Greater India Basin hypothesis and a two-stage Cenozoic collision between India and Asia

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Cenozoic convergence between the Indian and Asian plates produced the archetypical continental collision zone comprising the Himalaya mountain belt and the Tibetan Plateau. How and where India–Asia convergence was accommodated after collision at or before 52 Ma remains a long-standing controversy. Since 52 Ma, the two plates have converged up to 3,600 ± 35 km, yet the upper crustal shortening documented from the geological record of Asia and the Himalaya is up to approximately 2,350-km less. Here we show that the discrepancy between the convergence and the shortening can be explained by subduction of highly extended continental and oceanic Indian lithosphere within the Himalaya between approximately 50 and 25 Ma. Paleomagnetic data show that this extended continental and oceanic "Greater India" promontory resulted from 2,675 ± 700 km of North–South extension between 120 and 70 Ma, accommodated between the Tibetan Himalaya and cratonic India. We suggest that the approximately 50 Ma "India"–Asia collision was a collision of a Tibetan-Himalayan microcontinent with Asia, followed by subduction of the largely oceanic Greater India Basin along a subduction zone at the location of the Greater Himalaya. The "hard" India–Asia collision with thicker and contiguous Indian continental lithosphere occurred around 25–20 Ma. This hard collision is coincident with far-field deformation in central Asia and rapid exhumation of Greater Himalaya crystalline rocks, and may be linked to intensification of the Asian monsoon system. This two-stage collision between India and Asia is also reflected in the deep mantle remnants of subduction imaged with seismic tomography.

continent–continent collision | mantle tomography | plate reconstructions | Cretaceous

The present geological boundary between India and Asia is marked by the Indus–Yarlung suture zone, which contains deformed remnants of the ancient Neotethys Ocean (1, 2) (Fig. 1). North of the Indus–Yarlung suture is the southernmost continental fragment of Asia, the Lhasa block. South of the suture lies the Himalaya, composed of (meta)sedimentary rocks that were scraped off now-subducted Indian continental crust and mantle lithosphere and thrust southward over India during collision. The highest structural unit of the Himalaya is overlain by fragments of oceanic lithosphere (ophiolites).

We apply the common term Greater India to refer to the part of the Indian plate that has been subducted underneath Tibet since the onset of Cenozoic continental collision. A 52 Ma minimum age of collision between northernmost Greater India and the Lhasa block is constrained by 52 Ma sedimentary rocks in the northern, "Tibetan" Himalaya that include detritus from the Lhasa block (3). This collision age is consistent with independent paleomagnetic evidence for overlapping paleolatitudes for the Tibetan Himalaya and the Lhasa blocks at 48.6 ± 6.2 Ma (Fig. 2; *SI Text*) as well as with an abrupt decrease in India–Asia convergence rates beginning at 55–50 Ma, as demonstrated by India–Asia plate circuits (e.g., ref. 4). Structural (5) and stratigraphic (6) data show that ophiolites were emplaced over the Tibetan Himalaya in the latest Cretaceous (approximately 70–65 Ma), well before the Tibetan Himalaya–Lhasa collision. Paleomagnetic data suggest that these ophiolites formed at equatorial paleolatitudes (7).

Motion between continents that border the modern oceans is quantified through time using plate reconstructions based on marine magnetic anomalies. The Eurasia-North America-Africa-India plate circuit demonstrates 2,860 ± 30 and 3,600 ± 35 km of post-52 Ma India–Asia convergence for the western and eastern Himalayan syntaxes, respectively (4). It has long been recognized that the amount of upper crustal shortening since 52 Ma reconstructed from the geology of the Himalaya and Asia accounts for only approximately 30–50% of this total convergence (8) (Fig. 1). Previously proposed solutions for this "shortening deficit" include major unrecognized shortening in Siberia (8, 9), a >1,000-km eastward extrusion of Indochina from an original position within Tibet that would lead to >2,000 km of Cenozoic intra-Asian shortening (10–12), or a much younger Tibetan Himalaya–Lhasa collision (13). However, geologically reconstructed shortening of approximately 1,050–600 km (from west to east) within and north of the Pamir and the Tibetan plateau without invoking major Indochina extrusion (14) is consistent with 1,100 ± 500 km of paleomagnetically constrained convergence between the Indus–Yarlung suture and Eurasia since approximately 50 Ma (15). The excess convergence should therefore mostly have been accommodated in the Himalaya, to the south of the Indus–Yarlung suture.

