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 oceanic lithosphere is relatively dense and sinks into the asthenosphere, the greater sialic content of continental lithosphere ascribes positive buoyancy in the asthenosphere, which prevents 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 known as a suture, which usually preserves slivers of the oceanic lithosphere that formerly separated the continents, known as ophiolites.

Collision between the Indian subcontinent and what is now Tibet, about 55 Ma ago, has constructed the Himalaya-Tibet orogenic system. Continental collision involved and still involves north-south convergence throughout southern Tibet and most of the Himalayas. Collision is still active, and the 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 that separates India to the south, from the biggest Plateau in the world, the huge Tibetan plateau, with a mean elevation of 5000 m, which will be at the centre of one of the next lectures.
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) in the core of the eastern syntaxis and the Nanga Parbat (8138 m) in the western bend, 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 recent isostatic response of a thickened, low-density crust with the Himalayas undergoing rapid uplift at rates between 0.5 and 4 mm.a⁻¹. The mountain range is bounded at both extremities by strike-slip belts: The Quetta-Chaman fault system in the west, in Afghanistan, and the Sittang zone in Burma in the east.

![Map of the Himalayas and Tibet](image)

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

**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. 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 Late-Cretaceous (85-90 Ma).

**Chronology of the convergence**

Closure of the Mesozoic Tethys Ocean resulted in the collision between India and Asia. Paleomagnetic results 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 may have produced some Neogene anticlockwise rotational underthrusting of India along the Main Central Thrust. Marine magnetic anomalies of the Atlantic and Indian Oceans along with paleomagnetic measurements in Asia and India permit to accurately document the northward drift of cratonic India relative to cratonic Asia since the late Cretaceous. This motion represents ca. 8000 km of convergence, which provides an indicative size of the consumed Tethys lithosphere. Latest plate tectonic reconstructions predict 7500 and 8700 km at the longitudes of the western and eastern ends of the Himalayas, respectively.

![Relative movement between India and Eurasia since 70 Ma](image)
Up to Anomaly 22 (50 Ma) the displacement of India was very rapid, at a rate of 15-25 cm/a. In details, India-Eurasia convergence began to slow down around 52 Ma.

Between anomalies 22 and 21 (a time space of 2-3 Ma) an erratic displacement of India is attributed to the onset of the collision.

From Anomaly 22 to Anomaly 18 (42 Ma) the displacement rate decelerated sharply to 4-5 cm/year. Since then, the estimated average convergence rate between India and Eurasia has decreased exponentially to about 4 cm/a.

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

The 3-episode history accommodating the relative motion is interpreted on a dynamic point of view in the following way:

- Subduction of the Tethys oceanic lithosphere, with a long slab pulling India, thus enhancing fast movements.
- Subduction of the Indian continental lithosphere after it came into contact with Eurasia, which, also for buoyancy reasons (the continental lithosphere has a greater buoyancy than oceanic lithosphere), slowed down the relative convergence.
- Intracontinental thrusting and lateral extension at a slower rate controlled by deformability of the two continental lithospheres. The post-collisional decrease in convergence rate might instead be controlled by the strength of the deforming continental mantle lithosphere of Asia.

Age of collision
In the light of paleomagnetic information, collision between the continental parts of the Indian and Asian plates was placed in the Eocene, at about 55 Ma, when the northward motion of India slowed rapidly from >10 cm/yr to 5 cm/yr. This timing is consistent with that inferred from the age of coesite-bearing eclogites 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). Collision of India against Eurasia was felt around the world. In the Pacific, a major plate reorganisation at 43 Ma is recorded by the abrupt bend in the Hawaii-Emperor seamount chain and many of the volcanic arcs began to form at about 50 Ma (Tonga, Mariana, 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 on southern Tibet at around 55 Ma indicate that this northern part of India was stable while northward drift was still at a velocity of about 20 cm/a. At 50 Ma initial collision reflected by slower drift had started.

