the MHT is characterized by a number of arched and north-dipping reflections, of generally lower amplitude than the MHT reflection. The latter generally appear to flatten at or above the MHT. Although specific interpretation of these reflections awaits migration of the data and correlation with mapped surface structures, the general aspect of the reflectivity is consistent with the view developed from surface geology that the upper crust beneath the Tethyan Himalaya is imbricated on a large scale[6]. A particularly prominent reflection visible in the upper crust at the south end of the section, which dips to the north and appears to merge with the MHT, is in approximately the right position to originate from the South Tibetan Detachment (Fig. 2). Further surface geological investigation in the vicinity of the south end of the INDEPTH profile is required to test this correlation.

Finally, a notable feature of the seismic section is the occurrence of coherent reflections at echo-times which, in typical continental areas, would correspond to the upper mantle. Particularly prominent are two sets of reflections visible on the southern part of the profile—an upper band between approximately 23 and 24 s TWTT, and a lower discrete reflection at 25.2 s (Fig. 2). The reflections at 23–24 s almost certainly originate from the Moho at the base of the Indian continental crust underthrusting southern Tibet (Fig. 4): Sino-French refraction data[10] indicate that the crust in the general vicinity of the INDEPTH survey has a full thickness of ~75 km and a mean compressional velocity of ~6.3 km s^{-1}, yielding an expected vertical incidence echo-time for the Moho of 23.8 s. Although the Moho reflections are most prominent on the southern part of the profile, they do appear to extend intermittently across the entire profile. Analysis of the reflection data together with daily noise recordings suggests that the large lateral variation in the apparent amplitude of these reflections is a consequence of varying ambient noise levels along the profile—much of which was wind-generated. Interpretation of the apparently deeper reflection at 25.2 s is problematic. A short cross-line that was acquired to constrain the geometry of the deep reflections indicates that this reflection has a substantial component of eastward dip. Migration, in turn, indicates that its source lies within the lower-crust, west of the profile. The interpreted Moho reflections, in contrast, lie in the plane of the profile.

The INDEPTH profile, viewed in combination with existing geological and seismological constraints, suggests that an essentially complete section of Indian continental crust has been underthrust beneath the southern Tethyan Himalaya. At the location where the Moho reflections are most prominent on the profile, the thickness of interpreted Indian crust between the MHT and Moho is ~43 km. This thickness is not resolvably different from the ~40 km thickness that has previously been determined for the undeformed crust of northeastern India, south of the Ganga basin, based on combined interpretation of seismic refraction and gravity data[14]. Surface geological data imply that the crust above the MHT is composed principally of thrust-imbricated sedimentary and crystalline strata that were detached from the leading edge of India early in the Himalayan collision[5,6]. The reflection data, in turn, imply that the crust below the MHT is essentially intact Indian continental crust that was underthrust beneath this imbricate assemblage as a consequence of continuing convergence. Although the INDEPTH data do not directly constrain the shape of the Moho south of the profile, the implied regional dip of the Moho between the Himalayan foreland and southern edge of the Tethyan Himalaya is ~15° towards the north, which is compatible with previous estimates based on gravity modelling[15]. Dipping reflection segments visible on the seismic profile within the interpreted underthrust Indian crust might be manifestations of some internal strain; however, the crustal thickness estimate for the lower plate militates against substantial distributed shortening (thickening) of the underthrust Indian crust. Similarly, no substantial fault offsets of the underthrust Indian Moho are evident on the INDEPTH profile, though such offsets might exist to the north or south[16]. □

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