The Himalaya consists of upper continental crust that was decoupled from now-subducted Greater India (1, 2), which is generally considered to have formed the contiguous margin of northern India (2, 16–18). The Himalaya is divided into three tectonostratigraphic zones (Fig. 1). From north to south, these include the non- to low-metamorphic grade sedimentary rocks of the Tibetan Himalaya, separated by the South Tibetan detachment from the igneous and high-grade metamorphic Greater Himalaya, which overlies the low-grade, internally thrusted Lesser Himalaya along the Main Central thrust (1, 2) (Fig. 1).

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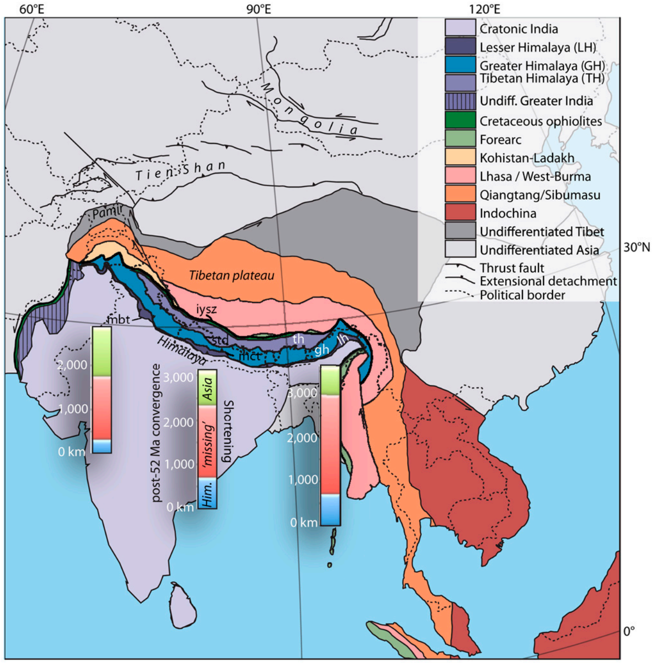

Fig. 1. Tectonic map of the India–Asia collision zone. Bars represent the amount of post-50 Ma India–Asia convergence, and the amount of intra-Asian (14), Himalayan (19, 20), and missing shortening along the collision zone. We calculated the Himalayan shortening deficit using a reconstruction of Asian deformation (14) embedded in global plate circuits (4, 34). Our maximum estimate of undocumented convergence uses (*i*) plate convergence estimates since 50 Ma, 3,600 ± 35 km for the eastern Himalayan syntaxis (4); (*ii*) approximately 600 km of shortening reconstructed in eastern Tibet since 50 Ma (14); and (*iii*) up to 650 km of shortening reconstructed from the eastern Himalaya (51), resulting in a 2,350 km deficit. Since approximately 25–20 Ma, the total amount of plate convergence is up to 1,300–1,000 km in the eastern Himalaya (4). Shortening since approximately 25 Ma in the Himalaya, along the main central thrust (MCT) and in the Lesser Himalaya (LH), is approximately 400–700 km (20), and in Tibet, approximately 200–300 km (14), leaving a modest shortening deficit of several hundreds of kilometers. We ascribe this deficit to uncertainties in the Tibet reconstruction, uncertainties in the timing of Tibetan Himalaya (TH) shortening, and the fact that balanced cross-sections provide minimum estimates. STD, South Tibetan Detachment; IYSZ, Indus–Yarlung Suture Zone; MBT, main boundary thrust.