![Geodynamic evolution of the India-South Tibet collision](image)

A thin continental margin in front of cratonic India may have been subducted for about 15 Ma without triggering any major plate tectonic signal until the end of the Eocene (ca 35 Ma), when the thicker Indian Craton came in contact with Asia. Increased compressional stresses then resulted in shortening deformation of the Tibetan Plateau and for a possible second reduction in convergence rate at 20–10 Ma. This model involves a several hundred kilometres 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

Most recent paleomagnetic and tomographic information suggest that sometime in the early Paleocene northern India was most likely collided with an intra-oceanic island arc located at near-equatorial latitudes. This situation led to two-stage India-Asia collision at 55-50 and 25–20 Ma.

After collision, India did not stop; it moved northward by over $1900 \pm 850$ km with respect to Asia at an average speed of 50 mm/year.
Greater India
The pre-collision extent of India’s northern continental part, known as Greater India, is difficult to constrain because of large uncertainties on collisional deformation and corresponding lithospheric “destruction”. However, the pre-collision size of India is a critical question since it addresses directly how and where collision began and how subsequent convergence between India and Asia may have been accommodated. Seismic data show that the Himalaya-South Tibet collision zone has an approximately 65 km thick crust, while the crust of India, south of the Himalayas, is only 35-45 km thick. Applying a simple, geometrical superposition after continental subduction suggests that Greater India was at least as wide as Tibet, where it has a twice-thick crust (Asian crust over India), hence several hundreds of kilometres. Tectonic reconstructions fitting the possible northern boundary of Greater India with the margins of Australia suggest around 800 km. However, the fast rate and the large amount of convergence since collision require that Greater India included a 1500 to 2500 km (from west to east) wide continental margin to the north of the Himalayas front. Paleomagnetic measurements on Tethys sediments infer >1300 km. The large discrepancy may be a hint for a very wide, strongly extended (thinned) continental margin in front of India, until collision.

Main tectonic and lithologic zones
Southwards-directed and propagating thrusting has assembled the Tsangpo Suture Zone and the Himalayas from four main tectonic and lithologic zones that extend the length of the mountain belt. From N to S these are:
- The Eurasia paleo-active margin, so-called Transhimalaya Batholith.
- The Tsangpo Suture that actually marks the site of the plate boundary along which the Tethys oceanic lithosphere that separated India and Tibet was subducted beneath Tibet.
- The northern margin of the Indian continent that comprises three sub-units:
  - The Tethyan zone
  - The metamorphic High Himalayas
  - The Lower Himalaya
- The Sub-Himalaya foredeep, south of the mountain belt.
Each zone is bounded by major faults and each has a distinctive stratigraphy and metamorphic-magmatic history. We will 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. Eight units are described from N to S to answer the same questions as in Oman.

**Eurasia active margin**

The Lhasa block, named after the capital of Tibet, formed the northern margin of the Tethys Ocean before the India-Asia collision. The Lhasa block is subdivided into a continental part in the north and a magmatic arc in the south.

**Lhasa Block**

The continual Lhasa Blocks consists of a gneissic and granitic Precambrian basement overlain by Paleozoic to Upper Cretaceous shallow-water sediments. Mesozoic sediments contain Cathaysian flora. Cathaysia was a microcontinent detached from Gondwana in early Mesozoic times and drifted across the Tethys until it collided with the Qiangtang terrane of southern Asia in Late Jurassic times. This collision produced the Banggong-Nujiang suture, perhaps after south-dipping subduction below the Lhasa Block. 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 depositional environment produced shallow water and subaerial sediments associated with a Cretaceous-Paleocene (70-65 Ma) ignimbritic series that lies unconformable on eroded folds of the Upper Cretaceous and older rocks. The southern marine Lower Mesozoic basin may have deposited on an undated oceanic crust.
Magmatic arc: the Transhimalaya Plutonic Belt

