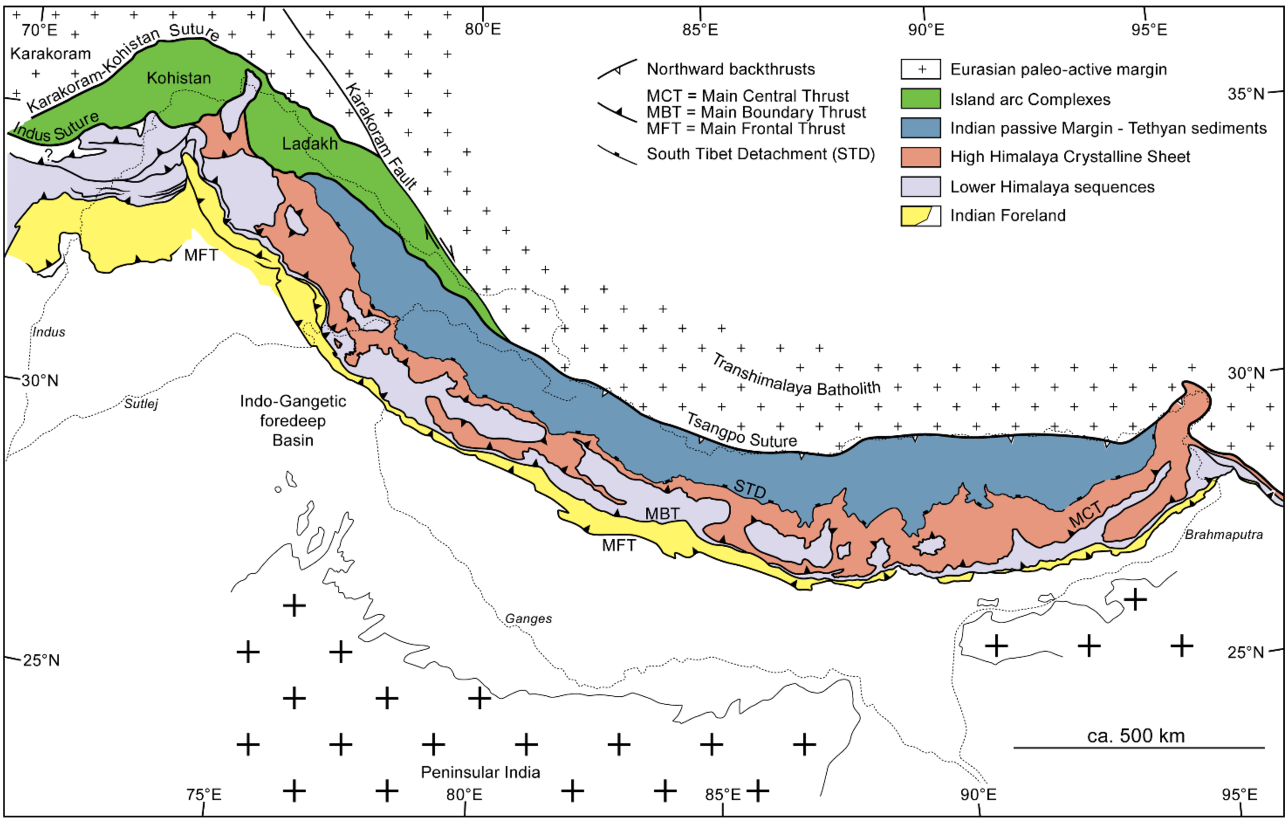
Himalaya - Southern-Tibet: the typical continent-continent collision orogen

When an oceanic plate is subducted beneath a continental lithosphere, an Andean mountain range develops on the edge of the continent. If the subducting plate also contains some continental lithosphere, plate convergence eventually brings both continents into juxtaposition. While the oceanic lithosphere is relatively dense and sinks into the asthenosphere, the greater sialic content of the continental lithosphere ascribes positive buoyancy in the asthenosphere, which hinders the continental lithosphere to be subducted any great distance. Consequently, a continental lithosphere arriving at a trench will confront the overriding continent. Rapid relative convergence is halted and crustal shortening forms a collision mountain range. The plane marking the locus of collision is a suture, which usually preserves slivers of the oceanic lithosphere that formerly separated the continents, known as ophiolites.
The collision between the Indian subcontinent and what is now Tibet began in the Eocene. It involved and still involves north-south convergence throughout southern Tibet and the Himalayas. This youthful mountain area is the type example for studies of continental collision processes.

The Himalayas

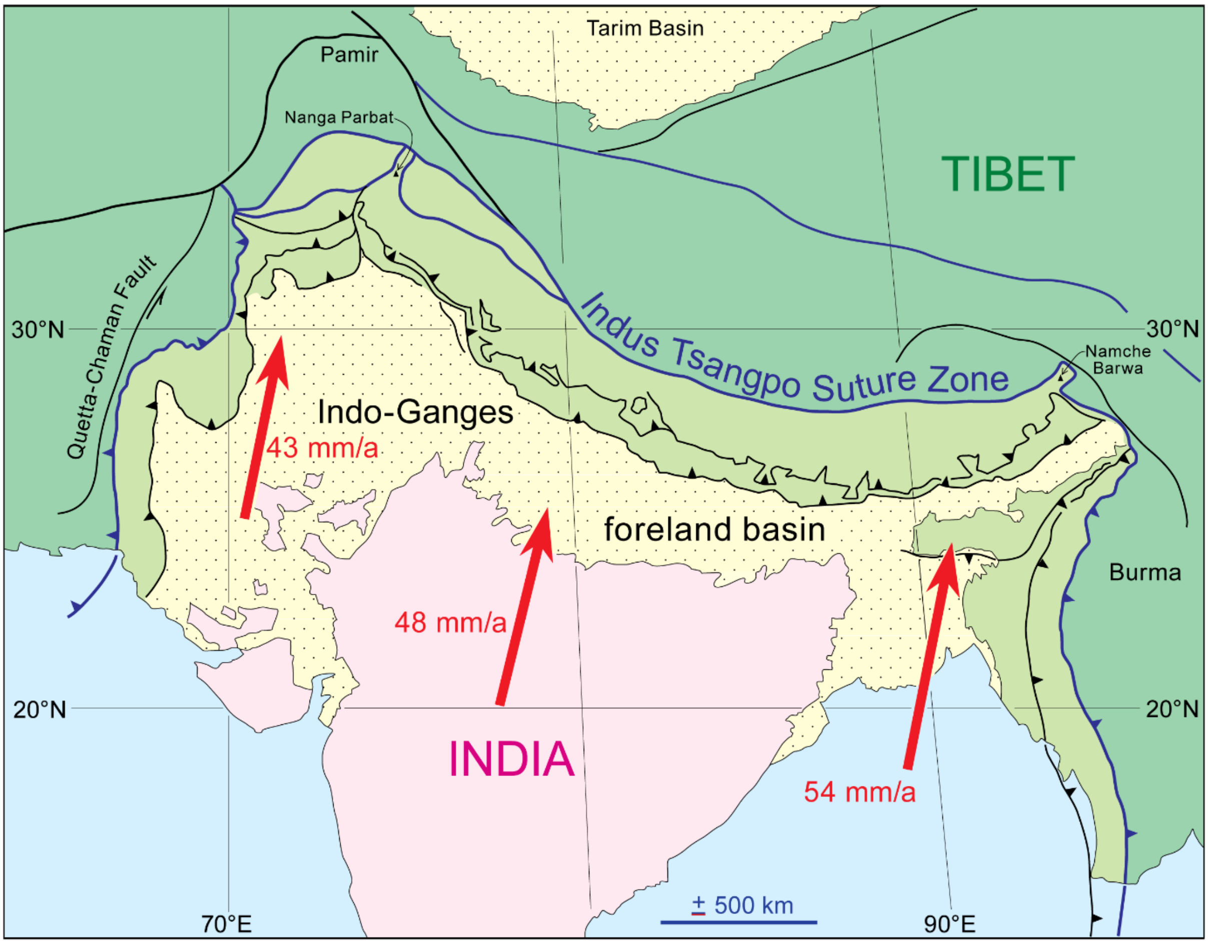
Location

The Himalayas form a nearly 3000 km long, 250-350 km wide range between India to the south and the huge Tibetan plateau, with a mean elevation of 5000 m, to the north. The Himalayan mountain belt has a relatively simple, arcuate, and cylindrical geometry over most of its length and terminates at both ends in nearly transverse **syntaxes**, i.e. areas where orogenic structures turn sharply about a vertical axis. Both syntaxes are named after the main peaks that tower above them, the Namche Barwa (7756 m) to the east and the Nanga Parbat (8138 m) to the west, in Pakistan.



Geological setting

The Himalaya contains the tallest mountain on the Earth, the 13 peaks that stand above 8000 m in elevation, and most of the next, above 7500 m. This great elevation is attributed to the isostatic response of a thickened, low-density crust with the Himalayas undergoing rapid uplift at rates between 0.5 and 4 mm/yr. The mountain range is bounded at both extremities by strike-slip belts: The Quetta-Chaman fault system in the west, in Pakistan and Afghanistan, and the Sittang zone in Burma in the east.



Convergence rates from DeMets *et al.* (1990) *Geophysical Journal International* **101(2)** 425-478

The Himalaya and the Tibetan plateau are remarkable features of the geological history of Asia, which, since the end of the Mesozoic Era, has been dominated by convergence with India, a small block of continental lithosphere derived from Gondwana. Both oceanic magnetic anomalies and paleomagnetism record well the relative motion.

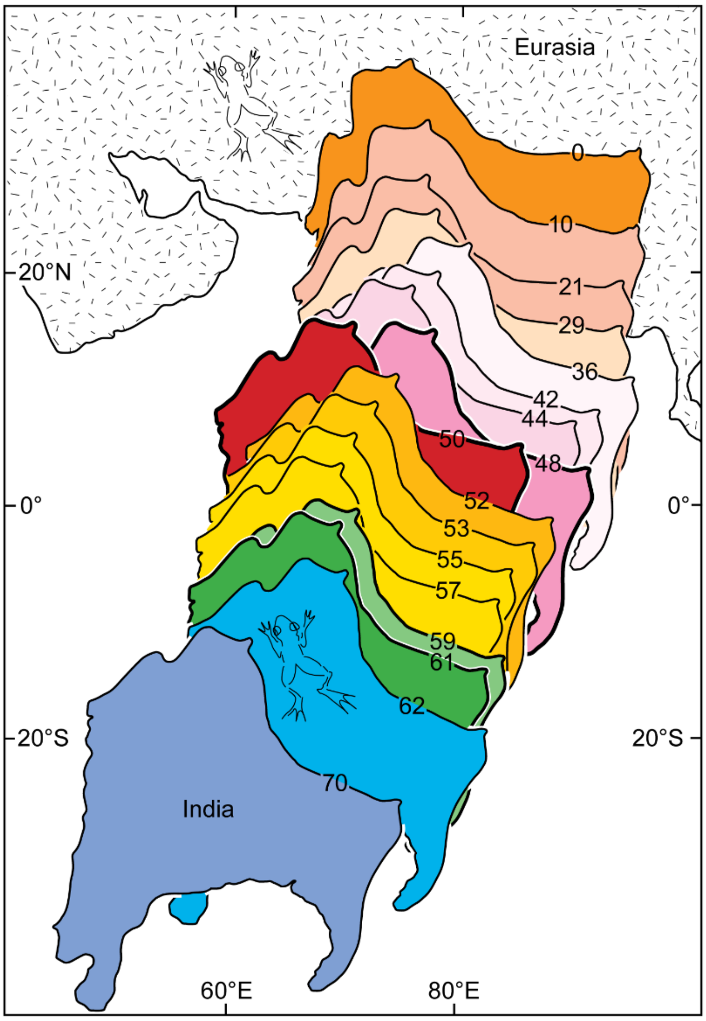
From rifting to ocean spreading

Lithological, paleontological, geochemical, and geochronological evidence from basement rocks and sedimentary cover indicates that India was part of Gondwana. Rifting along the northern Gondwana margin began in the late Paleozoic. Left lateral, tensional wrenching separated the northern part (Laurasia) and southern part (Gondwana) of Pangea and generated the Mesozoic Tethys Ocean from Permian to Cretaceous times. In Middle/Late Jurassic and Early Cretaceous times, the Gondwana supercontinent broke up into two landmasses: western Gondwana (Africa and South America) and eastern Gondwana (Australia, Antarctica, India, and Madagascar). These two lands fragmented further into their respective components during the Cretaceous. India separated from Antarctica and Australia in the Early Cretaceous (ca 130-135 Ma) and from Madagascar in the LateCretaceous (85-90 Ma).

Chronology of the convergence

The northward drift of cratonic India relative to cratonic Asia started 100-90 Ma ago. Closure of the Mesozoic Tethys Ocean resulted in the collision between India and Asia.

relative movement between India and Eurasia since 70 Ma
after Patriat & Achache (1984) *Nature*, **311(5987)**, 615-621



Numbered northern boundaries of India refer to ages in Ma and the corresponding position.
Frogs indicate a continental bridge at ca. 65 Ma (Jaeger *et al.* 1989 *Geology* **17(4)**, 316-319).
The smallest relative translation between 61 and 59 Ma likely points to beginning of collision.

Marine magnetic anomalies of the Atlantic and Indian oceanic floors along with paleomagnetic measurements in South Tibet and India offer an external time frame to the convergence history. Plate tectonic reconstructions predict ca. 7500 and 8700 km at the longitudes of the western and eastern ends of the Himalayas, respectively. This motion provides an indicative size of the consumed oceanic Tethys and continental North-India lithospheres.
Paleomagnetic data from Southern Tibet compared with apparent polar wander paths for the Indian plate show that intra-oceanic subduction and collision between India and Asia occurred at equatorial latitudes, with progressive suturing from Paleocene in the north-western Himalaya (at 67-60 Ma) until Early Eocene (ca. 50 Ma) in the eastern Himalaya. This indicates the anticlockwise rotation of India during its northward drift.

Up to Anomaly 22 (50 Ma), the displacement of India was very rapid, at a rate of 15-25 cm/yr. In detail, India-Eurasia convergence began to slow down around 52 Ma.

Between anomalies 22 and 21 (a time-space of 2-3 Ma), short-lived shifts in movement direction are usually attributed to the onset of continental subduction and India-Eurasia collision.

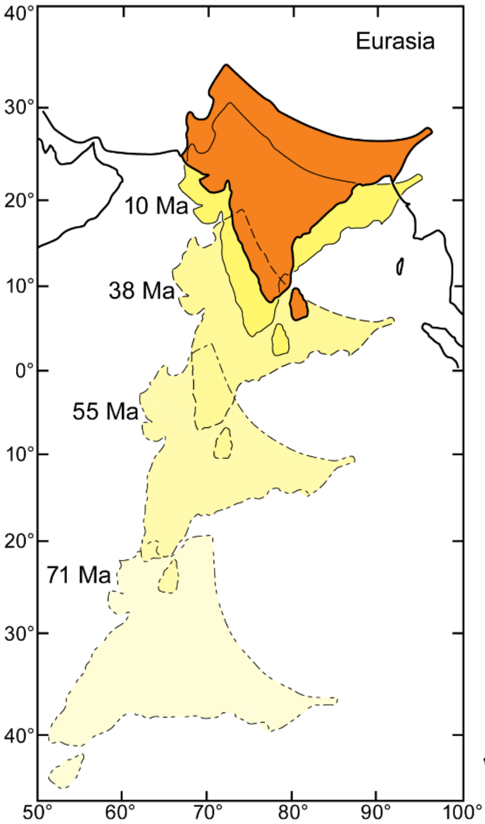
These rate and directional changes may reflect a fluctuating balance of pull vs buoyancy forces during the subduction of the irregular northern continental margin of India.

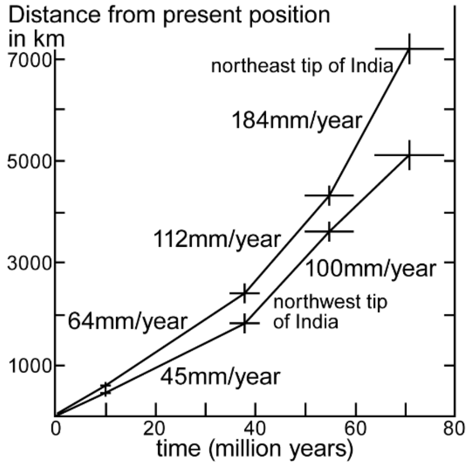
From Anomaly 22 to the 42 Ma Anomaly 18 the displacement rate decreased exponentially to 4-5 cm/yr. and remained nearly steady until a smaller slow down around 20 Ma.