Composite balanced cross-sections across the Himalaya documented approximately 500–900 km of shortening (19, 20). These estimates are the sum of (*i*) shortening in the Tibetan Himalaya (since the Paleogene); (*ii*) the amount of overlap between the Greater Himalaya and the Lesser Himalaya along the Main Central thrust that was largely established between approximately 25–20 and 15–10 Ma; and (*iii*) the amount of shortening within the Lesser Himalaya since approximately 15–10 Ma (2, 19, 20). The main uncertainty in the Himalayan shortening estimates are associated with the Greater Himalaya. Intense Miocene deformation has effectively overprinted any older structures in the Greater Himalaya, but well-dated prograde mineral growth and magmatism in the Greater Himalaya shows evidence for burial and heating between 45 and 25 Ma (21–23). The amount of shortening accommodated within or below the Greater Himalaya prior to the Miocene therefore remains geologically unconstrained, but could be considerable. Detrital zircon studies of the Lesser, Greater, and Tibetan Himalaya suggest that their Neoproterozoic to lower Paleozoic (Cambrian-Ordovician) stratigraphies are similar (16, 24–26), suggesting that the net effect of post-Ordovician tectonics within the Himalaya was limited to perhaps several hundreds of kilometers of shortening.

The amount of India–Asia convergence since 52 Ma (up to 3,600 ± 35 km, ref. 4) exceeds the estimated total crustal shortening within Asia and the Himalaya by up to 2,350 km (14, 19, 20) (Fig. 1). In this paper, we will consider several possible explanations of the observed discrepancy and propose a tectonic scenario that can reconcile the disparate estimates and identify the structure(s) that accommodated the 'missing' convergence.

Size of Greater India Through Time

The only available technique to quantify past motions between continental blocks that are not connected through a passive margin to oceanic basins is paleomagnetism. A wealth of paleomagnetic data from the Ordovician, Triassic, and lower Cretaceous rocks of the Tibetan Himalaya consistently demonstrates minor net North–South (N-S) motion of the Tibetan Himalaya relative to India since these times (*SI Text*). The youngest rocks that demonstrate a relatively small Greater India are approximately 120 Mya old and show a net convergence between India and the Tibetan Himalaya of 2.1 ± 5.5°, or 233 ± 877 km (Fig. 2). After adding the modern width of Greater India (i.e., the Himalaya, approximately 250 km N-S), these data suggest that Greater India in early Cretaceous time was not larger than approximately 900 km (*SI Text*). This conclusion is consistent with pre-Cretaceous Gondwana plate reconstructions (17, 27) as well as with the notion that the Paleozoic and older stratigraphies of the Himalayan zones are correlative, suggesting that during their deposition Greater India formed a contiguous continental margin (16, 24–26). By assuming that Greater India remained only several hundreds of kilometers wide until collision with Asia, Aitchison et al. (13, 28) demonstrated that the leading edge of Greater India would have passed the equator approximately 55 Ma ago, and suggested that the 55–50 Ma collision record (what is widely regarded as the Tibetan Himalaya–Asia collision) resulted from just the obduction of ophiolites onto the leading, Tibetan-Himalayan edge of Greater India. By also assuming negligible Cenozoic intra-Asian shortening, their model proposed that the India–Asia collision occurred at approximately 34 Ma. Paleomagnetic evidence from upper Cretaceous (approximately 68 Ma) and Paleocene (approximately 59 Ma) rocks from the Tibetan Himalaya (29–31) and cratonic India, however, demonstrate that during the late Cretaceous to Paleocene, the Tibetan Himalaya was separated by 22.0 ± 3.0° of latitude (2,442 ± 333 km N-S) from India (Fig. 2). These paleomagnetic data pass both fold and reversal paleomagnetic field tests at high confidence (*SI Text*), demonstrating their prefolding, primary magnetic acquisition. This much larger size of Greater India at the time of collision than during the early Cretaceous results in a paleomagnetically determined collision age of 48.6 ± 6.2 Ma (Fig. 2; *SI Text*), consistent with the 52 Ma age of first arrival of Lhasa-derived sediments in the Tibetan Himalaya (3). This large dimension of Greater India is also consistent with the position of the southern Asian margin at the time of collision based on restoration of intra-Asian deformation (14). Therefore, paleomagnetic data show that between 118 and 68 Ma, Greater India became extended and the Tibetan Himalaya drifted 24.1 ± 6.3° (2,675 ± 699 km N-S) northward relative to cratonic India (Fig. 2), followed by convergence of a similar magnitude after collision.