Magmatic rocks

The Trans-Himalaya is a mountain chain just north of and parallel to the Yalu Tsangpo (Brahmaputra in India), from which the second word of Indus-Tsangpo Suture derives. The long, linear and complex Transhimalaya Plutonic Belt (Chinese name: Gangdese) represents the Cretaceous to early Tertiary Andean-type magmatic arc formed on the southern portion of the Lhasa continent (then the active Asian margin), above the subduction system. Magmatic structures define imbricate plutons making up the calc-alkaline batholith of dominantly gabbroic to granodioritic compositions with subordinate granites. Radiometric ages range between 175 and 30 Ma. The growing number of geochronological results suggests two major stages separated by a period of relative quiescence: (1) The main magmatic stage is Late Cretaceous (ca. 113–80 Ma), ending with adakitic intrusions and (2) the second important emplacement episode is early Paleogene (ca. 65–46 Ma) with a culmination around 50 Ma. The plutonic belt is similarly divided into two belts: (1) the northern belt essentially consists in Cretaceous, peraluminous and S-type granites; (2) the southern belt is dominated by Late Cretaceous – Oligocene granitoids with mostly I-type compositions. The significance of this duality is still in discussion. The southern (Gangdese) belt is overlain by volcanic rocks of equivalent age (69–43 Ma) and chemistry, with an apparent southward migration of volcanism with time. The magmatic crisis at ca. 50 Ma is speculated to represent slab break-off.

Geochemistry indicates that Cretaceous-Eocene rocks derive from the partial melting of a basaltic oceanic crust with minor sediments (likely the Tethys slab) whereas younger (post ca. 35 Ma) rocks include ultra-potassic, adakitic and shoshonitic volcanism and NS trending dikes (ca. 23–8 Ma). These rocks are related, in the light of temporal relationships, to post collision, E-W extension. Geochemistry suggests that these late magmas are derived from mixing between mantle-derived and lower crust-derived melts, perhaps the molten Indian crust subducted below the Lhasa Block in Miocene times.
**Metamorphism**

Metamorphism of the rocks intruded by the Transhimalaya plutons is heterogeneously distributed; the highest temperatures conditions being documented by granulite facies assemblages (andalusite - cordierite - garnet - spinel) of high temperature - low pressure conditions at the contact between metapelites and intrusive gabbros. The regional grade is usually greenschist facies.

**Structures**

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

- Isoclinal F1 folds have a weak and axial planar S1 foliation bearing a north-south stretching lineation. The intensity of the F1 fabric and metamorphism increases towards the Yalu Tsango 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.

- F2 folding with fanlike S2 cleavage and subvertical axial surfaces is pervasive, and locally more pronounced than D1 fabric. The F2 structures have steepened the shallow dipping S1 and represent a period of continuing shortening, part of which between intrusions. This folding / intrusion association is compared to an Andean type orogen that included a retroarc thrust belt and foreland basin and that predates collision.

![Diagram](image)

**Geological History**

Paleoelevation reconstruction using oxygen isotopes from several sedimentary formations suggest 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 prior to the India-Asia collision. Arc magmatism stopped in Eocene times, presumably reflecting the time of collision and the cessation of subduction of oceanic lithosphere.
**Great backthrust**

To the south, conglomerates intercalated with red shales, sandstones and local basaltic and ignimbritic flows lay unconformable on the Transhimalaya Plutonic Belt. The narrow and discontinuous occurrences of Late Oligocene - Early Miocene (ca. 26 – ca. 15 Ma) sequence (also known as Kailas and Indus Molasse) were deposited by southward draining delta, braided-river and alluvial fan systems. Northwards and westward draining systems developed from 19 to 15 Ma. Eastward flowing rivers were established at ca 15 Ma and deposited conglomerates perhaps as late as the Early Pliocene (ca. 5 Ma). The modern Tsangpo River may be inherited from that system. 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. Slickenside striation on the fault plane and related fractures indicate dextral wrench faulting before northwards backthrusting in Mid-Miocene times. This fault zone has overprinted the presumably south-vergent, primary features of the suture.

**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, which are the eastern continuation of those recognised along the Indus River, in Ladakh, and in Southwest Tibet (western Himalaya). Three rock subunits are attributed to the hanging-wall plate of the suture. They are, from north to south 1) fore-arc turbidites (the so-called Xigaze series, after the second city of Tibet) 2) ophiolites and 3) associated deep sea sediments.