The present-day rate of convergence across the Himalaya is about 1.5 cm/yr., a bit less than half the total convergence rate.

The geodynamic interpretation of this 3-episode relative motion is generally as follows:

- Subduction of the Tethys oceanic lithosphere, with an increasingly long slab pulling India, thus enhancing fast movements.
- Subduction of the Indian continental lithosphere after coming into contact with Eurasia; deceleration of the relative convergence is attributed to the buoyancy of the continental lithosphere, which increasingly resists subduction while the volume of the subducted continent increases.
- Intracontinental shortening; the steady average convergence rate is controlled by deformability of the colliding continental lithospheres and potential pull forces of subducting continental India.





Position and displacement rate of India with respect to an arbitrarily fixed Eurasia
after Molnar & Tapponnier 1975 *Science* **189** 419-426

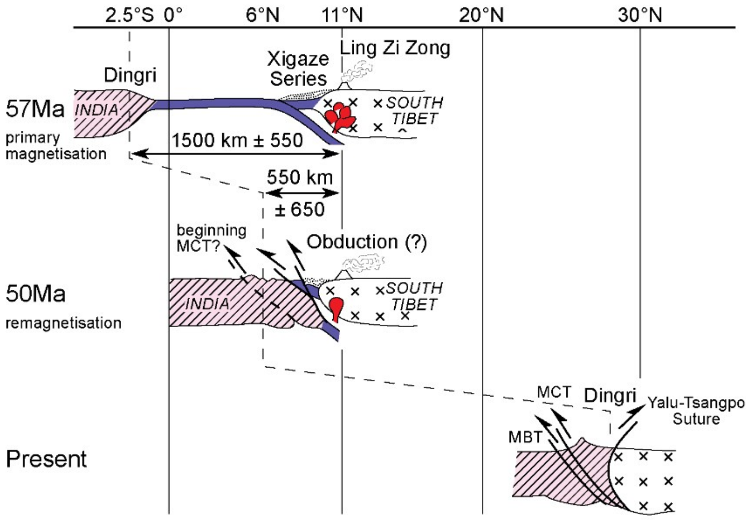
Age of collision

In the light of paleomagnetic information, the initial collision between the continental parts of the Indian and Asian plates is placed in the Eocene, at 60-55 Ma, when the northward motion of India slowed rapidly from >15 cm/ yr. to 4-5 cm/yr. This timing is consistent with that inferred from the age of coesite-bearing eclogites (metamorphic pressure > 3 GPa at 55-45 Ma) in Ladakh. Other arguments to date collision use the (1) youngest age of subduction-related granitoids (about 50Ma), but there might be some time lag between cessation of subduction and intrusion, or (2) the age of the youngest marine sediments along the suture zone (also about 50 Ma). The collision of India against Eurasia was felt around the world. The abrupt 43 Ma bend in the Hawaii-Emperor seamount chain in the Pacific records, a major plate reorganization and many of the volcanic arcs began to form at about

50 Ma (Tonga, Mariana, and Aleutian). In the north Atlantic, at about the same time, the ridge jumped from the Labrador Sea to the Reykjanes Ridge east of Greenland. Yet a single age all along the suture zone might be elusive.

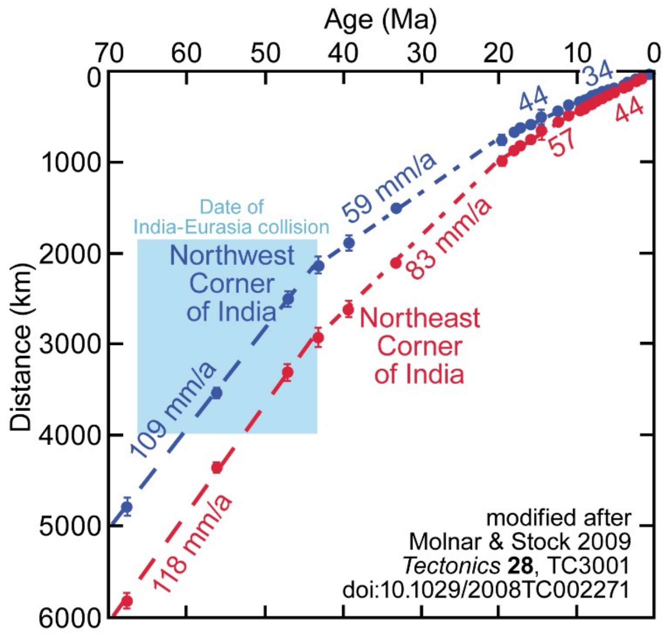
Long-lasting collision

Marine sediments deposited at around 55 Ma in South Tibet indicate that this northern part of India was stable while northward drift was still at a velocity > 10 cm/yr. Slower drift at 45 Ma suggests that initial collision had started.



Geodynamic evolution of the India-South Tibet collision
after Besse *et al.* 1984 *Nature* **311(5987)**, 621-626

A thin continental margin in front of cratonic India may have been subducted for several million years without triggering any major tectonic or sedimentary signal until the end of the Eocene (ca 35 Ma). For example, marine sedimentation continues in the Persian Gulf well after the collision between Arabia and Eurasia.



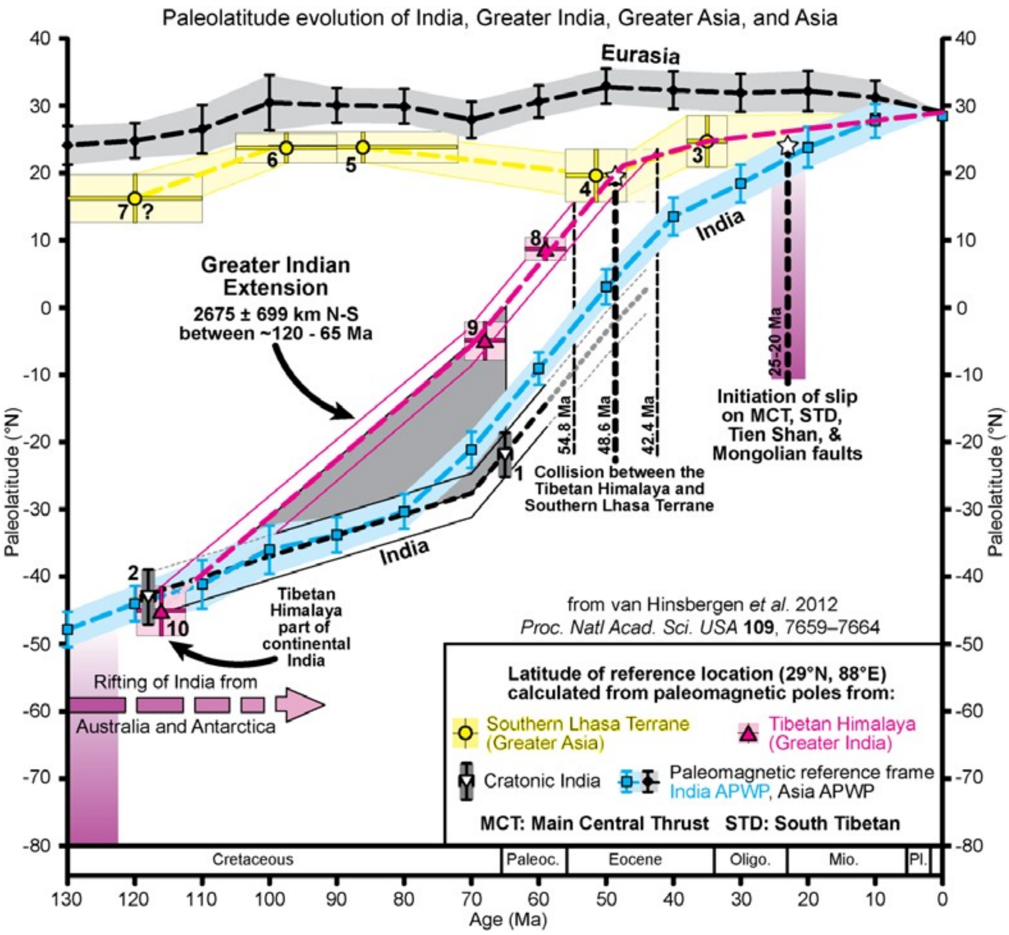
At ca. 35 Ma, the thicker, more buoyant Indian Craton increased compressional stresses, which resulted in the shortening of both the Indian and Tibetan crusts and a possible second reduction in convergence rate at 20–10 Ma. This model involves a several hundred kilometers wide and thin continental margin along North India.

Diachronous, eastward migrating collision

Continental faunas suggest that India and Asia were linked at 67 Ma in the West Himalayas. Accordingly, some authors suggested that collision may have started earlier in the west and subsequently propagated eastward all along the Himalaya, This is consistent with slightly faster convergence rates on the eastern corner of India than on its western corner.

Multiple collisions

Paleomagnetic and tomographic information suggests that sometime in the early Paleocene northern India possibly collided with an intra-oceanic island arc at near-equatorial latitudes. This situation led to a two-stage India-Asia collision at 60-55 and 25–20 Ma.



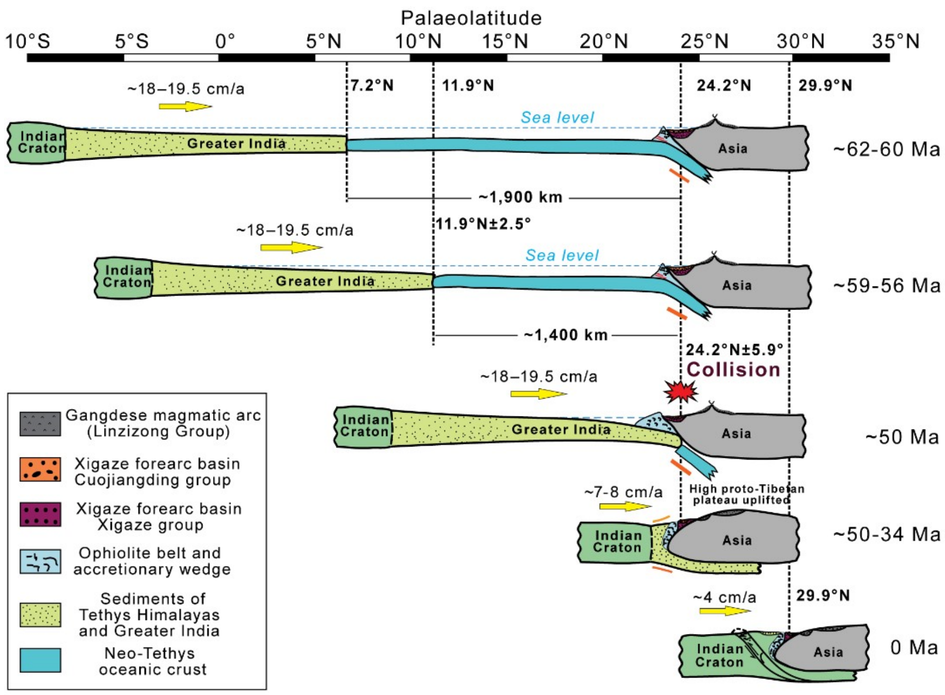
After the collision, India did not stop; it moved northward by over 1900 ± 850 km to Asia at an average speed of 4-5 cm/yr.

Greater India

The pre-collision size of India is a critical question since it directly addresses how and where collision began and how subsequent convergence between India and Asia has been accommodated.

Greater India names the pre-collision extent of India's northern continental part. Its dimensions are difficult to constrain because of large uncertainties on collisional deformation and corresponding lithospheric "destruction". Seismic data show that the South Tibet - Himalaya collision zone has an approximately 65 km thick crust, while the crust of India, south of the Himalayas, is only 35-45 km thick. A simple geometrical superposition explaining the nearly twice-thick crust of the Tibetan plateau (Asian crust over India) suggests that Greater India may have been as wide as Tibet. Tectonic reconstructions fitting the possible northern boundary of Greater India with the margins of Australia in the Early Cretaceous (ca 130-135 Ma) imply an about 800 km wide Greater India. However, the fast rate and a large amount of convergence since the 60-55 Ma collision require that Greater India included a 1500 to 2500 km (from west to east) wide continental margin to the north of the Himalayas. Paleomagnetic measurements on Tethys sediments infer >1300 km. Any of these figures is a hint for a very wide, strongly extended (thinned) continental margin in front of India, until the collision.

Kinematic and dynamic evolution of the India–Asia collision

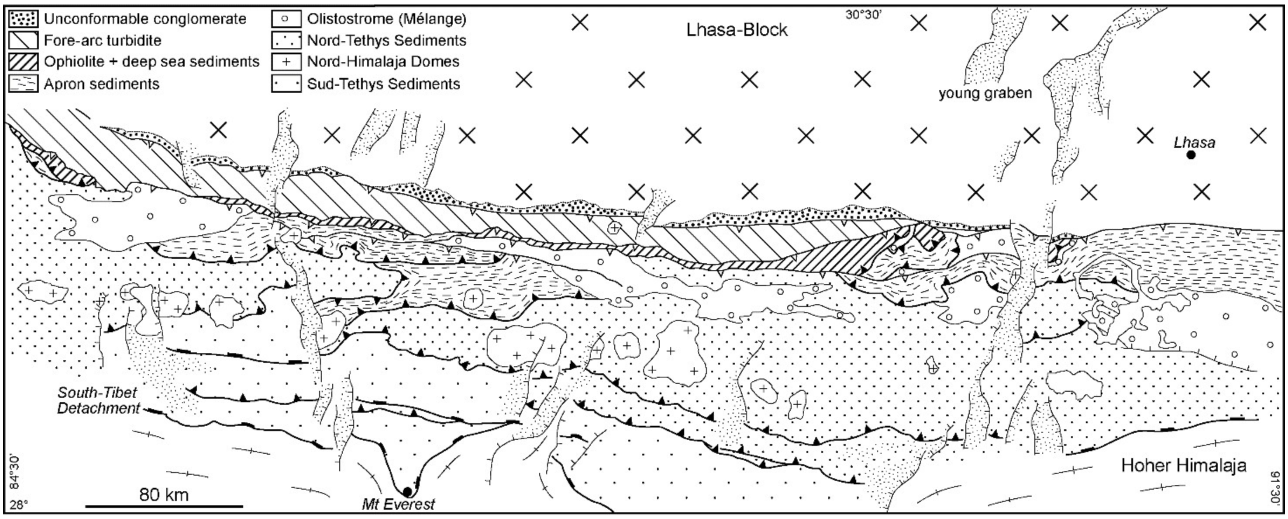


from Meng *et al.* 2012 *Scientific Reports* **2(925)**, doi: 10.1038/srep00925

Main tectonic and lithologic zones

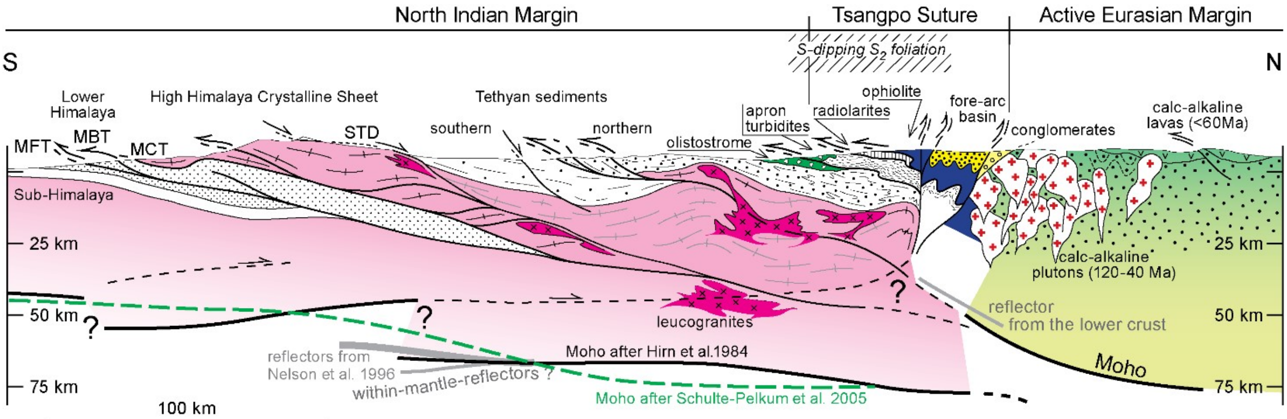
Southwards-directed and propagating thrusting has assembled South Tibet and the Himalayas from four main tectonic and lithologic units that are remarkably consistent all along the length of the mountain belt. Major faults bound each of these units, which display distinctive stratigraphy and metamorphic-magmatic history. From N to S, i.e. from the structural top to bottom, these units are:

- The Eurasian paleo-active margin, so-called Transhimalaya or Gangdese Batholith in South Tibet, which continues into the Karakoram Batholith in the western Himalayas.
- The Tsangpo Suture Zone that delineates the plate boundary along which the Tethys oceanic lithosphere that separated India and Eurasia was subducted beneath Tibet.
- The Tethys Himalaya exposing sediments deposited on the North Indian passive margin and its continental rise, which have been intruded by Eocene and younger granitoids of the North Himalaya domes.
- The Indian continent that comprises the High Himalaya and underlying thrust sheets of the Lower Himalaya over the Indian foreland.