Cretaceous Greater Indian N-S Extension

Cretaceous extension within Greater India has previously been inferred from sedimentary facies changes in the Tibetan Himalaya (17, 18) and from lower Cretaceous (140–100 Ma) alkali-basaltic volcaniclastic sediments with a geochemistry interpreted to record intracontinental rifting (32, 33). The 2,675 ± 700 km of N-S extension between 118 and 68 Ma, inferred from paleomagnetic data (Fig. 2), requires minimum extension rates of 40–67 mm/y. Such rates are typical for midoceanic ridges (predrift continental extension rates rarely exceed 20 mm/y, ref. 34), and the magnitude of extension is an order of magnitude larger than that of typical extended continental margins (34). Thus, at least one oceanic basin—the Greater India Basin(s) (GIB)—must have formed between the Tibetan Himalaya and cratonic

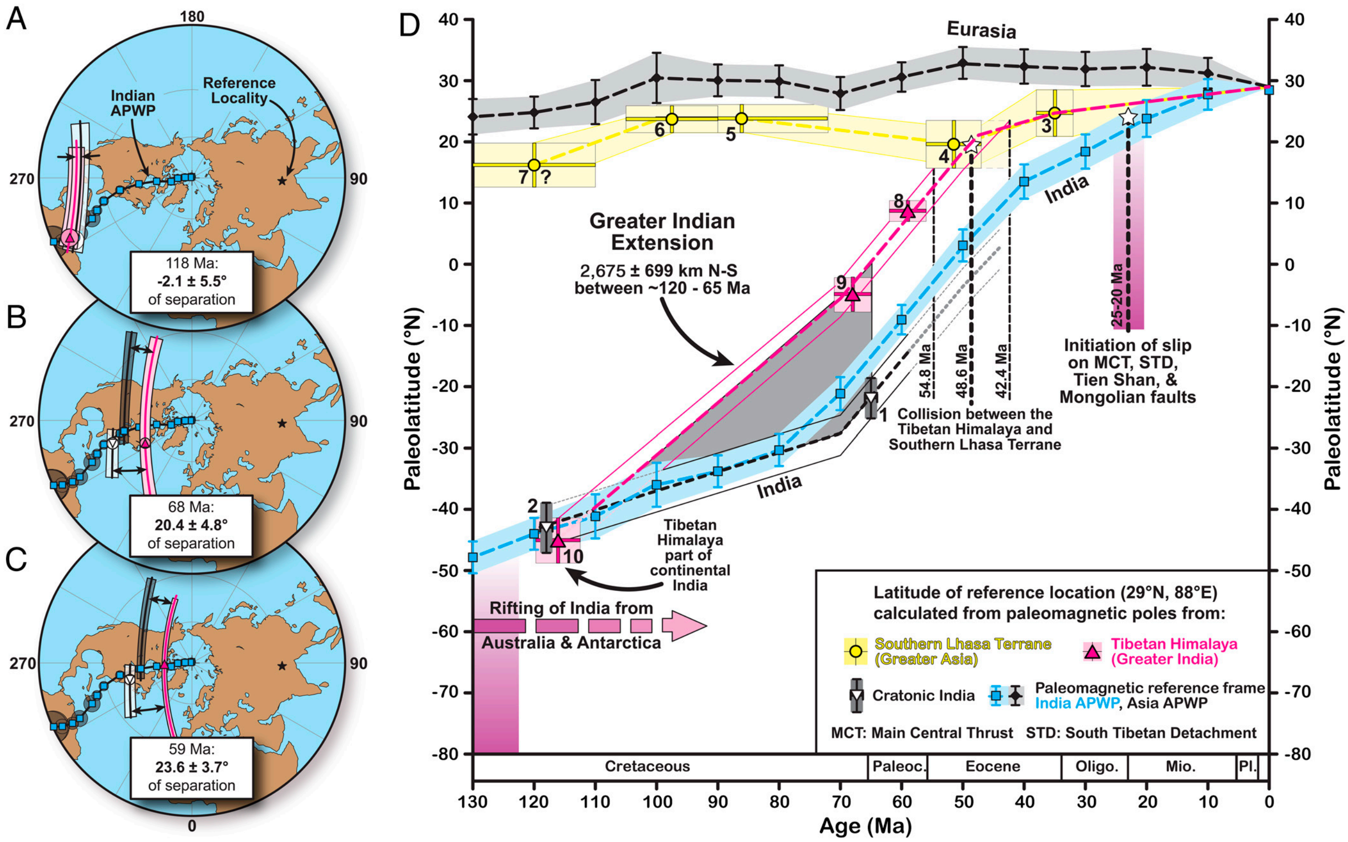

Fig. 2. Paleolatitude evolution of India, Greater India, Greater Asia, and Asia. (*A*) Paleomagnetic poles for the Tibetan Himalaya (magneta upright triangle) and cratonic India (white downward triangle) at 118 Ma, compared to the Indian apparent polar wander path (APWP) (blue squares), indicating that the net N-S drift of the Tibetan Himalaya relative to India since 118 Ma was negligible; Greater India was not larger than approximately 900 km (*SI Text*). Ninety-five percent confidence intervals of the pole positions are also shown. (*B* and *C*) Same as *A*, but at 68 and 59 Ma, respectively, indicating 2,675 ± 699 km of northward drift of the Tibetan Himalaya relative to continental India compared to their 118 Ma position. (*D*) Paleolatitudes of a reference site (29°N, 88°E) located on the present-day position of the Indus–Yarlung Suture