**Fore-arc turbidites**

The northern section of the Xigaze series is composed of a virtually unmetamorphosed turbidite sequence deposited from early Cretaceous to Maastrichtian times (110-65 Ma). Interlayered limestones are paleontologically dated Late-Albian. Late Cretaceous conglomerates with pebbles from the Transhimalaya plutonic and volcanic calc-alkaline rocks indicate erosion of the already thickened crust of the Andean-style margin on the Lhasa Block, which provided clastic material to a basin near the southern margin of the continental arc. Shallow marine, Paleocene to lower Eocene limestone, volcano-clastic sediments and volcanic tuffs 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 (TiO₂ generally < 0.1 wt%) appeared during the Paleocene (65 to ~55 Ma).
The southern, deepest section is composed of pelagic sediments with Albian-Cenomanian radiolarites forming the sedimentary cover of pillow lava. The Xigaze sediments are interpreted as an upward-shoaling fore arc basin lying on the plutonic belt to the north and on the ophiolites to the south. It started with early Cretaceous (ca. 130-115 Ma) deep-water turbidites and radiolarites and continued as slope, shelf and eventually deltaic and fluvial deposits from the late Cretaceous onward (post ca. 75 Ma).

The Xigaze series appear within a large east-west trending synclinorium shortened by 40-50% after the early Cenozoic with dominantly southward verging, tight-to-open folds, a steep dipping cleavage and no metamorphism. This relatively simple and late general structure may result from the high strength of the underlying ophiolite. Additional, undefined amounts of shortening were involved into thrusting below, and backthrusting over the Lhasa Block and, in place, the ophiolites.

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

**Ophiolites**

Thin sheets of ophiolite and deep water sediments (radiolarite) 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 thermal erosion of the supra-subduction oceanic lithosphere.
Island arc
Island arc igneous and volcaniclastic rocks (boninitic pillows, basaltic-andesitic breccias and dykes, dacites, rhyolites, diorites and leucogranites) are dated between ca 160 and ca 150 Ma. They form a dismembered and overturned sequence imbricated with fore-arc and subduction-complex 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 originally generated from a MORB-source upper mantle. The y are mostly chromite-bearing harzburgites and lherzolites; dunites are scarce. Petrology and geochemistry indicate forearc spreading ridge origin and subsequent (boninitic) alteration in the supra-subduction mantle wedge. The associated mafic rocks (lavas, dolerite dykes and cumulate gabbros) also recorded this two-stage evolution. 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: 13-15 kbars, 750-875°C) representing an intra-oceanic thrust sole, which formed during inception of a subduction. 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 supports a model in which the new 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
The related radiolarites of Late Triassic to Senonian age, and locally basalt, form an imbricate thrust-stack. A marked stretching lineation associated with polyphase deformation: sheath folds, and south-
facing, second phase folds that deform the early, north-south lineation. The deformation features are interpreted to indicate transport from north to south during greenschist facies metamorphism. They 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 Zone, 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 F1 folds have inverted the stratigraphical series. South-west verging mesoscopic F1 folds trend N030-180 and contain an S1 slaty cleavage formed in low-grade conditions of metamorphism. Quartz fibres and long axes of pressure fringes are parallel to the N340-030 stretching lineation Lc that can be equated with a transport direction. Basal thrusts of this subunit and of the ophiolites and their sole cut the F1 structures and are marked by some crush zones, metres thick, formed in non or very low grade conditions of metamorphism.

![Fig. 5 Two detailed cross-sections in the Triassic-Liassic turbidite flysch. They show polyphase deformation with S1 cleavage and S2 crenulation cleavage. Bedding S0-S1 relationships and younging directions (arrow) give evidence for several kilometres inverted series. Thickening of F1 hinges is voluntary exaggerated. Lower Cretaceous calcischists underlie the wildflysch.](image)

Both the thrust contacts and the F1 folds are folded about F2 structures in various ways, as the upright chevron folds (interlimb angles 110-500) may coexist with subisoclinal folds with rounded hinges and overturned to the south. The F2 axes are parallel to a N060-120 crenulation lineation. F2 folding increases in intensity northwards and is contemporaneous with intrusion of two mica granites recognised in the North Himalayan Belt. Local N040-130 kinks with different axial plane attitudes are attributed to an F3 event and may be contemporaneous with post-F2 movement along basal thrusts.
The turbidites are attributed to a continental margin apron of Upper Triassic to Late Mesozoic age, intensely deformed during southward shearing and transport of Lower Paleocene age. The study of detrital zircons suggests that some Upper Triassic sequences are derived from the Lhasa Block, thus represent the northern margin of the Tethys Ocean basin rather than India.