Simplified geological map of South-Tibet, after Burg & Chen (1984) *Nature* **311** 219-223

We first concentrate on a detailed section across the Tibetan side of the Himalayas to describe the lithological and structural record of the geodynamic and orogenic evolution.



Crustal-scale section across the Tsangpo Suture Zone

Eurasia active margin

The Lhasa Terrane, named after the capital of Tibet, formed the active continental margin of Eurasia during the north-dipping Tethys subduction. The Lhasa Terrane comprises a continental part in the north and a magmatic arc in the south.

Lhasa Block

The continental Lhasa Terrane consists of a gneissic and granitic Precambrian basement covered with Paleozoic to Upper Cretaceous shallow-water sediments. Mesozoic sediments contain Cathaysian flora. Cathaysia was a microcontinent detached from Gondwana during the Late Paleozoic and drifted across the Tethys until it collided with the Qiangtang terrane of southern Asia in the Late Jurassic. This collision produced the Banggong-Nujiang suture, perhaps after south-dipping subduction below the Lhasa Terrane. Cretaceous clastic sequences with plagioclase-rich volcano-clastic sandstones were deposited in a basin that underwent a progressively increasing subsidence rate. This basin is interpreted as a retro-arc foreland basin in front of a northward-propagating thrust system between 105 and 53 Ma. A major change in the depositional environment produced shallow water and subaerial sediments associated with a Cretaceous-Paleocene (70-65 Ma) ignimbritic series that lies unconformably on eroded folds of the Late Cretaceous and older rocks. The southern marine Early Mesozoic basin may have deposited on an undated oceanic crust.

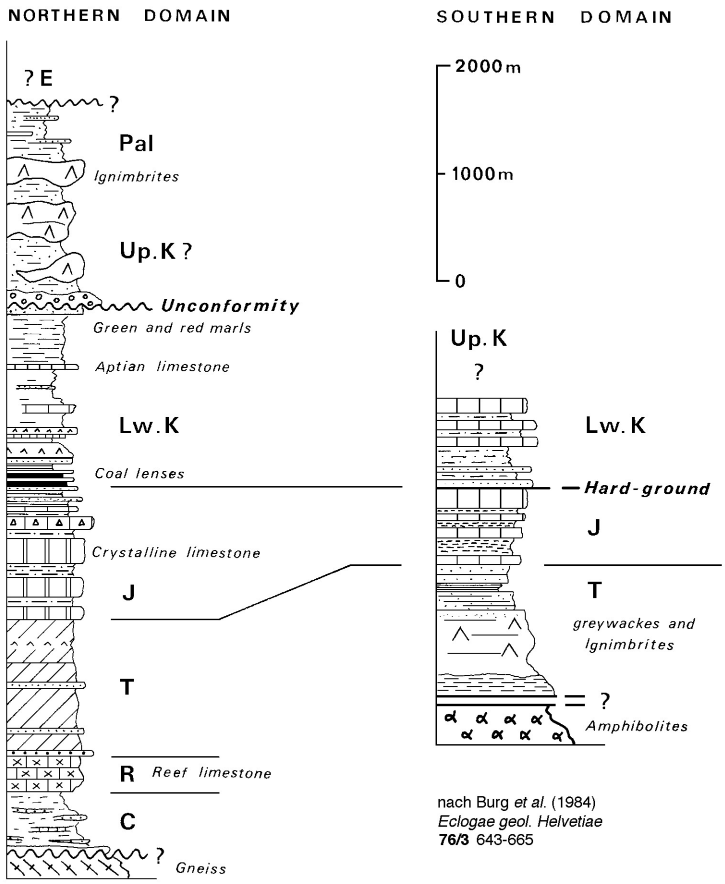


Fig. 3. Tentative lithostratigraphic log of the Lhasa block.

Magmatic arc: the Transhimalaya Magmatic Belt

Magmatic rocks

The Transhimalaya is a long, linear mountain chain just north of and parallel to the Yalu Tsangpo River (the Brahmaputra in India). The Transhimalaya (Chinese name: Gangdese) represents the Cretaceous to early Tertiary Andean-type magmatic arc formed on the southern portion of the Lhasa Terrane (then the active Asian margin), above the Tethys subduction. Magmatic structures define imbricate plutons making up the calc-alkaline batholith with ages between 175 and 30 Ma. This batholith includes two belts with distinct magma sources:

(1) The northern belt consists essentially of Cretaceous granitoids and peraluminous, S-type granites. Zircons with negative εHf(*t*), indicate the re-melting of an older crust. The sediments are Permian–Carboniferous to Late Jurassic–Early Cretaceous carbonates and volcaniclastic rocks.

(2) Late Cretaceous – Oligocene granitoids with mostly I-type (dominantly gabbroic to granodioritic) compositions dominate the southern belt. Zircons with positive εHf(*t*), indicate a juvenile source due to the partial melting of a basaltic oceanic crust with minor sediments (likely the Tethys slab). The sediments in this belt are mainly Jurassic–Cretaceous, overlain by volcanic rocks of an equivalent age (70-43 Ma) and chemistry. Volcanism apparently migrated southward with time.

The growing number of radiometric ages suggests that a period of relative quiescence separates two major magmatic stages. The significance of this duality is still in discussion.

(1) The main stage is Late Cretaceous (ca. 113–80Ma), ending with adakitic intrusions.

(2) The second episode is early Paleogene (ca. 65–46Ma) with ~~a~~ culmination around 50 Ma. The ca. 50 Ma magmatic crisis is speculated to represent slab break-off.

Geochemistry indicates that post ca. 35 Ma rocks include ultra-potassic, adakitic, and shoshonitic volcanism and NS trending dikes (ca. 23-8 Ma). In the light of temporal relationships, these rocks are related to post-collision, E-W extension. Geochemistry suggests also that these late magmas mixed mantle-derived and felsic lower crust-derived melts, perhaps the molten Indian crust subducted below the Lhasa Terrane in Miocene times.

Metamorphism

Metamorphism of the rocks intruded by the Transhimalaya plutons is heterogeneously distributed. The regional grade is usually very low grade to greenschist facies. High-temperature - low-pressure granulite facies assemblages (andalusite - cordierite - garnet - spinel) occur at the contact between metapelites and intrusive gabbros.

Structures

Polyphase deformation dominates the southern part of the Lhasa Terrane. In particular:

- Isoclinal F_1 folds have a weak and axial planar S_1 foliation bearing a north-south stretching lineation. The intensity of the F_1 fabric and metamorphism increases towards the Yalu Tsangpo suture. This deformation gradient is ascribed to north-dipping subduction of the Tethys oceanic lithosphere while calc-alkaline magmatism of the Transhimalaya Belt took place possibly along a continent-ocean margin, leaving remnants of continental Precambrian crust to the north and of (Triassic?) oceanic crust to the south. This event affected Lower Cretaceous sediments.
- F_2 upright folding with fanlike S_2 cleavage is pervasive and locally more pronounced than the F_1 fabric. F_2 structures represent a period of continuing shortening, part of which between Transhimalaya intrusions. This folding/intrusion association is compared to an Andean-type orogen that included a retro arc thrust belt and foreland basin before the continental collision.

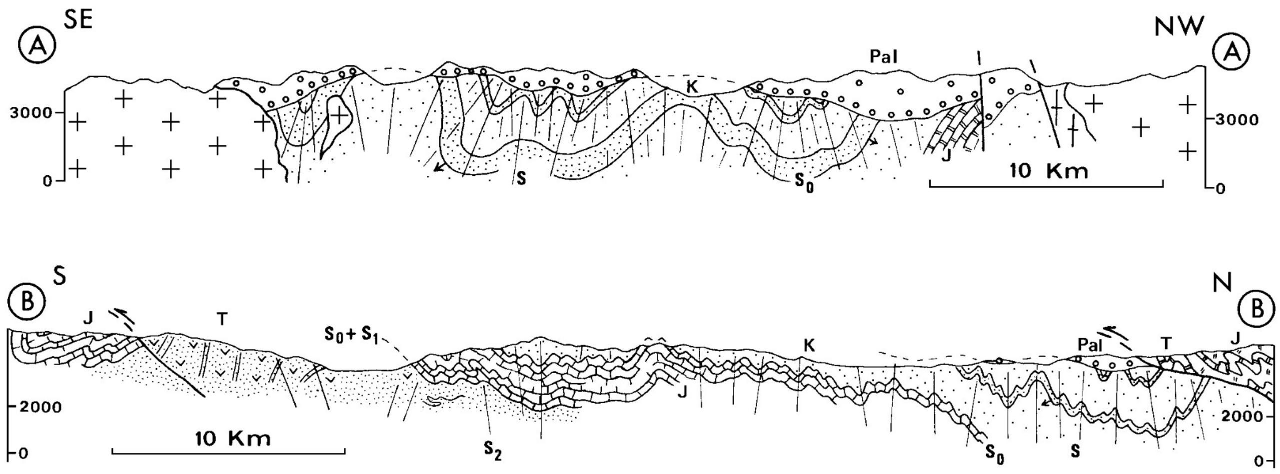


Fig. 6. Detailed cross section in the Lhasa block (situation on Fig. 2). Pal = Paleocene, K = Cretaceous, J = Jurassic, T = Triassic. Arrows indicate bottom of layers.
nach Burg *et al.* (1984) *Eclogae geol. Helvetiae* **76/3** 643-665

- Emersion and erosion by latest Cretaceous times truncated F_1 and F_2 structures. The unconformable Paleocene has undergone minor shortening (ca. 10%) with low amplitude and several kilometers wavelength undulations. Low-angle reverse faults with less than a few kilometers displacement cut in place 10 Ma-old lava. This indicates that significant crustal shortening (nearly 50%) was completed here by Palaeocene times, before the collision with India.

Geological history

Paleoelevation reconstruction using oxygen isotopes from several sedimentary formations suggests that the magmatic arc had reached ca 4500 m elevation in Paleocene-Early Eocene times. Altogether, the tectonic and paleotopography history suggests that the continental margin of Asia underwent crustal thickening, elevation gain, and erosion before the India-Asia collision. Arc magmatism stopped in Eocene times, presumably reflecting the time of the collision and the cessation of the subduction of oceanic lithosphere.

Great backthrust

Conglomerates intercalated with red shales, sandstones, and local basaltic and ignimbritic flows lay unconformable on the southern Transhimalaya Magmatic Belt. Southward draining delta, braided-river, and alluvial fan systems deposited the narrow and discontinuous occurrences of Late Oligocene - Early Miocene (ca. 26 – ca. 15 Ma) sequence. Northwards and westward draining systems developed from 19 to 15 Ma. Eastward flowing rivers established at ca 15 Ma laid conglomerates perhaps as late as the Early Pliocene (ca. 5 Ma). The modern Tsangpo River is perhaps inherited from that system. These deposits are similar to the Indus Molasse in Ladakh and the Kailas regions. Suture-parallel, north-verging folds with a weak, steep dipping cleavage are related to the near-vertical to south-dipping fault traced along the southern margin of the Lhasa Block. Striations on the fault plane and related fractures indicate dextral strike-slip faulting before northwards backthrusting in Mid-Miocene times. This major fault zone has overprinted the presumably south-verging, primary features of the suture where Indian units are in direct contact with the Transhimalaya lithologies.

Tsangpo Suture: The oceanic domain

The narrow (generally < 15 km) Yalu-Tsangpo Suture separating the Indian and Eurasian Plates in South Tibet is traditionally traced along the ophiolite sheets. Three rock subunits represent the hanging-wall plate of the suture. They are, from north to south 1) forearc turbidites (the so-called Xigaze series, after the second city of Tibet) 2) ophiolites, and 3) deep-sea sediments.

Forearc turbidites

The northern section of the Xigaze series is composed of a virtually unmetamorphosed and volcano-plutonic turbidite sequence deposited from early Cretaceous to Maastrichtian times (115-65 Ma). Interlayered limestones are paleontologically dated Late-Albian. Late Cretaceous conglomerates with pebbles from the Transhimalaya plutonic and volcanic rocks attest for topographic growth and deep erosion of the already thickened crust of the Andean-style margin on the Lhasa Terrane. Shallow marine, Paleocene to lower Eocene limestone, volcano-clastic sediments and volcanic tuffs stratigraphically cover the Cretaceous turbidites. Marine sedimentation ceased at about 50 Ma, giving way to continental, molasse type deposits in a narrow, Oligocene to Miocene depression. Detrital chromium-rich spinel of ophiolite affinity (TiO_2 generally < 0.1 wt%) appeared during the Paleocene (65 to ~55 Ma).

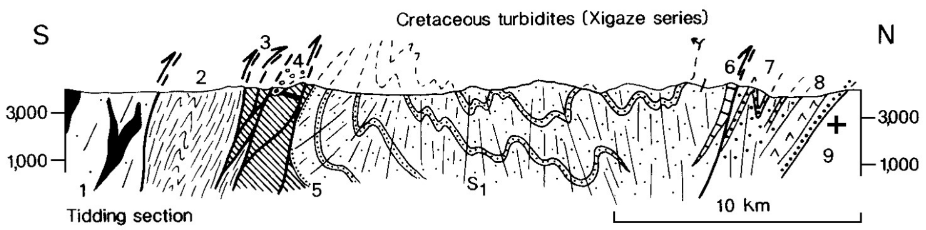


Fig. 3 Tidding cross-section. 1, Late alkaline gabbros intruded into north Tethyan Jurassic calcschists; 2, radiolarites; 3, ophiolites; 4, Oligo-Miocene (Liuqu conglomerate for the Academica Sinica[32]) conglomerates unconformable onto northward dipping thrusts in the ophiolites; 5, stratigraphical contact between Albian–Cenomanian cherts and pillow-lavas; 6, orbitolinid-bearing limestones (Aptian–Albian); 7, Eocene(?) conglomerate (pebbles >50 cm) interlayered with 8, ignimbritic and basaltic flows unconformably lying on calc-alkaline granodiorite (8). S_1 cleavage of the Xigaze series. The arrows indicate the younging direction.