Zone in Eurasian, Greater Asian, Tibetan-Himalayan, and Indian reference frames. Numbers correspond to paleomagnetic poles described and listed in the *SI Text*. Pl, Pliocene; Mio, Miocene; Oligo, Oligocene; Paleoc., Paleocene; MCT, main central thrust; STD, South Tibetan detachment. Age uncertainties are based on the age of the units determined from either radiometric dates or geologic stages (52, 53), and latitude uncertainties are calculated from the corresponding poles at the 95% confidence level. Question mark next to estimate 7 indicates that this pole may insufficiently average paleosecular variation. See *SI Text* for details.

India, separating a microcontinent from cratonic India (Fig. 3). The paleogeography of extended Greater India may have consisted of one or more deep basins alternating with (stretched) continental fragments, similar to Mediterranean paleogeography (35). The Cretaceous extension that would have opened the GIB (2,675 ± 700 km) encompasses the approximately 2,350 km of plate convergence that remains undocumented in the geological record of the Himalaya (Fig. 1). Numerical models demonstrate that continental lithosphere can subduct if its buoyant upper crust becomes decoupled from the subducting continent, but denser oceanic or thinned continental lithosphere can subduct without accretion (36). These modeling results are consistent with the observation that many convergent margins with oceanic subduction are nonaccreting (37). If 2,675 ± 700 km of extension created up to approximately 2,350 km of oceanic crust and highly extended continental margins in the GIB, subduction of that crust thus provides a straightforward explanation for the discrepancy between convergence and shortening.