**Olistostrome**

An olistostrome with a black, shaly matrix is partly transgressive on the rocks and recumbent fabrics of the turbidites. Oldest exotic blocks are Late Permian limestones derived from the Indian continental margin or from oceanic plateaux. The youngest blocks, which appear to have been folded prior to their redeposition, are Globotruncana limestones yielding Maastrichtian to lowermost Paleocene ages. The youngest fossils found in the matrix are Late Paleocene, which is taken as the age of this synorogenic formation overlain by undated black shales and quartzites. 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 unit 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; this cleavage is a crenulation cleavage in the older rocks. The folding is correlated with the F2 event of the turbidite nappes where this cleavage is a crenulation cleavage.

**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 began to subduct 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 localised 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 turbidite of up to Maastrichtian age involved in polyphase deformation. The Late Cretaceous pelagic environment seems to have disappeared from east to west. Undated basic dykes 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 S1 with a N350-040 stretching lineation. The bulk strain increases northwards towards the Yalu Tsangpo Suture and upwards under the ophiolitic and associated nappes. The unconformable wildflysch with exotic blocks is lying on these deformations. If the Maastrichtian to Palaeocene age of the wildflysch is correct, the major thrusting events are thus Upper Cretaceous-Palaeocene in age.

The structurally lower metamorphic rocks show a comparable polyphase deformation with an unexpected downward increase in intensity of the fabric contemporaneous with the intermediate pressure metamorphism. The problem arises from radiometric ages of micas at 13 Ma (Ar/Ar method) and hence inconsistent with the Maastrichtian-Palaeocene age of the F1 structures as suggested above. 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 they are different in age, 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 7-8 kbar for ca 650°C) at 45-35 Ma and protracted melting of the Indian-derived middle crust until intrusion of the late Miocene (ca. 15 Ma) two-mica granites. These domes exposing mid-crustal rocks deformed, metamorphosed and melted during the Himalayan orogeny are attributed to thrusting and subsequent extension or diapirism or a combination of all of these mechanisms.

South Tethys sediments

The southern Tethys sediments range in age from Cambrian to mid-Eocene without any significant unconformity and are of the10-km thick platform type series identical to that 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 sediments over the stable Indian shelf. In more details, 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 Cretaceous southern passive margin of the Tethys Ocean.

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

In contrast to the deeper water north Tethyan 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 kilometres along their axial traces. 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.
Note that there was no pre-alpine tectonic episode and that youngest marine sediments are ca. 10 Ma
younger than collision.

Indian Continent
Convergence between India and Eurasia continued after their initial contact, up to the present (about
5 cm/yr). Several hundred kilometres of shortening, and possibly as much as 1500 km took place
between the Tethyan Himalaya and the Indian craton since the Paleocene. Large-scale thrust
imbrication with 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 10 to 25 mm/a
of shortening is currently taken up within the Himalaya. The Himalayan topographic front, i.e., the
zone where the averaged 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 occurrence 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 tectono-stratigraphic units which isotopic data
qualify as late Proterozoic to early Paleozoic gneiss, migmatites and schists of the upper continental
crust of India. Mesozoic sediments of Tethyan origin, which all were originally situated on the
northern margin of India, lay locally on the gneiss and schists.