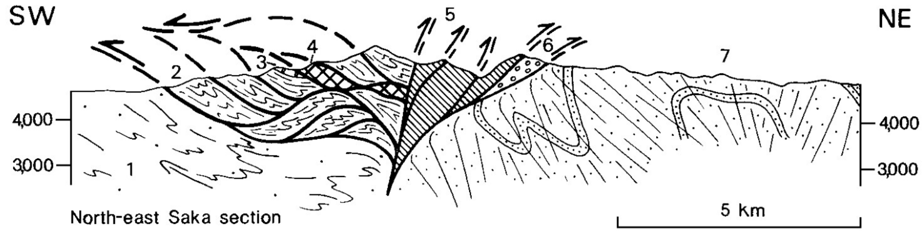
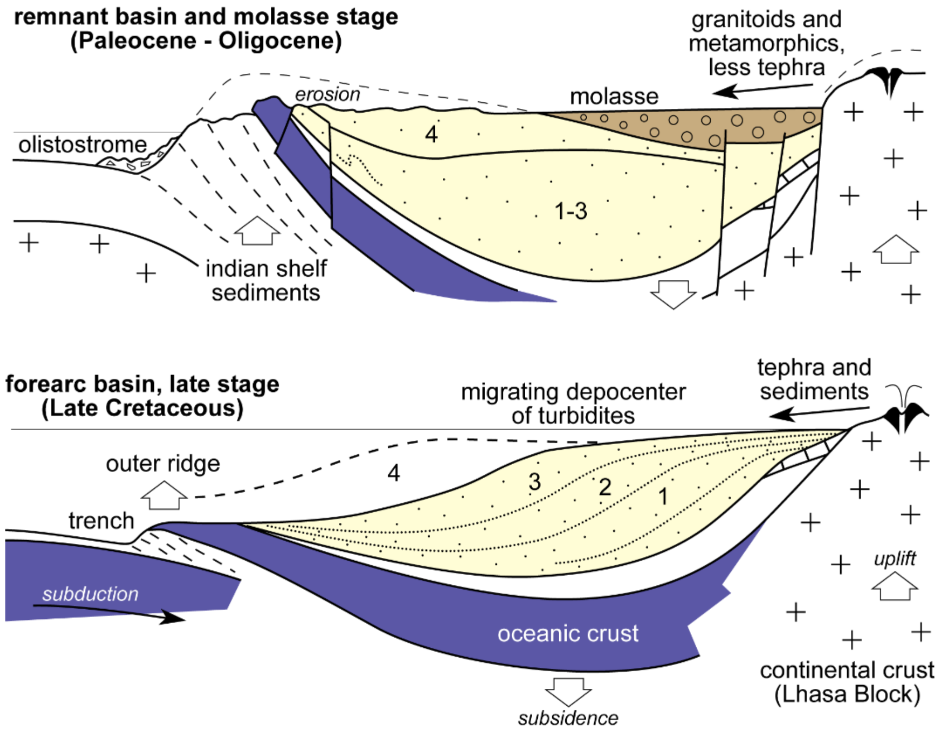


Fig. 4 North Saka cross-section. 1, North Tethyan sediments with isoclinal folding and subhorizontal S_1 cleavage. 2, Radiolarite slices containing recrystallized limestones and imbricate (3) with, basalts and tuffs (4), ophiolites (5) backthrusted onto, Oligo-Miocene (Liuqu) conglomerates (6) and Xigaze series (7).

nach Burg & Chen (1984) *Nature*, **311**, 219-223

The Xigaze sediments represent an upward-shoaling forearc basin lying on the plutonic belt to the north and the ophiolites to the south. Sedimentation started with the Early Cretaceous (ca. 130- 115 Ma) deep-water tuffaceous chert and siliceous mudrocks with Albian-Cenomanian radiolarites forming the sedimentary cover of pillow basalts of the adjacent ophiolite and continued as slope, shelf, and eventually deltaic and fluvial deposits from the Late Cretaceous onward (post ca. 75 Ma).



The Xigaze forearc basin in hypothetical N-S cross-sections
after Einsele *et al.* (1994) *Sedimentary Geology* **90**, 1-32

These several-kilometer-thick series appear within a large east-west trending synclinorium shortened by 40-65% after the Early Cenozoic with dominantly south-verging, tight-to-open folds, a steep dipping cleavage, and no metamorphism. This relatively simple structure may result from the high strength of the underlying ophiolite. Additional, undefined amounts of shortening were involved in thrusting below and backthrusting over the Lhasa Terrane.

The basin is squeezed between backthrusts along both its northern and southern boundaries. Local structures are associated with Post-Oligocene-Miocene backthrusting on both sides of the synclinorium. In Ladakh, similar associations of the same age occur in the Dras formation where calc-alkaline lavas overlie oceanic basalts.

Ophiolites

Thin sheets of ophiolite and deep water sediments (radiolarites) occur discontinuously for nearly 2500 km along the Tsangpo suture. They have preserved a bulk normal polarity. Where they are absent, only backthrusts and strike-slip faults (locally marked by alignments of geysers) are seen.

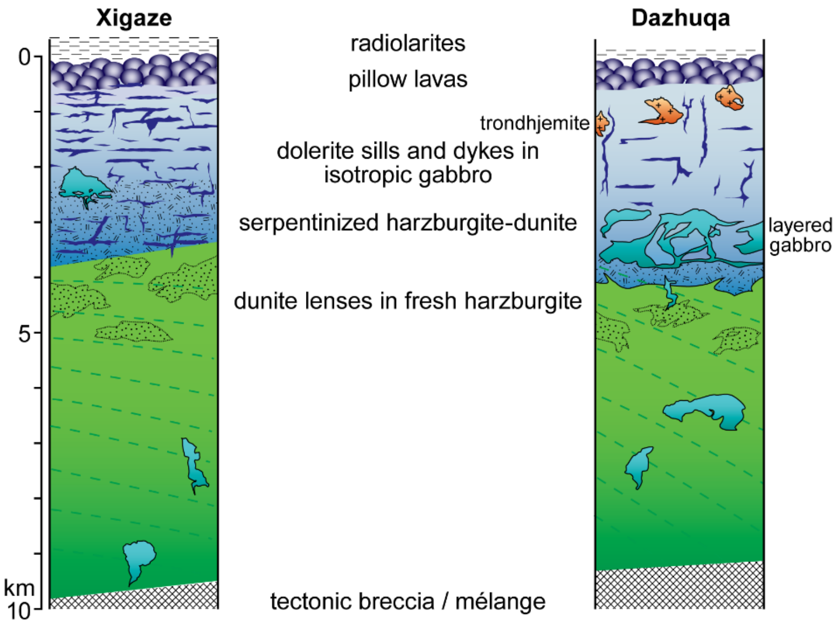
Two ophiolitic successions of different ages, petrography, and geochemical affinity are described. The older represents an island arc succession, the younger represents the supra-subduction oceanic floor. These ophiolites have been thrust southward for as much as 80 km from the suture over the Tethys sediments. Remnant klippen partly represent Cretaceous (ca 125 Ma) seamounts that existed in the Tethys Ocean. The related volcanism may be evidence for the thermal erosion of the supra-subduction oceanic lithosphere.

Island arc

Island arc igneous and volcaniclastic rocks (boninitic pillows, basaltic-andesitic breccias and dikes, dacites, rhyolites, diorites, and leucogranites) are dated between ca 160 and ca 150 Ma. They form a dismembered and overturned sequence imbricated with the forearc and the tholeiitic ophiolites. The island-arc (called Zedong Terrane) was active in Mid-Jurassic to Early Cretaceous times.

Tholeiitic ophiolites

The tholeiitic ophiolites have ages from ca. 130 to ca. 120 Ma, consistent with radiolarian biostratigraphic data from the sedimentary cover of pillow basalts. They represent a tectonically disrupted oceanic lithosphere. The ultramafic rocks were generated from a MORB-source upper mantle. They are mostly chromite-bearing harzburgites and lherzolites; dunites are scarce.



Two schematic, representative sections of the Yalu Tsangpo ophiolites in South Tibet
redrawn after Girardeau & Mercier 1988 *Tectonophysics* **147(1-2)** 33-58
and Hébert *et al.* 2003 *Geol. Soc. London Spec. Pub.* **218** 165-190

Petrology and geochemistry indicate forearc spreading ridge origin and subsequent (boninitic) alteration in the supra-subduction mantle wedge. The associated mafic rocks (lavas, dolerite dikes, and cumulate gabbros) also recorded this two-stage evolution. These arguments support the interpretation that these ophiolites formed in the forearc of the Transhimalaya magmatic arc. Forearc spreading may sign slab rollback.

Metamorphic sole and ophiolitic mélange

A discontinuous serpentinite "mélange" at the base of the ophiolite thrust sheets contains garnet-amphibolites (peak metamorphic conditions: 1.3-1.5 GPa, 750 - > 900°C) interpreted as elements of a dismembered intra-oceanic thrust sole. Zircon U–Pb results date the protoliths at 124–125 Ma. Ar-Ar ages on amphiboles span 70-130 Ma. The 120-130 Ma cooling ages are slightly younger or overlap magmatic and sedimentary ages obtained from the overlying ophiolite. This age coincidence and the high metamorphic temperatures support a model in which the subducted oceanic crust was nascent while the thrusting lithospheric mantle was still hot. In short, the subduction zone started near the spreading axis that formed the ophiolites.

More generally, low-temperature mylonites and serpentinites floor the ophiolites. Below, an ophiolitic mélange characterized by blocks of sandstone, chert, siliceous shale, limestone, basalt, mafic schist, and ultramafic rocks is interpreted to be fragments of accretionary prism and trench rocks, within a strongly deformed matrix of serpentinite, sandstone, and siliceous shale. Ar-Ar cooling ages of amphiboles from mafic schist yielded 65-60 Ma ages. Stretching lineations are north-south. Small-scale south verging folds and asymmetric boudinage structures indicate a top-to-south sense-of shear.

Deep-sea sediments

Late Triassic to Senonian radiolarites, turbidites, and locally basalt, form an imbricate thrust-stack. South-facing folds deform the early, north-south stretching lineation associated with sheath folds. These structures indicate transport from north to south during greenschist facies metamorphism. These deep-sea sediments would represent material off-scraped from the down-going slab and accreted into the subduction complex during the Late Early Cretaceous.

Indian passive margin

Three major structural and lithological zones represent different proximal-to-distal parts of the ancient passive margin of northern India. From north to south they are:

- The Tethys Himalaya.
- The High Himalaya.
- The Lower Himalaya and Indian continent.

Tethys Himalaya

Generally non- to low-metamorphic grade sediments, now situated directly south of the Tsangpo Suture, represent the former leading edge of India. Several units are identified.

Apron turbidites

The ophiolites and the radiolarites are thrust onto an allochthonous turbidite sequence with late Triassic to Liassic or Cretaceous (?) marine fossils.
Large-scale recumbent, subisoclinal F_1 folds have inverted in many places the stratigraphy. South-west verging mesoscopic and non-cylindrical F_1 folds trend N030-180 and contain an S_1 slaty cleavage formed in low-grade conditions of metamorphism. Quartz fibers and long axes of pressure fringes are parallel to the N340-030 stretching lineation equated with the transport direction. Meters thick crush zones formed under non or very low-grade conditions of metamorphism delineate the basal thrusts of these turbidites, the ophiolites, and their metamorphic sole. They cut the F_1 structures.

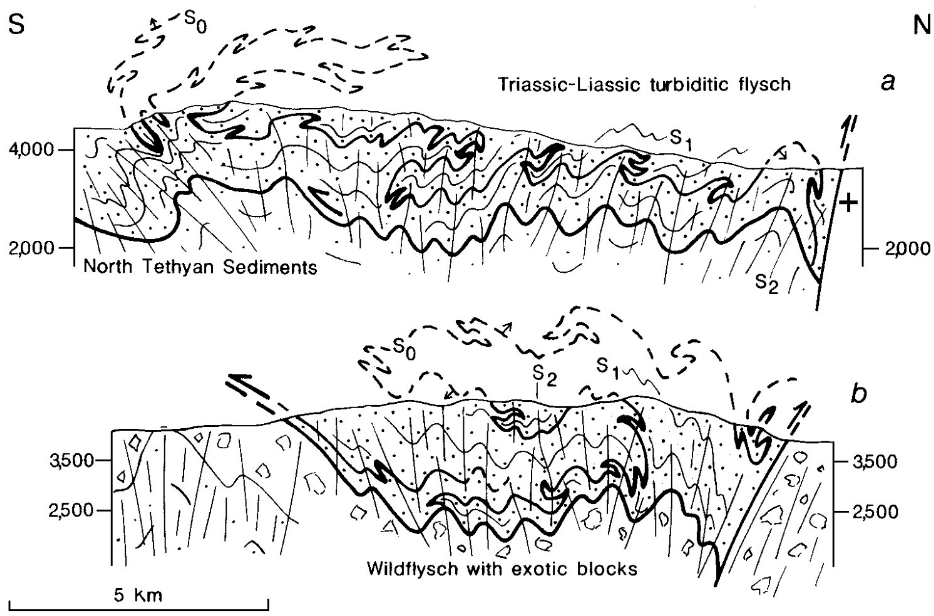


Fig. 5 Two detailed cross-sections in the Triassic–Liassic turbidite flysch. They show polyphase deformation with S_1 cleavage and S_2 crenulation cleavage. Bedding S_0–S_1 relationships and younging directions (arrow) give evidence for several kilometres inverted series. Thickening of F_1 hinges is voluntary exaggerated. Lower Cretaceous calcschists underlie the wildflysch.

nach Burg & Chen (1984) *Nature*, **311**, 219-223

Both the thrust contacts and the F_1 folds are folded about F_2 structures in various ways, as upright chevron folds (interlimb angles 110-50^o) may coexist with subisoclinal folds with rounded hinges and overturned to the south. The F_2 axes are parallel to a N060-120 crenulation lineation. F_2 folding increases in intensity northwards. Local N040-130 kinks with different axial plane attitudes represent an F_3 event and may be contemporaneous with post-F_2 movement along basal thrusts.
The Late Triassic to Late Mesozoic turbidites are attributed to the continental margin apron of India, intensely deformed during Early Paleocene southward shearing and transport. The study of detrital zircons suggests that some Upper Triassic sequences are derived from the Lhasa Terrane thus may represent the northern margin of the Tethys Ocean rather than India.

Olistostrome

An olistostrome with a black, shaly matrix is partly transgressive on the recumbent fabrics of the apron turbidites. Oldest exotic blocks are Late Permian limestones derived from the Indian continental margin or oceanic plateaux. The youngest blocks, folded before redeposition, are Maastrichtian to lowermost Paleocene Globotruncana limestones. The youngest fossils found in the matrix are Late Paleocene, which is taken as the age of the olistostrome. The various lithologies seen in the blocks attest for distinct paleogeographic environments such as the distal Indian continental margin, pelagic horsts, and oceanic seamounts (equivalent to the Oman exotics?).
This formation is folded, along with the turbidites, about the east-west trending, upright to south-facing folds, with a non-metamorphic fanning cleavage parallel to the bulk axial plane. The folding is correlated with the F_2 event with crenulation cleavage in the apron turbidite nappes.

Tethys Himalaya

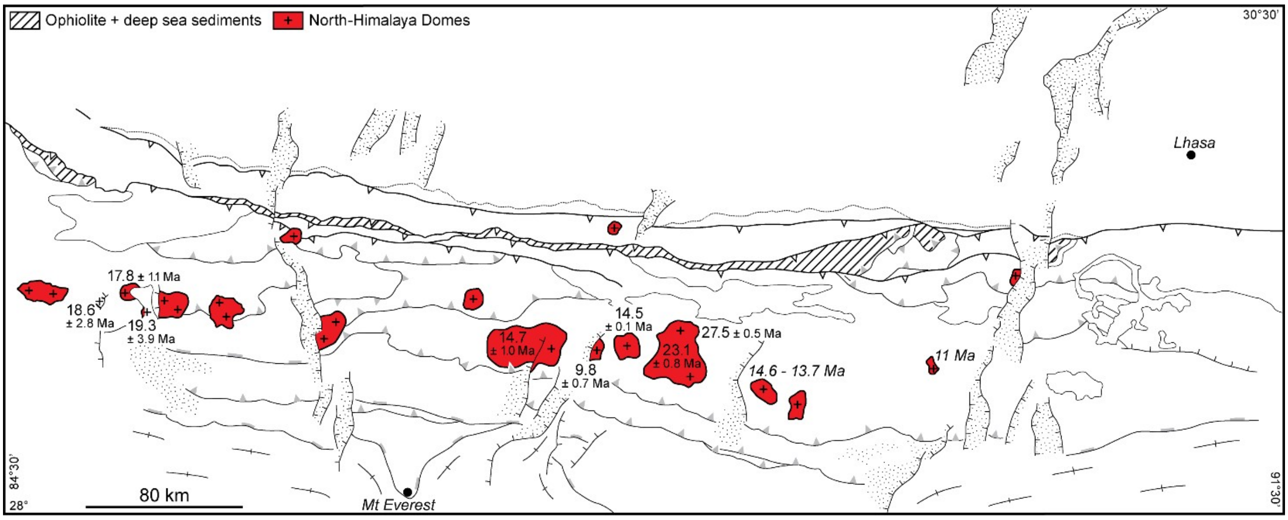
The fossiliferous Cambrian to Eocene sedimentary sequence that formed a continental shelf environment on the Indian continental margin (clastic strata, carbonates, and shales) passed northwards into a deeper water facies (distal shelf and slope pelites and turbidites). Southward propagating, imbricate thrusting, and folding commenced as the Indian continent subducted northward under the Eurasian plate. A major thrust separates the northern and southern Tethys sequences thus defining two subunits.