Subduction History and Mantle Tomography

Subduction of the GIB following the approximately 50 Ma Tibetan Himalaya–Lhasa collision is consistent with seismic tomographic images of the mantle beneath India and Tibet. These images reveal three prominent velocity anomalies that have been interpreted as subducted Indian plate lithosphere (38–40) (Fig. 4). The deepest anomaly, at approximately 900 km and greater depth, is generally considered subducted Neotethyan oceanic lithosphere, detached sometime after the Tibetan Himalaya–Lhasa collision (38–40). A shallower anomaly between approximately 400- and 850-km depth would hence be Cenozoic in age (38–40); it projects directly below the reconstructed position of the Tibetan Himalaya between 50 and 25 Ma (Fig. 4). A third conspicuous body imaged horizontally below Tibet over a distance of approximately 500 km from the Himalayan front represents Indian continental lithosphere that has underthrust Asia since the last phase of slab break-off (39, 41). Taking Asian shortening (14) into account, this horizontal body represents the last 10–15 Ma of India–Asia convergence.

Seismic tomographic images also show anomalies in the lower mantle at equatorial latitudes (Fig. 4*A*), generally interpreted as a result of Cretaceous intraoceanic subduction (40, 42). Aitchison et al. (28) suggested that this anomaly resulted from intraoceanic subduction that terminated with ophiolite obduction onto the leading edge of Greater India. We agree that this anomaly represents the relict of an intraoceanic subduction zone, but we note that the much larger size of Greater India in late Cretaceous time shown by paleomagnetic data (Fig. 2) positions the northern margin of the Tibetan Himalaya above this equatorial lower mantle anomaly around 70 Ma, not 55 Ma (Figs. 3 and 4). This reconstruction is consistent with structural and stratigraphic evidence for ophiolite obduction onto the Tibetan Himalaya at approximately 70 Ma (5, 6).

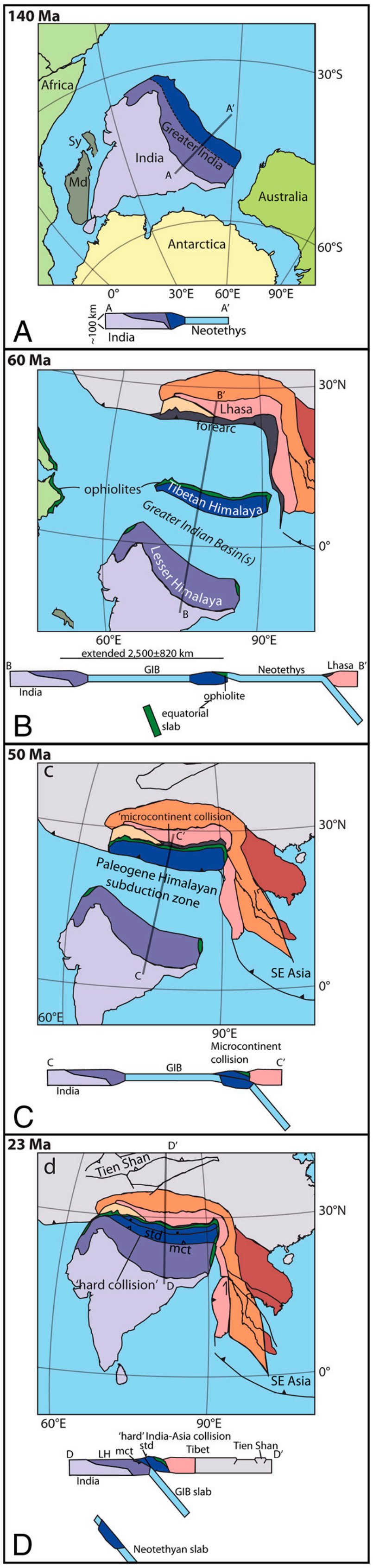

Fig. 3. Plate reconstruction of the India–Asia collision (4, 54). A small Greater India (*A*) was extended in the Cretaceous (*B*), leading to a "soft" collision and ongoing subduction around 50 Ma (*C*) and a "hard" collision with thick, continuous Indian lithosphere between 25 and 20 Ma (*D*). MCT, main central thrust; Md, madagascar; STD, South Tibetan detachment; Sy, Seychelles.