Orogen-parallel normal fault
The contact that juxtaposes very low grade to unmetamorphosed hanging wall sediments of the
Tethys Himalaya on higher grade schists and Miocene leucogranites of the High Himalayas (also
called Main Central Crystalline Sheet) is a north-dipping normal fault: the South-Tibetan
Detachment. It is responsible for northward shearing of the leucogranites and superposition of
unmetamorphosed sediments onto staurolite-garnet schists. Ductile normal faulting is dated from 24
to 11 Ma. To the east, steeply dipping, brittle normal faults separate Jurassic schists from gneisses
indicating several tens of km down-to-the-north vertical movement. Normal faulting is Miocene to
perhaps Pliocene in age and 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 huge,
monotonous gneiss sheet that varies in thickness from 2 km to 10 km. This thrust sheet is a deeply
rooted crustal slice whose bottom consists of biotite-garnet-kyanite micaschists and the middle and
upper parts are sillimanite-kyanite, K-Feldspar assemblages and sillimanite-cordierite-garnet metapelites.

The gneiss and migmatites bear evidence of multiple deformation and recrystallisation events ascribed to Himalayan southward shearing, with the dominant fabric defined by amphibolite facies assemblages. The stretching and mineral lineations are roughly normal to the thrust trace all along the belt and parallel everywhere the shear direction defined by numerous and various 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.

The oldest metamorphic record is represented by strongly altered eclogites found towards the top of the gneiss pile. Eclogite facies metamorphism (670°C at >15 kbar) is dated at 23-16 Ma, which is at odd with the age of the surrounding gneiss recrystallised under Barrovian-type metamorphic conditions. The polyphase, metamorphic history implies three stages:
1) Barrovian-type metamorphism (550-680°C at 8-14 kbar) at 45-35 Ma (but younging eastward) took place during burial of the Precambrian protolith following continental collision.

2) Early exhumation occurred at higher temperature and lower pressure (T 650-800°C for P 4-7 kbar) during the Miocene (30-18 Ma). This is the dominant metamorphic event, which obliterated most of evidence for the earlier, higher pressure event.

3) Further exhumation later in the Miocene occurred at lower pressure and temperature (500-700°C at 2-4 kbar), with sillimanite grade at 20-15 Ma.

The Barrovian metamorphic structure is important on a conceptual point of view. The gneiss pile above the MCT shows a northward, upward decreasing metamorphic sequence from ca. 550°C near the MCT up to 700°C about 5 km above, in the overlying migmatites, with pressures consistent with a lithostatic gradient. 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 successively staurolite, garnet, biotite and lower grade metamorphic zones.

Three classes of models are considered to explain these 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. This critical feature has been attributed to the ironing effect.

- Syn-metamorphic inversion of isotherms: Viscous heating associated with the MCT produced an inverted thermal structure.
The last two processes suggest that downward conductive heating of the underlying Lower Himalaya from the High Himalaya gneiss is coupled with cooling of the High Himalaya hanging wall. In that case, inverted geotherms developed during slip on the thrust. Recent dating of the metamorphic history, which follows a classical, clockwise Pressure - Temperature - time loop, indicates that thrust reactivation exhumed the sequence rapidly enough to preserve the inverted metamorphic gradient. Symmetamorphic shearing evolved at 20-25 Ma. Burial of the footwall rocks ceased at 10 Ma but further reactivation lasted into Late-Miocene (5-8 Ma) times.

**Leucogranites**
Melting of the continental crust generated the 25 to 12 Ma plutonism, which produced tourmaline-muscovite-garnet leucogranites. These leucogranites define a belt of small plutons, stokes and dyke networks in the upper levels of the High Himalaya. Their shear fabrics give evidence for normal faulting and rapid denudation 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 400 MPa). Mineral ages between 18 Ma and 15 Ma indicate exhumation at a rate of 0.7 to 0.8 mm/a.

**Main Central Thrust**
The amphibolite facies High Himalaya gneiss have been thrust over a series of lower (greenschist) grade metasedimentary, metavolcanic and metagranitoid rocks, including Miocene metasediments, along the Main Central Thrust. The thrust is a north-dipping ductile zone that has had a protracted history. It 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, the Himalayan orogeny proper is characterised by intra-plate, continental subduction of southern India along this contact.