North Tethys sediments

The north Tethys sediments show downward increasing metamorphism from regional low grade to localized staurolite kyanite schist. In the structural section, the lowest rocks are Lower Ordovician orthogneiss underlying metamorphosed rocks and recrystallized Permian limestones. Overlying the Permian, the Mesozoic includes a thick and monotonous calcareous turbiditic sequence of up to Maastrichtian age involved in polyphase deformation. The Late Cretaceous pelagic environment seems to have disappeared from east to west. Undated basic dikes and sills suggest continental rifting.
The first major structural event generated large-scale recumbent folds overturned to the south-west and a well-developed slaty cleavage with an N350-040 stretching lineation. The bulk strain increases northwards towards the Yalu Tsangpo Suture and upwards under the ophiolitic and associated nappes. The Late Palaeocene olistostrome is unconformably lying on these structures.
The structurally deeper metamorphic rocks show a comparable polyphase deformation with a downward increase in the intensity of the fabric contemporaneous with the intermediate pressure metamorphism. The problem arises from the radiometric ages of micas as young as ca 10 Ma (Ar/Ar method) and hence inconsistent with the Maastrichtian-Palaeocene age of the recumbent folds previously described. Both the deformation and the metamorphism of the lower rocks may be associated with a ductile thrust zone whose deformation front does not reach the upper part of the pile but instead produces the thrust and locally a trailing imbricate fan to the south between the northern and southern Tethyan sediments. The juxtaposition of two areas having comparable fabrics, though different ages, is one of the striking features of the northern subunit. This is a consequence of the heterogeneity of the shear deformation during thrusting, which affects areas close to the thrust plane and preserves the sequence away from the thrust.

North Himalaya Domes

A long antiform occurs, about 50km south of and parallel to the suture. A string of domes of Proterozoic (ca 1800 Ma) basement gneiss with small volumes of 46-30 Ma granitoids and late Miocene (19-7 Ma) two-mica granites (collectively called North Himalayan Belt) stretches along this antiform. Gneiss and granitoids provide evidence for increasing metamorphic pressure and temperature (up to 0.7-0.8 GPa for ca 650°C) at 45-35 Ma and protracted melting of the Indian-derived middle crust until the intrusion of the late Miocene two-mica granites. The domes exposing mid-crustal rocks deformed, metamorphosed, and melted during the Himalayan orogeny are attributed to thrusting, subsequent extension or diapirism, or a combination of all of these mechanisms.



Ages of granites in the North-Himalaya Domes (Italic= Ar-Ar age)

South Tethys sediments

The southern Tethys sediments range in age from Cambrian to mid-Eocene without any significant unconformity. They are identical to the10-km thick platform-type series known further west in Ladakh. The sediments consist of mixed clastics and carbonates up to early Permian and mainly shelf carbonate in the late Permian to early Eocene. They represent nearly continuous deposition of shallow-water, marine strata over the stable Indian shelf. In more detail, it is a composite of two superposed rift-to-passive margin sequences: the early Paleozoic to Carboniferous one that accumulated in the Paleotethys Ocean until the breakup of Pangea, and the Permian to the Cretaceous southern passive margin of the Tethys Ocean.

In contrast to the deeper water North Tethys sediments, the South Tethys sediments are non-metamorphosed and have suffered one main phase of east-west trending box and chevron folds that can be followed for tens of kilometers along their axial traces. The intensity of shortening decreases southward up to the faulted contact between the southern Tethys sediments and the metamorphosed schists and gneiss of the High Himalaya.

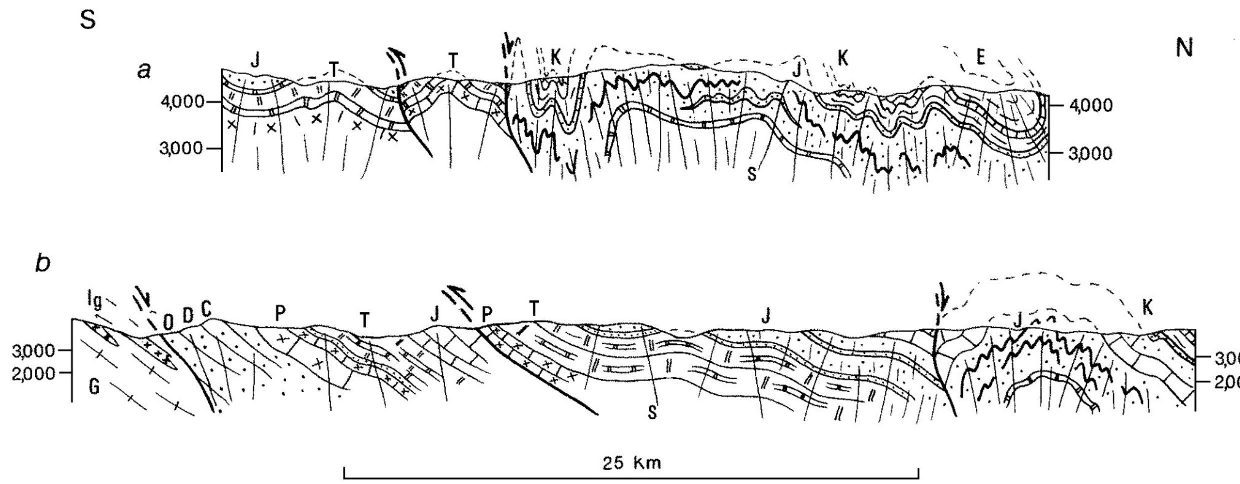


Fig. 6 Two examples of section across the south Tethyan sediments: G, gneisses of the Main Central Crystalline Sheet intruded by 1g, Miocene leucogranites; O, Ordovician; D, Devonian; C, Carboniferous; P, Permian reef limestones; T, Triassic; J, Jurassic limestones, shales and sandstones; K, Cretaceous calcschists and limestones; E, Eocene nummulite-bearing limestones; S, weak spaced cleavage.

nach Burg & Chen (1984) *Nature*, **311**, 219-223

Note that there was no pre-alpine tectonic episode and that youngest marine sediments are Priabonian (38-34 Ma) ca. 10 Ma younger than collision, if it is Early Eocene.

Indian Continent

Convergence between India and Eurasia continued after their initial contact, up to the present (about 5 cm/yr.). Several hundred kilometers of shortening, and possibly as much as 1500 km took place between the Tethys Himalaya and the Indian craton since the Paleocene. Large-scale thrust imbrication with the propagation of shortening towards the foreland absorbed a major part of this intracontinental shortening. The resulting Himalaya is the fold-and-thrust wedge formed within the Indian continent. It consists of three thrust-bounded units that extend all along the belt, from top to bottom:

- The High Himalaya is a southward-extruded wedge of high-grade metamorphic gneiss intruded by variably deformed Miocene leucogranites. It is bounded by a normal fault on the top and the largest Himalayan thrust within the Indian plate at the bottom (the Main Central Thrust = MCT). The MCT accommodated up to 250 km of thrust movement.
- The Lower Himalaya is mostly composed of Precambrian to Mesozoic low-grade metasediments. Its bottom is another important, north-dipping intraplate thrust, which is still active: the Main Boundary Thrust (MBT).
- The Indian Foreland (called Sub-Himalaya) and the adjacent Gangetic foredeep.

Seismic studies and the rate of southward advance of the foreland basin indicate that the Himalayas currently absorb10 to 25 mm/yr. of shortening. The Himalayan topographic front, i.e., the zone where the average elevations relatively abruptly change from about 2 km to about 5 km, defines a small circle on a sphere and closely coincides with the MCT. This coincidence suggests a genetic relationship between the bending and underthrusting of the Indian subcontinent beneath the Himalayan blocks and the formation of the High Himalaya just north of the MCT.

High Himalaya

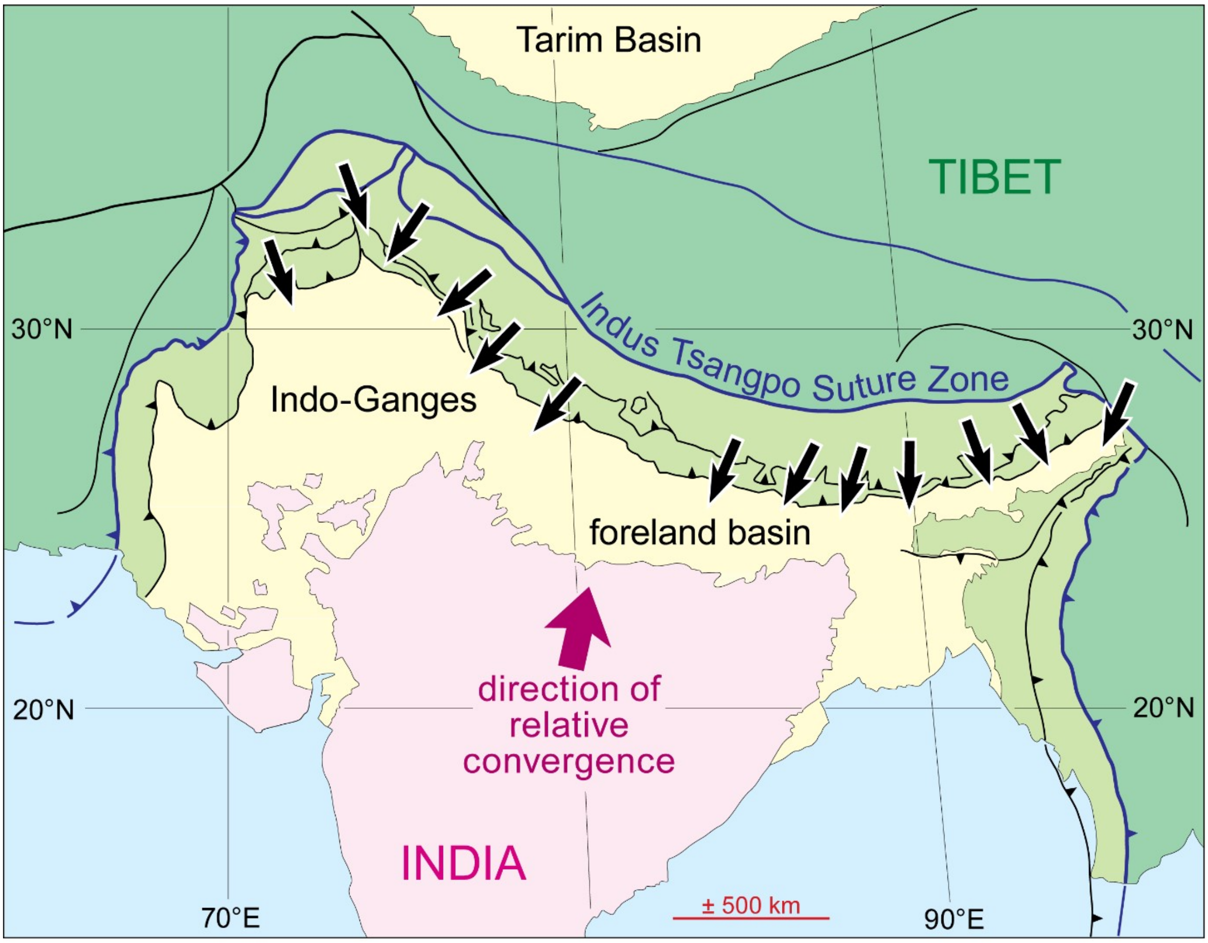
The Himalaya consists of a north-dipping pile of tectonostratigraphic units that isotopic data qualify as late Proterozoic to early Paleozoic gneiss, migmatites, and schists of the upper continental crust of India. Tethyan Mesozoic sediments, originally situated on the northern margin of India, lay locally on the gneiss and schists.

Orogen-parallel normal fault

The contact juxtaposing the hanging wall sediments of the Tethys Himalaya on schists, gneiss, and Miocene leucogranites of the High Himalayas is a north-dipping normal fault: the South Tibetan Detachment (STD). It is responsible for northward shearing of the leucogranites and superposition of unmetamorphosed sediments onto staurolite-garnet schists. To the east, steeply dipping, brittle normal faults separate Jurassic schists from gneisses indicating several kilometers down-to-the-north vertical movement. Ductile normal faulting, dated from 24 to 11 Ma, perhaps lasted to the Pliocene. Normal faulting is contemporaneous, for at least part of its history, with structurally lower, southward thrusting on the MCT.

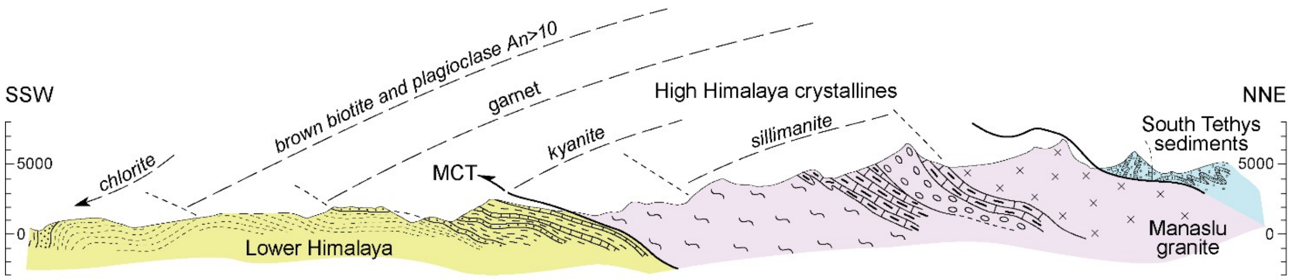
Gneiss and inverted metamorphism

Rocks of the Indian continental shield and its Pre-Paleozoic sedimentary cover underwent high-grade regional metamorphism and intrusion by leucogranites during the Cenozoic formation of the mountain range. The gneiss and migmatites bear evidence of multiple deformation and recrystallization events ascribed to the Himalayan southward shearing, with the dominant fabric defined by amphibolite facies assemblages. The stretching and mineral lineations are roughly normal to the trace of the MCT all along the belt and parallel everywhere the shear direction defined by ubiquitous kinematic indicators. This fabric indicates the transport direction of the thrust sheet. However, the range-scale radial pattern implies that the local motion does not correspond to the average plate convergence.



Distribution of senses of shear in the High Himalaya compared to the plate convergence
simplified after Brunel M. (1986) *Tectonics*, **5**, 247-265

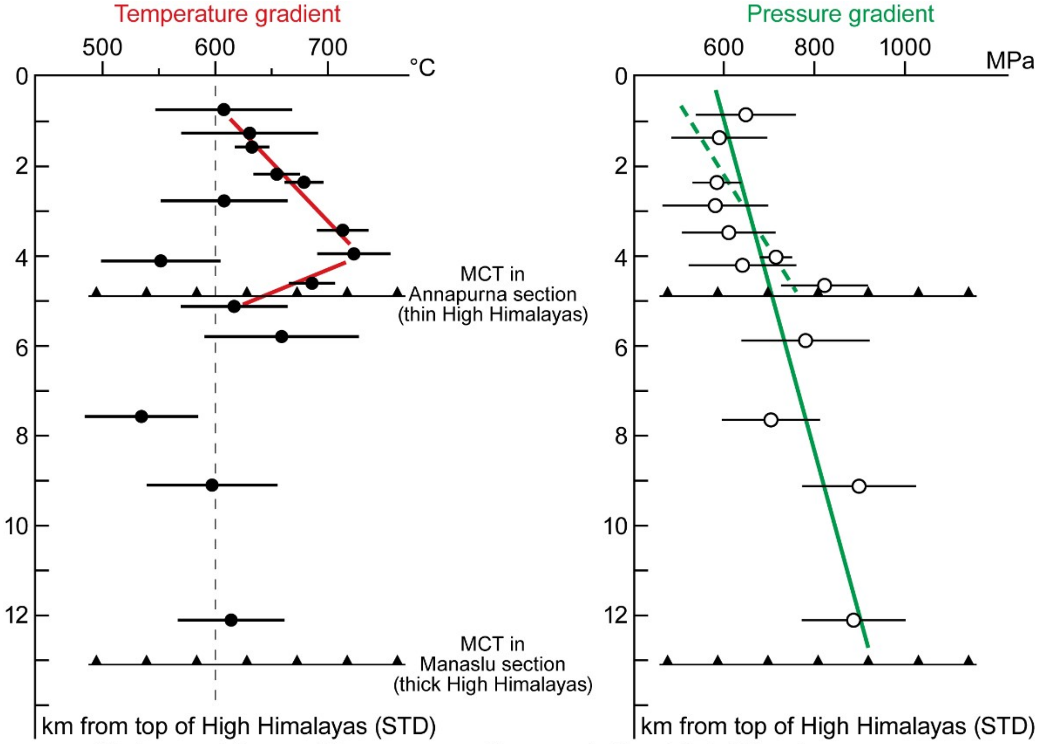
The 2 to 10 km thick thrust sheet is a deeply rooted crustal slice whose bottom consists of biotite-garnet-kyanite micaschists and the middle and upper parts of sillimanite-kyanite, K-Feldspar assemblages and sillimanite-cordierite-garnet metapelites.