Location of a Paleogene Subduction Zone Within the Himalaya

The collision between the Tibetan Himalayan microcontinent and Asia at approximately 50 Ma, and the subsequent closure of the Greater India Basin south of this microcontinent, requires a Paleogene to Miocene subduction zone south of (i.e., structurally below) the Tibetan Himalaya. The location of this subduction zone must be located somewhere within the modern Himalayan thrust belt, and therefore has implications for the interpretation of existing geological evidence on the contemporaneous evolution of the Himalaya (Fig. 3).

Since the onset of thrusting of the Greater Himalaya over the Lesser Himalaya along the Main Central thrust approximately 25–20 Ma ago, cumulative shortening in the Himalaya (19, 20) and Asia (14) is close to contemporaneous India–Asia convergence (4) (approximately 1,000 km). The continental clastic rocks of the Lesser Himalaya demonstrate continuous subduction of continental lithosphere and accretion of its upper crust to the Himalaya in this time interval. Thus, the discrepancy between predicted convergence and measured shortening is largely concentrated between 50 and approximately 25–20 Ma. Because the Tibetan Himalaya collided with Asia at or before approximately 50 Ma, and the deformation of the Lesser Himalaya is Miocene in age (43), 50–25 Ma convergence must have been accommodated structurally below (i.e., south of) the Tibetan, but above (i.e., north of) the Lesser Himalaya. As mentioned before, the total displacement along the Main Central thrust, as well as convergence accommodated within the Greater Himalaya, remains unknown due to severe Miocene deformation; however, well-dated prograde mineral growth and magmatism (21–23, 44) in the Greater Himalaya shows evidence for burial and heating between 45 and 25 Ma. If Cretaceous extension opened a single Greater Indian Ocean separating a microcontinent from India (Fig. 3), then these Paleogene metamorphic ages would suggest that the Greater and Tibetan Himalaya both belonged to a single microcontinent that collided with and accreted to Asia around 50 Ma. During the 50–25 Ma subduction of the Indian Plate (i.e., the GIB), the Greater and Tibetan Himalaya would then have thickened and metamorphosed as part of the compressed overriding plate (i.e., together with the Tibetan plateau to the north). Subduction—without accretion—would have been concentrated along a precursor of the Main Central thrust. If the GIB had a more complex paleogeography, then the Greater Himalaya could contain a ductile thrust stack (duplex) of deep marine rocks underplated and metamorphosed below the Tibetan Himalaya throughout the Paleogene. Pre-25-Ma prograde metamorphic ages in the Greater Himalaya vary considerably, from 45 Ma migmatitic rocks in gneiss domes in the Tibetan Himalaya (21) to 25 Ma eclogites in Nepal (23); these ages may represent the different times at which Greater Himalayan rocks were structurally buried in the duplex. In any case, the GIB suture lies either structurally within or below the Greater Himalaya.

Microcontinent–Continent Collision (50 Ma) and India–Asia Collision (25–20 Ma)

In our model, the approximately 50 Ma India–Asia collision epresents collision of an extended microcontinental fragment (that contained the rocks now found in the Tibetan Himalaya) and continental Asia. This collision led to orogeny (14, 45), but was followed by ongoing oceanic subduction of the GIB. The hard continent–continent collision followed approximately 25 Ma later with the arrival of much less extended, contiguous continental Indian lithosphere to the collision zone, leading to increased coupling at the plate contact (46). Such increased coupling is consistent with (*i*) the similarity between shortening and convergence since 25–20 Ma; (*ii*) the onset of Greater Himalayan extrusion along the South Tibetan detachment and Main Central thrust (2); and (*iii*) the simultaneous and sudden onset of far-field