**Exhumation problem**
The concomitance between the STD and the MCT involves 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. Forward extrusion of this wedge was envisaged as being driven by gravitational collapse in response to the extreme topographic gradient along the southern margin of the Himalayas. Analogue modelling of continental subduction suggests gravity-driven, upward extrusion of a continental wedge subducted to depths where its buoyancy overcomes the crustal strength, resulting in upward (forelandward) movement of the wedge over a new, crustal-scale thrust (MCT) while the upper boundary of the exhuming wedge records normal sense of movement.
- Mechanical modelling attributed 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**

More recent models proposed a laterally continuous, low viscosity, mid-crustal “layer” of partially molten gneiss that flowed southwards from beneath the Tibetan Plateau between sub-parallel STD and MCT and eventually extruded towards the Himalayan range front. In these “channel flow” models, the horizontal gradients in lithostatic pressure between the Tibetan Plateau and the Himalayan front provide the driving force behind extrusion. Exhumation of the gneiss from mid-crustal depths to the surface is initiated by 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.
**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 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 to 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**

Tectonic loading of the northern edge of the Indian subcontinent during 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 continent-continent collision at 55 Ma. The oldest strata are transgressive marine Latest Paleocene–middle Eocene sandstones (57-41.5 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 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 details the discontinuous series comprises most of the Cenozoic but there was a general lack of sedimentation during 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 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.

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**Focal mechanisms**

The Himalayas are seismically very active. During the past century, four earthquakes of magnitude > 8 have occurred along the Himalayas, with a large number of small and medium size 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 crustal blocks. The gently dipping fault planes exhibit slip in a sub-horizontal direction, normal to the Himalayan arc. 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 that corresponds 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 down 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 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 Main Central Thrust reflector apparently 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 Yalu Tsangpo 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.

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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, Nyunzhong 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 and then migrated at 6 km/s. Sections south of the Yangbajain 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 that a decoupling surface within the crust separates deep crustal from upper-crustal tectonics. The major thrust units (MCT, MBT and the northern Tethys sediments) correspond to prism-shaped seismic structures of the upper crust whose superposition occurs along imbricate north-dipping thrusts. South-dipping thrusts in the lower crust may involve upper mantle rocks. Decoupling and thrusting separating lower and upper crustal layers with opposite vergence produces crustal shortening and thickening of the North Indian Margin. The subducting Indian crust deforms and thickens, producing a complex duplex of gently dipping ductile shear zones below a decoupling surface. The base of the duplex would lie near the base of the crust or within the sub-crustal lithosphere. The upper crust can slide and/or fold independently of the lower crust.
**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.

![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 to a depth-section (S–N on Fig. 1) across the High Himalayas under the assumption of negligible variation of mean crustal velocity along it.](image)

This supports 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 underthrust Tibet as far as half the plateau width, namely 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 underplating of mafic magma during generation of the magmatic arc. However, 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 broken off the Indian plate at about the time of collision. This slab is that far to the south because the Indian plate has drifted northward, above this reference sunk in the asthenosphere, since then. 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.
Global Positioning System measurements
The convergence rate varies along the Himalayan front. The rate indicated by GPS data (about 35 mm/a) is lower than the long-term average north-northeastward convergence rate between stable Eurasia and India (nearly 50 mm/a).

Paleodynamic evolution of the Tsangpo Suture Zone in Tibet
Basic sills and dykes in the Permian and Lower Triassic are taken as due to a rifting phase related to early stages of opening of the Tethyan ocean. Considering differences in facies become evident in Triassic times. Platform-type sediments were deposited on top of the Indian continental sedimentary sequence to form the Tethyan sequences. Pelagic sedimentation probably began during the Upper Triassic, just north of the Indian continent. Thus, in the Upper Triassic an Indian continental margin existed although the existence of Triassic ocean crust has not yet been proved in the Tsangpo suture zone.

Northward subduction of the oceanic lithosphere beneath Eurasia promoted the production of a vast volume of magma that has lasted through Upper Cretaceous times and that was associated with an Andean-type orogen in the active continental margin. Subduction may already have started during the Lower Cretaceous when India started to drift northward with respect to Eurasia. Sedimentation continued during Cretaceous times on the Indian foreland and in the fore-arc basin. Shallow-water marine sedimentation continued up to the Eocene on the Indian platform.