Simplified geologic and metamorphic cross section through the Himalaya of Central Nepal
after Le Fort 1986 *Geological Society of London, Special Publication* **19**, 159-172

The polyphase, metamorphic history implies three stages:

1) The oldest metamorphic record is inferred from Lu/Hf garnet ages (ca 55 Ma) and ca 45 Ma U-Pb ages measured on zircons. Ages of zircons in strongly altered eclogites (670°C->1.5 GPa) found towards the top of the gneiss pile are 23-14 Ma, which is at odds with the 45-35 Ma (perhaps younging eastward) monazite and zircon ages of the surrounding gneiss recrystallized under Barrovian-type metamorphic conditions (550-680°C - 0.8-1.4 GPa). This metamorphic stage took place during the burial of the Indian crust following the continental collision.
2) Early exhumation occurred at ~~a~~ higher temperature (650-800°C) and lower pressure (0.4-0.7 GPa) during the Miocene (30-18 Ma). This is the dominant metamorphic event, which obliterated most of the evidence for the earlier, higher-pressure event.
3) Further exhumation occurred later in the Miocene (20-15 Ma U-Pb ages of sillimanite grade rocks) at a lower temperature (500-700°C) and pressure (0.2-0.4 GPa).

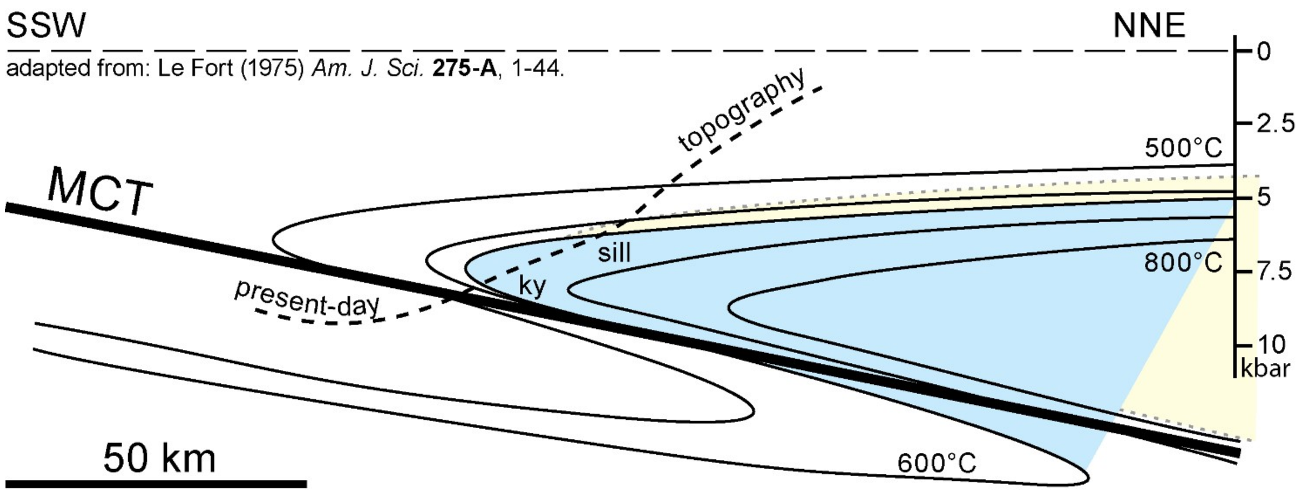


Metamorphic conditions across the crystalline High Himalayas
synthesis after Pêcher 1989 *Journal of metamorphic Petrology* **7(1)** 31-41

The Barrovian metamorphic structure is important on a conceptual point of view. The gneiss pile above the MCT records metamorphic temperatures from ca. 550°C near the MCT up to 700°C in the overlying migmatites. Corresponding pressures decrease upward. Conversely, the metamorphic sequence is inverted in the footwall rocks, with a continuous decrease in metamorphic grade and temperature downward: The sillimanite-bearing migmatites and gneiss occur above a narrow zone of kyanite-bearing schists, in turn above successive staurolite, garnet, biotite, and lower grade metamorphic zones.

Three classes of models explain such inverted metamorphic zones:

- Post-metamorphic isograd inversion: Late thrusts or recumbent folds deformed pre-existing isograds and produced the apparent thermal inversion.
- Syn-metamorphic isograd inversion: Large scale, foreland-directed thrusting brought a hot metamorphic pile (rocks that were once > 650°C) overriding and metamorphosing underlying sediments that never reached such temperatures.
- Syn-metamorphic inversion of isotherms: Viscous heating associated with the MCT produced an inverted thermal structure.



Thrusting a several tens of kilometres thick pile of hot rocks brings and transmits heat to the underlying colder rocks while the thrust units cool down. This is compared to the ironing effect.
The isotherms in profile display a typical Z-form over ca. 30 Ma.

The last two processes suggest that downward conductive heating of the underlying Lower Himalaya from the High Himalaya gneiss is coupled with the cooling of the High Himalaya hanging wall. In that case, inverted geotherms developed during slip on the MCT (the ironing effect). Dating of the metamorphic history, which follows a classical, clockwise Pressure-Temperature-time loop, indicates that thrusting exhumed the sequence rapidly enough to preserve the inverted metamorphic gradient. Synmetamorphic shearing evolved at 20-25 Ma. Burial of the footwall rocks ceased at ca. 10 Ma but further reactivation lasted into the Late-Miocene (5-8 Ma).

Leucogranites

Melting of the continental crust generated the 25 to 12 Ma tourmaline-muscovite-garnet leucogranites. These leucogranites define a belt of small plutons, stokes, and dike networks in the upper levels of the High Himalaya. Their shear fabrics give evidence for the normal faulting on top of the High Himalaya. Residual and/or peritectic andalusite along with sillimanite and biotite inclusions in cordierite indicate that melts formed by dehydration melting of biotite at T = 660-700 °C under low-pressure conditions (P < about 0.4 GPa). Mineral ages between 18 Ma and 15 Ma indicate exhumation at a rate of 0.7 to 0.8 mm/yr.

Main Central Thrust

The amphibolite facies High Himalaya gneisses have been thrust over lower grade (greenschist) metasedimentary, metavolcanic, and metagranitoid rocks, including Miocene metasediments, along the MCT. The MCT is a north-dipping ductile zone that was intermittently active between 22 and 5 Ma accumulating a minimum 140 km throw, and perhaps as much as 300-600 km. Despite large uncertainty, intra-plate, continental subduction of southern India along this contact characterizes the Himalayan orogeny proper.

Exhumation problem

The concomitance between the STD and the MCT involves the southward movement of the gneiss in between. Several kinematic and mechanical models have attempted to explain this orogenic process.

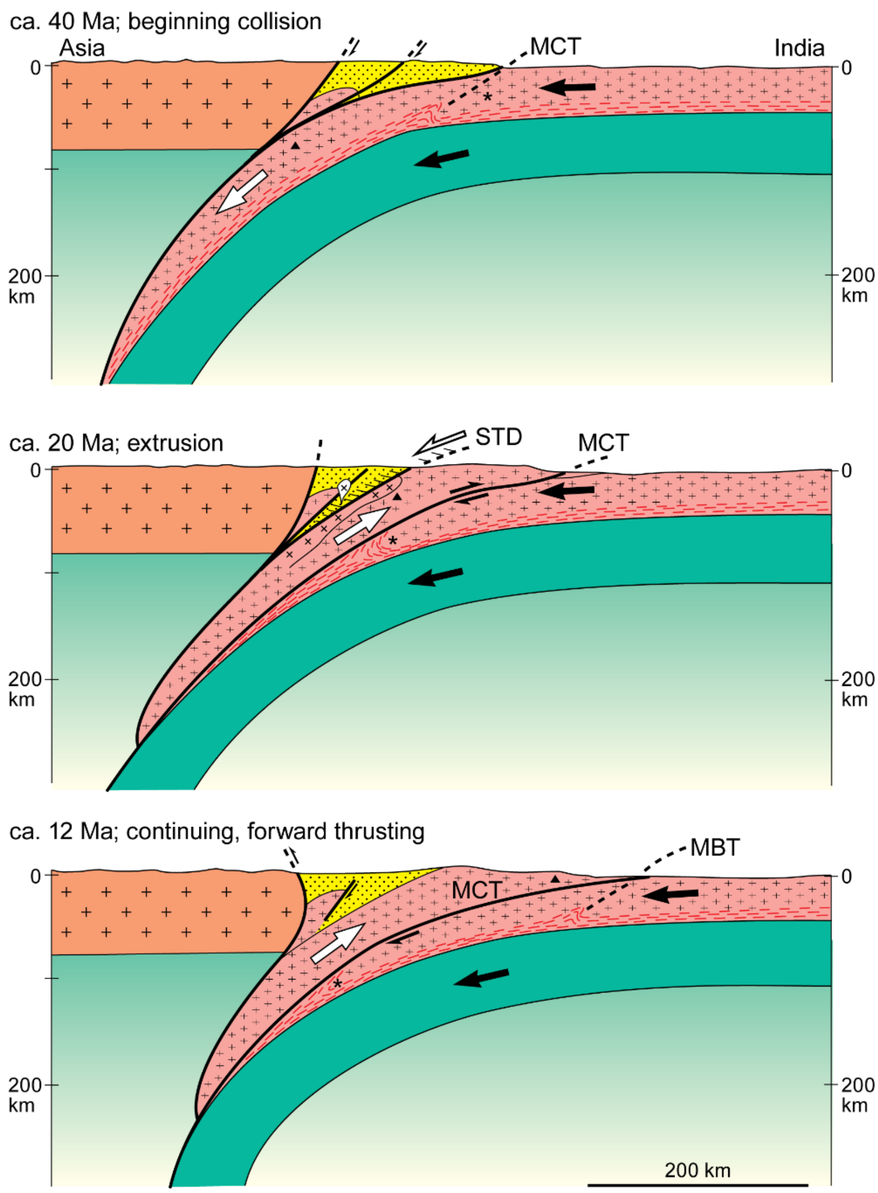
Gravity-driven extrusion

Initial models involved wedge-shaped High Himalaya gneiss sequences with the STD and the MCT merging at depth. Two interpretations pictured the forward extrusion of this gneiss wedge.

- Analog modeling of continental subduction suggests gravity-driven, upward extrusion of a continental wedge subducted to depths where its buoyancy overcomes the crustal strength. The wedge moves upward and forelandward along a new, crustal-scale thrust (MCT) while its upper boundary records a normal sense of movement (STD).

Evolutionary model of the Himalayas

after Chemenda *et al.* 2000 *Earth and Planetary Science Letters* **174**(3-4) 397-409



- Mechanical modeling attributes extrusion to gravitational collapse in response to the extreme topographic gradient along the southern margin of the Himalayas in Miocene times. This extension would affect the upper crust only.

Mid-crustal channel flow

Some mechanical models propose a laterally continuous, low viscosity, mid-crustal "layer" of partially molten gneiss flowing southwards from beneath the Tibetan Plateau between sub-parallel STD and MCT and eventually extruding towards the Himalayan range front. In these "channel flow" models, the horizontal gradient in lithostatic pressure between the Tibetan Plateau and the Himalayan front provides the driving force. Efficient and focused erosion (i.e. denudation) on the southern slopes of the Himalayas, along the high relief between the plateau and the orogenic front, initiates exhumation of the gneiss from mid-crustal depths to the surface.

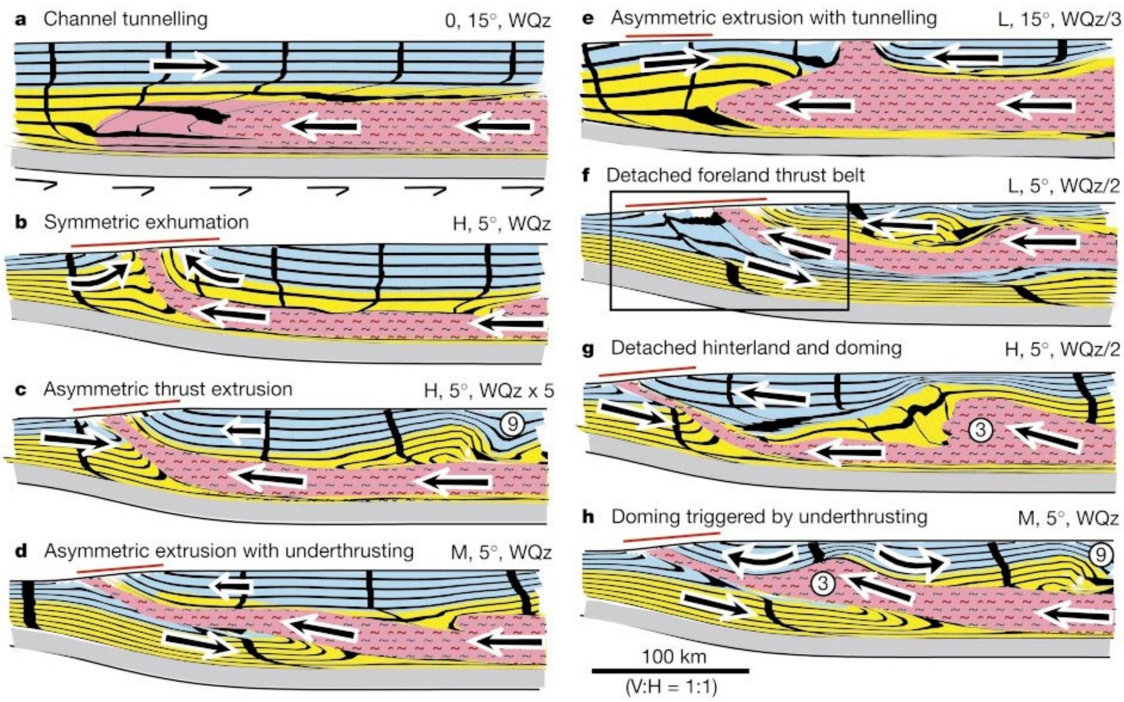


Figure 3 Model channel flow modes and exhumation/extrusion styles. Properties as for model 2 except for upper-crust rheology (blue; $\phi = 5°$ or 15°; WQz, wet quartzite flow law[14], effective viscosity scaled as shown) and erosion rate, which ranges from 0 to low (L, <0.4 cm yr $^{-1}$), moderate (M, 0.4–1.4 cm yr $^{-1}$), or high (H, >1.4 cm yr $^{-1}$) where surface slope is maximum for the time step shown. **a**, Channel tunnelling, no denudation[12,13]; **b**, symmetric exhumation (models 1, 2); **c**, asymmetric thrust extrusion; **d**, asymmetric extrusion with underthrusting; **e**, asymmetric extrusion with tunnelling; abandoned extrusion zone translated into plateau; **f**, detached foreland fold-thrust belt; box outlines region similar to that shown in Fig. 4; **g**, detached hinterland followed by doming and extension; **h**, dome triggered by underthrusting. Colours as for Fig. 1; red line above model surface indicates denudation front; pink indicates melt-weakened channel flow zone (strongly deformed grid removed for clarity); arrows show flow direction; (3) indicates structures resembling north Himalayan gneiss domes[19]; (9) indicates suture.