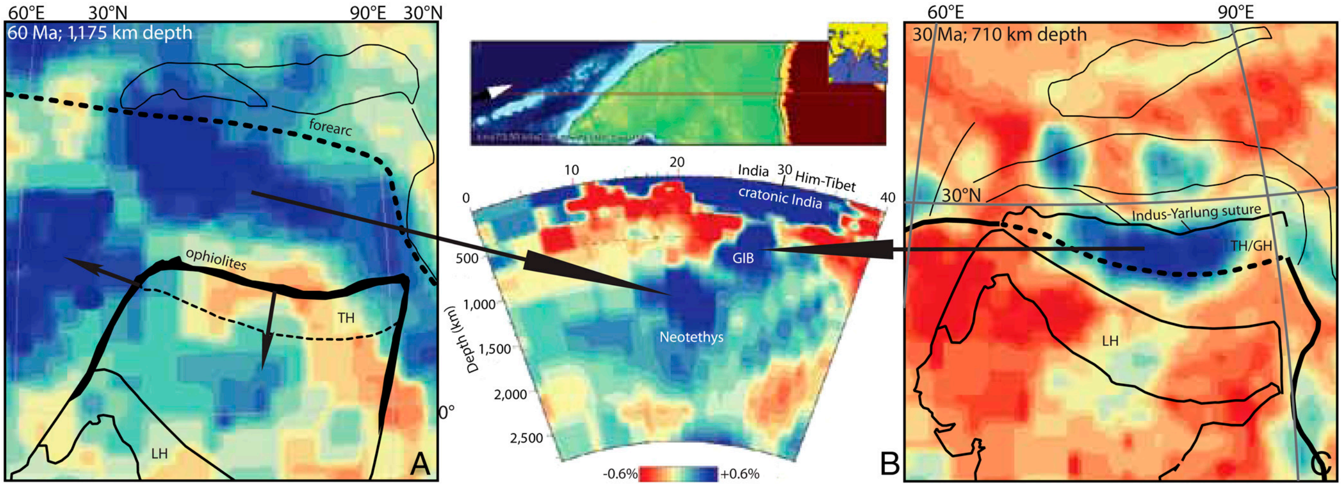

Fig. 4. Seismic tomographic images of subducted slabs compared to India–Asia restorations. (*A* and *C*) Sixty and 30 Ma plate reconstructions of the India–Asia collision zone in a moving hotspot reference frame (54) projected above seismic tomographic images, derived from the UU-P07 model (55), at 1,175 (0.6% contours) and 710 km (1% contours) depth, respectively, with previously identified intraoceanic subduction zones (40, 42). (*B*) Vertical cross-section (0.6% contours) of the mantle below the India–Asia collision zone indicating the three major Indian plate mantle anomalies. TH, Tibetan Himalaya; LH, Lesser Himalaya; GH, Greater Himalaya.

deformation into Central Asia (14) (e.g., deforming and uplifting the Tien Shan, ref. 47) (Fig. 1). Comparison of our plate and deformation reconstructions with seismic tomography suggests that this latter collision was followed by slab break-off at approximately 15–10 Ma and horizontal underthrusting of India below Tibet thereafter. The onset of this last phase of India–Asia collision is contemporaneous with a period of outward growth and extension of the Tibetan plateau (10, 12, 48).

The recognition of major Cretaceous extension in India and a multistage India–Asia collision history no longer requires models invoking major continental extrusion from Tibet predicting >2,000 km of Cenozoic intra-Asian convergence (10–12), but is consistent with kinematic and paleomagnetic reconstructions showing <1,000 km of intra-Asian shortening (8, 14, 15, 49). Our model does not require younger initial collision ages (13) and is in line with geological data from the Indus–Yarlung suture zone (3), suggesting an approximately 50 Ma Tibetan Himalaya–Asia collision. It identifies the Greater Himalaya as the exhumed mid- to lower-continental crust that resided directly above a subduction zone from approximately 50 to 25 Ma. Finally, the hard collision was followed by a substantial increase in erosion rates within the Himalayan system, which may reflect a more virgorous South Asian monsoon (50), highlighting another potential link between geodynamic processes forming the Tibetan-Himalayan mountain belt and climate evolution.

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