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Lower Himalaya

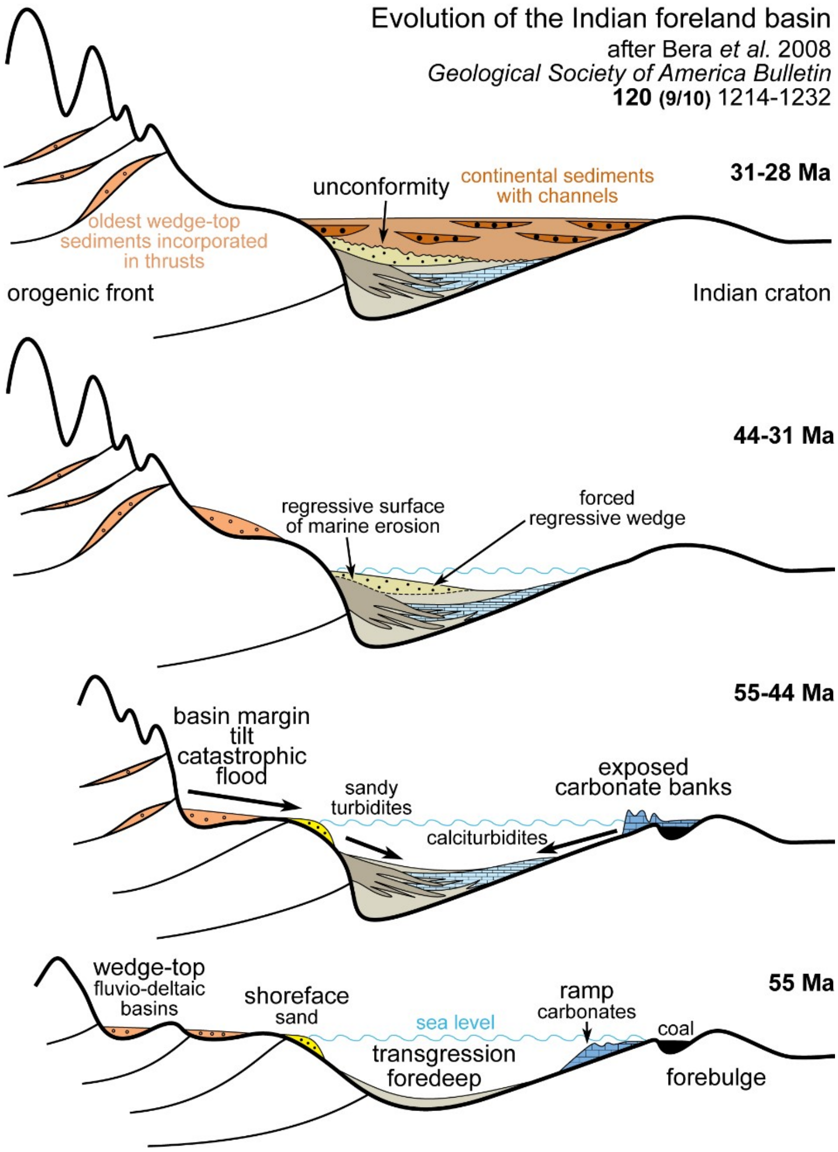
The Lower (or Lesser) Himalaya is bounded to the north by the MCT and to the south by the MBT (Main Boundary Thrust), which initiated in late Miocene time, when the thrust belt front propagated southward into the foreland region. The MBT is still active and focal mechanism solutions define a simple planar zone from about 10 km and 20 km depth with an apparent dip of 15°N.

The Lower Himalaya is a low-grade assemblage of a 20 km thick, imbricate thrust pile of mid-Proterozoic to Cenozoic sequences originally deposited on the Indian continental crust. Cambrian stromatolitic dolomites record the epicontinental marine transgression on 1.5 - 2.2 Ga old gneisses. ~~and~~ 500 Ma old granitoids ~~that~~ have been deformed into orthogneiss. Metasediments are lower grade yet similar lithologies as those of the High Himalaya but with no Cenozoic igneous activity. Much of the Phanerozoic shelf sequence (shales, sandstones, and limestones) is of Gondwana type but does not correlate with the sediments of the Tethys Himalaya. Thermochronologic studies suggest that before 13 Ma most of the Lower Himalaya rocks were located either beneath a paleo-foreland basin or beneath MCT-related nappes. Late Oligocene to Early Miocene fluvial formations registered the emergence of the Himalaya Mountains. Most of the Himalayan thrusting system in the Lower Himalaya developed during the last 15-10 Ma.

Indian Foreland

The tectonic loading of the northern edge of the Indian subcontinent during the growth of the Himalaya created the large Indo-Gangetic flexural basin, which extends along the entire southern side of the mountain range. The ~10-km-thick, mostly non-marine, fluvial, clastic sediments of this basin have preserved the denudation records of intimate interplay between tectonics and erosion of the India-Asia collision and the subsequent development of the Himalayas.

The development of the foreland basin begins with the initiation of the continent-continent collision at 55 Ma. The oldest strata are transgressive marine Latest Paleocene–middle Eocene sandstones (5741.5 Ma). They predominantly recycled an ophiolitic and a volcanic sedimentary source and contain ca. 50 Ma detrital zircons. Diachronous arrival of ophiolitic to low-grade metamorphic detritus in the foreland sediments from Pakistan to Bangladesh is consistent with progressively younger closure of Tethys, from the latest Paleocene in the west to Eocene or even later in the east.



In Oligocene-Miocene times alimentation from suture rocks drastically reduced while the metamorphic grade of detrital grains increased from very low to low grade. In the latest Oligocene, the embryonic thrust belt partially separated the suture zone from the Himalayan foreland basin. Himalaya-derived detritus appear sometime between 35 and 40 Ma in the east like in the west of the basin. The occurrence of metamorphic grains coincides with the timing of displacement along the Main Central Thrust. As convergence and the subsequent tectonic activity went on, the resultant flexural depression migrated progressively southwards and was filled by a 5 to 8 km thick continental and terrigenous sequence derived from the rising/being eroded Himalayas and dated mostly from the Miocene.

These synorogenic molasse conglomerates siltstones and shales (often termed Siwalik or Sub-Himalaya sediments) were laid down in giant, interfingering alluvial fans that lap onto the Indian Shield. In detail, the discontinuous series comprises most of the Cenozoic but there was a general lack of sedimentation during the Late Eocene and almost the entire Oligocene. This 15-20 Ma-long sedimentary gap may reflect an important change in orogenic processes. One interpretation involves the passage of the flexural forebulge migrating southward through India.

Deformation varies in space and time from tightly folded and faulted sequences to almost undeformed. Most folds and thrusts are sub-parallel to the topographic front of the Himalaya, which coincides with the MFT (Main Frontal Thrust). The bulk shortening intensity decreases southward, away from the MFT, the youngest and active thrust that places the molasse atop sediments of the Indo-Gangetic flexural basin. This basin is the present-day foredeep established upon the basement of Peninsular India. Acceleration in the molasse-sedimentation rate indicates that the MBT was first active at about 11 Ma. This is the same age as in the western Himalaya (see lecture on Kohistan), which suggests that initiation of the MBT was nearly synchronous along the entire length of the Himalaya. This interpretation is supported by the onset of erosion of the Lower Himalaya at 10-8Ma, after uplift induced by thrust tectonics on the MBT. The MFT became active in Pliocene time and truncates Quaternary conglomerates.

Geophysical structures

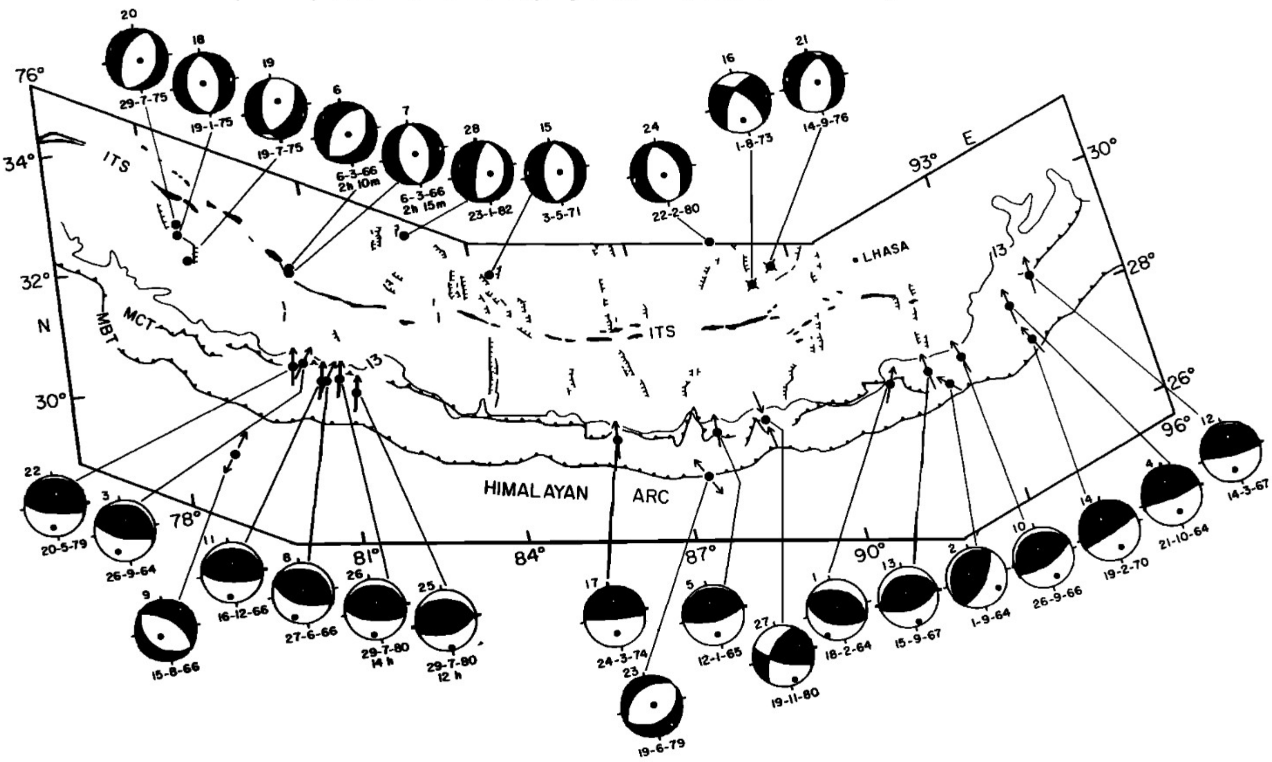
Knowledge of the deep structures is essential to understand why the High Himalaya and the suture zone have attained their impressive height.

Focal mechanisms

The Himalayas are seismically very active. During the past century, four earthquakes of magnitude > 8 have occurred in the mountain range, with a large number of small and medium-sized events. The best-located epicenters define a relatively simple, planar zone having an apparent northward dip of about 15°. Focal mechanisms indicate that it is a master thrust separating the footwall Indian continental crust from the overriding Himalayan gneiss sheet. The gently dipping fault planes exhibit slip in a sub-horizontal direction, normal to the Himalayan arc.

Ni and Barazangi: Seismotectonics of the Himalaya

(1984) *Journal of Geophysical Research* **89-B2**, 1147-1163



The presence of seismicity at 80-110 km depths in southern Tibet indicates that the upper mantle is cold enough to experience brittle deformation.

Seismic reflection

Geophysical imaging has extended surface geological studies to depth.

Crustal structures

Seismic reflection profiling shows a 12° north-dipping band of reflections corresponding to the crustal thrust (décollement) beneath which the Indian lithosphere is underthrusting the Himalaya. The MFT, MBT, and MCT are depicted as splay faults merging into a <10° northward dipping shear zone traced to at least 225 km north of the Himalayan deformation front to a depth of c. 50 km beneath roughly the North Himalayan Belt of granite domes in Southern Tibet. The shear zone seems to slice down northward from near the top of the upper crust into the mid-crustal interface. This geometry suggests that the Indian upper crust detaches along the shear zone from the deeper crust. The Indian upper crust is incorporated into the Himalaya while the lower crust continues being subducted with its lithospheric mantle under Tibet.

However, the geometry of the subducted India north of the Tsangpo Suture is not well constrained.

Prominent reflections with unusually high amplitudes (bright spots) and coincident negative polarities appear at depths of 15-18 km near where the MCT reflector terminates. A combination of free aqueous fluids overlying a layer of granitic magmas gives the most consistent explanation to seismic and magnetotelluric data. Few reflections occur within the crust beneath the bright-spot horizon that extends north, beyond the Tsangpo Suture, into the Lhasa Block. The southern edge of this layer is located 50 to 100 km south of the suture, at a depth of 20-30 km. This would indicate that a partially molten mid-crustal layer of unconstrained thickness exists beneath southern Tibet.

Brown *et al.* 1996 *Science* **274 (5293)**, 1688-1690

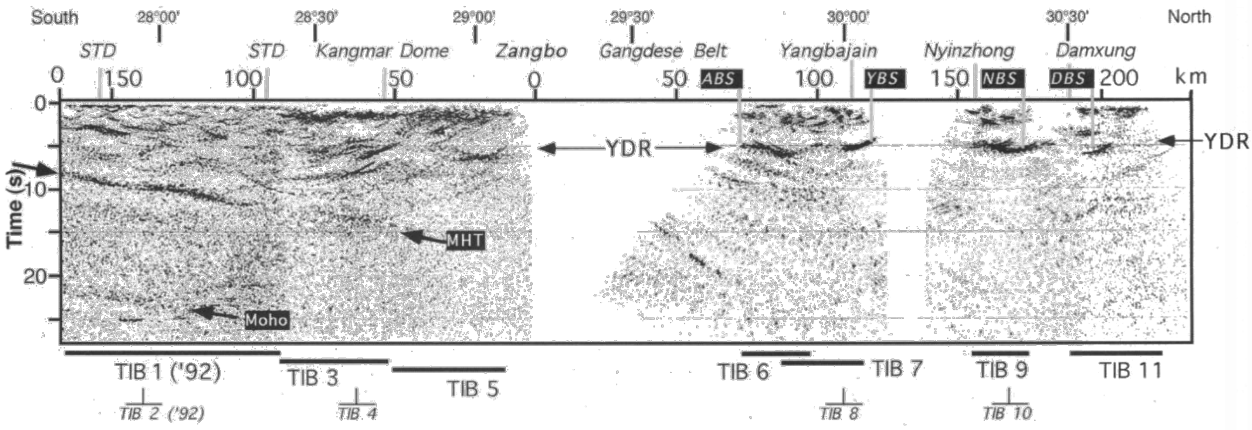


Fig. 1. Composite migrated depth section of reflection profiles collected during INDEPTH I (1992) and II (1994). MHT, Main Himalaya Thrust; STD, South Tibetan Detachment System; YDR, Yamdrok-Damxung Reflection band; ABS, Angang bright spot; YBS, Yangbajain bright spot; NBS, Nyinzhong bright spot; DBS, Damxung bright spot. Note that individual profiles are offset laterally (*1*). Here the profiles were merged after relatively standard common midpoint (CMP) processing, including FX deconvolution and coherency enhancement then migrated at 6 km/s. Sections south of the Zangbo were projected onto a north-south line, the remainder onto a line following the trend of the Nyainqentanglha Mountains.

Older reflection and wide-angle reflection data suggested a decoupling zone within the crust, the upper crust sliding, and/or folding independently of the lower crust. The major thrust units (MCT, MBT, and the North Tethys sediments) correspond to prism-shaped seismic structures superposed along imbricate, north-dipping thrusts in the upper crust. Conversely, thrusts in the lower crust dip to the south and may involve upper mantle rocks. Decoupling and thrusting the lower and upper crustal layers allow crustal shortening and thickening of the North Indian Margin in a complex duplex of gently dipping ductile shear zones with opposite vergence. The base of the duplex would lie near the base of the crust or within the sub-crustal lithosphere.

Moho

India has a typical shield S-wave velocity structure with a thick, high-velocity lithosphere overlying the asthenosphere. The Moho is nearly horizontal at about 45 km depth beneath the Indian Shield. It deepens over a distance of 120 km beneath the Himalaya to reach about 75 km depth in southern Tibet.

Hirn *et al.* 1984 *Nature* **307**, 23-25

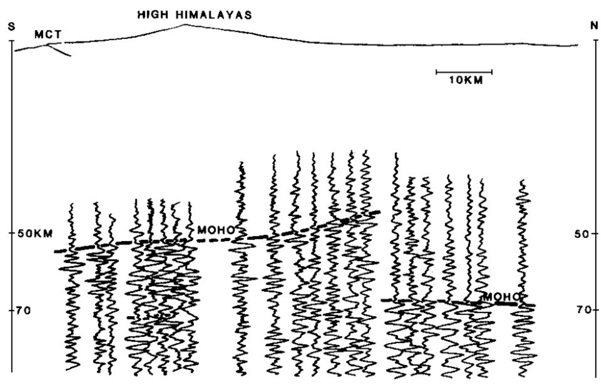


Fig. 3 Fan-profile to the west from shotpoint Dingjie. Correlated phases at these shotpoint distances from 180 to 300 km correspond to reflections at the crust–mantle boundary (see Fig. 2). Reflection times are corrected to a constant offset of 200 km, so that the time-section is directly transformed in a depth-section (S–N on Fig. 1) across the High Himalayas under the assumption of negligible variation of mean crustal velocity along it.

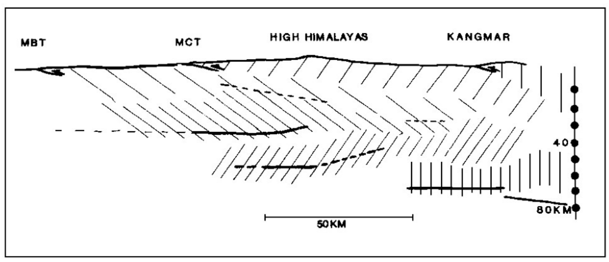


Fig. 4 Sketch of elements of seismic structure across the High Himalayas. Dashed line: interface between upper and lower crustal velocity material. Solid line: interface between crust and mantle velocity material. Loose hatching: upper crust layers. Their superposition is supposed to occur along flat thrusts at the base of the overriding unit. Tight hatching: lower lithospheric units. These are comprised of the lower crust, Moho and a sole of uppermost mantle material and are assumed to be brought to the present position, attested by the position and shape of the Moho marker, as a result of thrusting and superposition along levels of decoupling in the middle or lower crust and at shallow depth in the uppermost mantle. Possible correspondence of upper and lower units is indicated by hatching of same direction. MBT, Main Boundary Thrust; MCT, Main Central Thrust.

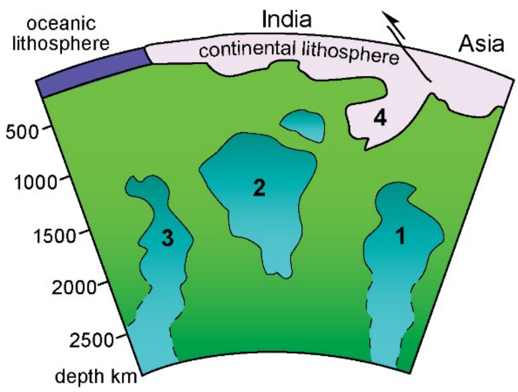
This supports the underthrusting of the Indian plate to be responsible for the double thickness of the crust of South Tibet and somewhat contradicts earlier interpretations of a stepped Moho in an imbricate crust.

Lithosphere

Deep seismic reflections indicate that the Indian continental lithosphere has underthrusted Tibet as far as half the plateau width, namely to the Bangong-Nujiang suture. This is inferred from a high P-wave velocity layer at depths of 60-75 km beneath the Transhimalaya Belt. However, this layer may indicate the underplating of mafic magma during the generation of the magmatic arc.
The lithosphere beneath Tibet appears to be thinner than that beneath India, indicating that at present the Indian Plate is not underthrusting the whole of the Tibetan Plateau and that Tibet is not a typical shield region.

Seismic tomography

Seismic tomographic images reveal high-velocity anomalies in the mantle beneath India and Tibet. The deepest and isolated anomaly, ca 1000 km beneath the present-day southern tip of India, is interpreted as Tethys oceanic lithosphere broke off the Indian plate at about the time of the collision. This slab is that far to the south because the Indian plate has drifted northward, above this reference sunk in the asthenosphere, since the break-off. A second, around 500 km deep anomaly beneath India would be another Tethys slab separated from its plate after slab break-off about 20 Ma ago. The high-velocity mantle below Tibet up to 500 km from the Himalayan front is interpreted as the Indian continental lithosphere pushed beneath Asia since the last slab break-off.



Subduction zone remnants (numbered)
revealed in the asthenosphere beneath India by seismic tomography
after van der Voo *et al.* 1999 *Earth and Planetary Science Letters* **171(1)**, 7-20

Global Positioning System measurements

The convergence rate varies along the Himalayan front. The rate indicated by GPS data (about 35 mm/yr) is lower than the long-term average north-northeastward convergence rate between stable Eurasia and India (nearly 50 mm/yr).

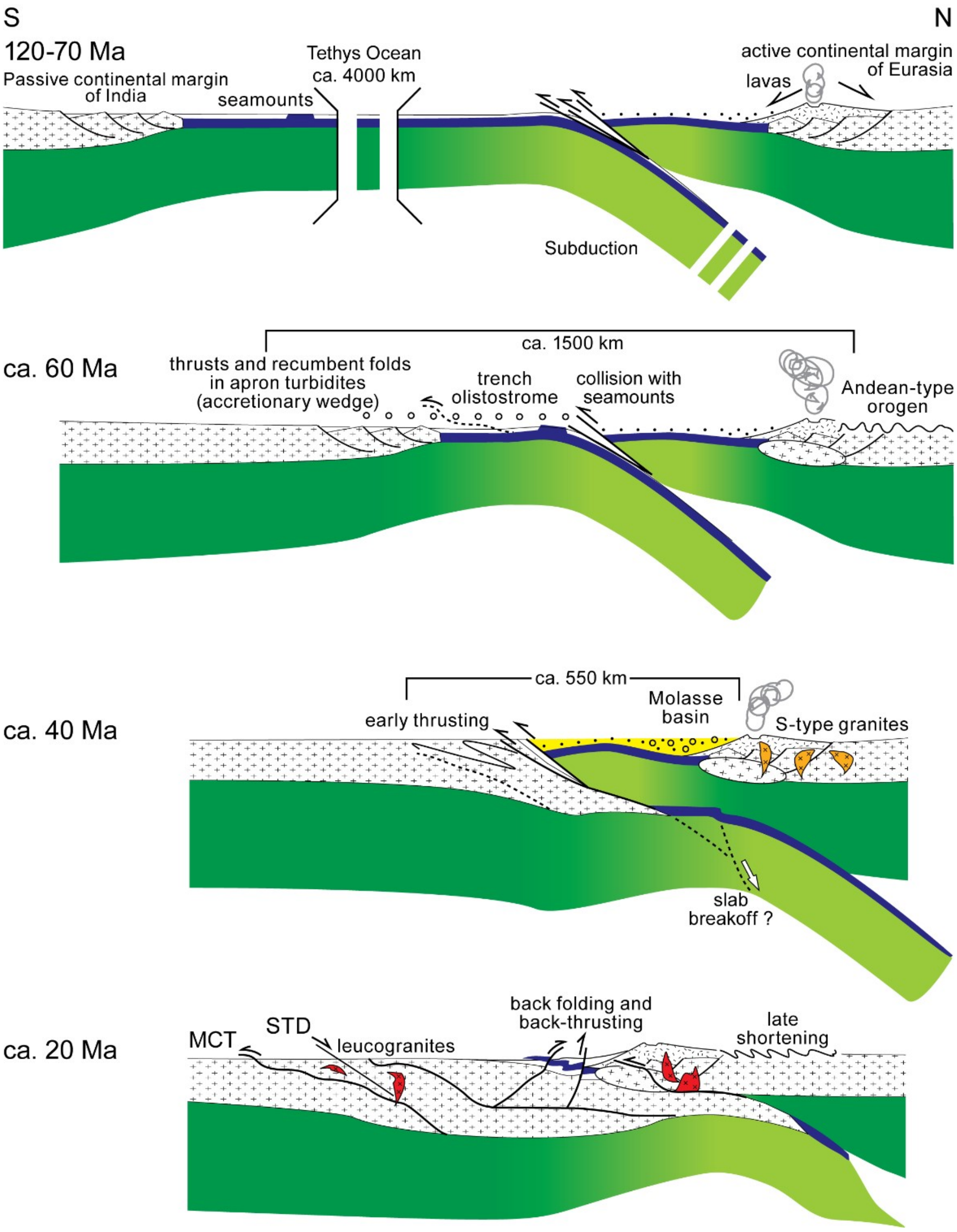
Tectonic evolution of the Tsangpo Suture Zone in Tibet

Opening of the Tethys Ocean

Basic sills and dikes in the Permian and Lower Triassic are attributed to rifting preceding the opening of the Tethys Ocean. Pelagic sedimentation probably began during the Late Triassic, just north of the Indian continent. Thus, an Indian continental margin existed at that time, but no Triassic oceanic crust has been found in the Tsangpo suture zone. Afterward, platform-type sedimentation formed the Tethyan sequences on top of the Indian continental margin.

Subduction

Northward subduction of the Tethys oceanic lithosphere produced a vast volume of magma that lasted through the Late Cretaceous and built an Andean-type orogen in the active continental margin of the Lhasa Terrane. Subduction may already have started during the Early Cretaceous when India began to drift northward with respect to Eurasia. The magmatic arc, with thermal gradients elevated above the steady-state geotherm, was thickened and being eroded before the collision. Magmatism terminated in the Eocene. At this time, the overriding plate was less deformed than the subducted plate, except along its southern edge. Sedimentation continued during Cretaceous times on the Indian foreland and in the forearc basin. Shallow-water marine sedimentation continued up to the Eocene on the Indian platform.



The magmatic quiescence in the Transhimalaya and the sudden rise in the convergence rate between ca. 70 and 60 Ma may correspond to the rollback of the subducting Tethys slab. The enhanced gravitational pull of the slab also accounts for the general lack of Paleocene shortening along the Transhimalaya arc and in the Lhasa Terrane. Southward migration of the asthenospheric convection beneath Tibet may have accompanied the slab rollback, hence enhanced the asthenospheric corner flow and changed the thermal structure of the mantle wedge. Thus, a dominant asthenospheric mantle source component characterized the final phase of Transhimalaya arc magmatism.

Obduction

The southward obduction of the suture rocks took place while the olistostrome was deposited (Maastrichtian-Palaeocene?). The bulk strain of this age increases upwards in the suture region with the development of a subhorizontal cleavage and roughly north-south stretching lineation.

Collision

Collision commenced in the Paleocene with the arrival of the apron turbidites and the olistostrome in the subduction zone. The exotic blocks of this olistostrome witness seamounts, pelagic horsts, and the distal parts of the Indian continental margin. The tectonic emplacement and recumbent folding of the apron and North Tethys sequences, and shear deformation of the northern Indian margin represent early thrusting, which possibly involved the olistostrome bottom. This edifice rests upon Upper Cretaceous sediments.

The onset of the India–Asia ‘‘hard collision’’ at ca. 45 Ma suggests cessation of pull forces after break-off of the Tethys oceanic slab. This slab breakoff would have interrupted the Transhimalaya arc magmatism and triggered topographic uplift, similar to that proposed for modern Central America. If so, a high but relatively narrow mountain range, akin to the Altiplano–Puna plateau of Central Andes may have existed since the Middle Cretaceous in southern Tibet.

Continued continental convergence led to the dramatic shortening of the crust (nearly 550 km in the suture zone and >400 km in the Himalayas) through the development of imbricate low-angle thrust systems associated with intermediate pressure metamorphism, two-mica granite intrusions, widespread upright folding, and steepening of the suture zone. Final southward transport of north-dipping, ophiolite, and radiolarite thrust sheets took place at this stage. Crustal stacking on the subducting Indian plate propagated southward towards more and more external areas with a stretching lineation coincident with the relative motions of the converging crustal segments. Thrust-related heterogeneous deformation has contributed to the total thickening of the orogen. The major thrust zones dip in the same way as the initial subduction zone in the upper parts of the crust. Thrust zones with upward decreasing deformation created deformation belts different in ages though having the same fabric feature because they result from persistent north-south compression.
Post-collision movements were north-directed and led to the reactivation of the suture proper and thrusting of the forearc turbidites on autochthonous molasses (Eocene conglomerates of the southern fringe of the Lhasa Terrane). The relationship between contemporaneous backthrusting in the suture and collapse normal faulting above the High Himalaya is unclear.

The general structure of the Tsangpo Suture Zone in Tibet results from three periods of thrust faulting and major crustal thickening. The sequence of events is (1) nappe movements and burial of Indian sequences, (2) shortening and isoclinal folding, and (3) backfolding. This sequence corresponds well to the sequence of orogenic events observed in the other parts of the Himalaya and many recent orogens such as the Alps or the Oman mountains.

Mechanisms of the continental collision seen from the Himalayas

The Himalaya-Southern Tibet suture zone is a young analog for the ancient continent-continent collisions. It is composed of several thrust sheets with distinct stratigraphy, state of deformation and metamorphic grade. It bears evidence for the previous existence of oceanic lithosphere (the ophiolites), a passive and an active continental margin.

Pre-collision stages

The subduction - obduction dip can be identified from:

- The facing and dips in the ophiolites and associated nappes
- The persistent dip of axial planes, cleavages, and facing-direction of folds
- Location of the calc-alkaline magmatism on the active margin side of the suture.

Syn-collision stages

The incoming, strong, and cold continent (India) is subducted behind its leading oceanic slab until buoyancy forces overwhelm the strength of the continental lithosphere. Subsequent intracontinental thrusts create:

- Upward decreasing strain.

- Essentially forelandward initiation and propagation of deformation (in sequence thrusting).

- Complex deep structures.

- Deformation belts have different ages but similar regional trends because they result from a persistent convergence direction. Conversely, there should be variations in structural directions if the bulk geodynamics change.

- Unconformities such as that of the olistostrome are not necessarily an orogenic pause as coeval thrusting may develop in the lower parts of the crust and farther in the foreland.

- The rheology of the two newly assembled plates controls deformation partitioning in the new continent.

- There is no evidence that a phase of isobaric heating exists between the assembly of a thrust system and the onset of erosion.

Post-collision stages

- A few kilometers more erosion and the ophiolite klippen will disappear, leaving little trace of former oceanic material. Deeply eroded suture zones of old collision belts may simply occur as deformed boundaries separating terranes. They are **cryptic** sutures.

- Exposure of high-grade rocks results as much from tilting and movement along major thrusts as from uplift and erosion consequent on tectonic burial.

- A thickened crust experiences collapse, which is additional to the erosion process for the exhumation of deeper rocks.

- Subduction produced calc-alkaline magmatic rocks and leucogranites formed during nappe stacking. Leucogranites are a hallmark of post-collisional crustal shortening and should be recognizable in Himalayan-type collision orogens.

Conclusion

The previously vast Tethys Ocean subducted. in front of the northward migrating Indian plate beneath the southern margin of the Eurasian plate. The Cenozoic collision of India with Eurasia created and continues to shape the Himalaya-South Tibet suture zone. The most significant thrusts are synthetic, i.e. parallel to the initial subduction zone, suggesting that the pre-collision subduction zone determines the basic polarity of thrust-driven collisional shortening. Continued convergence led to the deformation of the Indian continent with the successive formation of the MCT and MBT thrusts. The Himalaya Mountains formed to the south of the suture zone, entirely within the Indian continent, during about the last 20 Ma.

Closure of the Tethys Ocean involved two collision events: collision/subduction of intraoceanic island arcs with the Eurasian margin took place 70-50 Ma ago and collision of Greater India with Eurasia around 45 Ma. Slab-pull forces are only active while the intervening ocean is shrinking, and cease when the ocean becomes fully closed. Another contributor to the continued northward movement of India may be the ridge-push exerted on the southern margin of the Indian plate.

The welding of two continents (suturing) is a long-lived and diachronous process. Structures similar to those found in the Himalaya - Southern Tibet range can be expected in many places along the suture zone between Eurasia and Gondwana-derived continents and microblocks. For example in the Alps, where major thrust zones merge towards the inner part of the belt into a unique shear zone. The origin of the merging shear zones may be connected with the subduction zone itself. The evolution of the thrust system leads to the steepening of the inner thrust planes (and the suture) by the growth of the underlying outer thrust sheets. The vertical inner thrust zones and the suture then become rejuvenated as wrench faults, as observed in South Tibet. This structural scheme is consistent with the lower crust behaving in a manner different from that of the upper crust. These features should be kept in mind when the deep structure of old and deeply eroded orogens is interpreted.

Exercises

Which forces are involved in a continental collision? Which mechanisms may explain the rapid slow-down of northward drifting India?

What are the similarities and differences between the collisional orogens in the Alps and Southern-Tibet?

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