The Lhasa Block and the ophiolites that carry the Xigaze series represent the overriding plate. This plate was thickened and being eroded prior to the collision. Thermal gradients were elevated above the steady state geotherm. Magmatism terminated in the Eocene. At this time, the deformation of the overriding plate was substantially less than that of the subducted plate except along its southern edge.

The Transhimalaya magmatic gap and the sudden rise in the convergence rate between ca. 70 and 60 Ma may correspond to rollback of the subducting Neo-Tethys slab. This would have enhanced gravitational pull of the slab, which would not only account for the increase in the convergence rate but also explain the general lack of Paleocene contraction and shortening along the Transhimalaya arc and elsewhere in the Lhasa terrane, despite a substantial indentation of the Indian continent during this time. The slab rollback would have been accompanied by a southward migration of the asthenospheric convection beneath Tibet, which should have significantly enhanced the asthenospheric corner flow and changed the thermal structure of the mantle wedge. Thus, the final phase of Transhimalaya arc magmatism was characterized by a dominant asthenospheric mantle source component.

The southward obduction of the suture rocks took place while the wildflysch 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 commenced in the Paleocene with the arrival of the apron turbidites and the mélangé in the subduction zone. This complex lithologic assemblage is assumed to represent a strip of seamounts, pelagic horsts and the distal parts of the Indian continental margin now preserved as the exotic blocks. The first nappe movements are represented by the emplacement of the apron turbidite nappes and shear deformation of the northern Indian margin. This edifice rests upon Upper Cretaceous sediments and possibly involved the bottom part of the mélangé.

The onset of the India–Asia “hard collision” at ca. 45 Ma suggests cessation of pull forces due to break-off of the Neo-Tethys oceanic slab. This slab breakoff would have interrupted the Gangdese arc magmatism and triggered a substantial amount of topographic uplift, similar to that proposed for the modern Central America. Thus, 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.
The dramatic shortening of the crust (nearly \(550\) km in the suture zone and \(>400\) km in the Himalaya) and steepening of the suture zone resulting from continued continental convergence led to the isoclinal recumbent folding of the apron and north Tethyan sequences and the development of imbricate low-angle thrust systems associated with intermediate pressure metamorphism. Final southward transport of north-dipping thrust sheets of ophiolites and radiolarites took place at this stage. Crustal stacking on the Indian plate propagated southward towards more and more external areas with a stretching lineation that coincides with the relative motions of the converging crustal segments. Thickening of the crust has contributed to the total Tibetan thickening by heterogeneous deformation. The major thrust zones dip in the same way as the initial subduction zone in the upper parts of the crust. Post-collision deformation involved intracontinental thrust zones in the subducted plate, associated with intermediate pressure metamorphism, two-mica granite intrusions and widespread upright folding. In the North Indian Margin, intracontinental thrust zones with upward decreasing deformation create deformation belts different in ages though having the same fabric feature because they result from persistent north-south compression.

The latest movements were north-directed and led to reactivation of the suture proper and the over thrusting of the fore-arc turbidites on autochthonous molasses (Eocene conglomerates of the southern fringe of the Lhasa Block). The relationship between contemporaneous backthrusting in the suture and collapse normal faulting above the main crystalline thrust sheet is unclear.

The complex thrust geometry depicted in 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 in many recent orogens such as the Alps or the Oman mountains.

**What can be learned from the Himalaya to understand mechanisms of continental collision?**

The Himalaya-Southern Tibet ranges may represent a young analogue for ancient continent-continent collision. The geology of southern Tibet shows that a suture zone is composed of several thrust sheets with distinct stratigraphy, state of deformation and metamorphic grade. In particular, it provides evidence for the previous existence of oceanic lithosphere (the ophiolites), a passive and an active continental margins.

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**Pre-collision stages**

The subduction - obduction dip can be identified from:

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

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**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 accordance with rules of thrusting.
- Complex deep structures.

Deformation belts have the same regional trends but differ in age because they result from a persistent convergence direction; conversely, there should be variations in structural directions if the bulk geodynamics change. A deformation pause may be represented by unconformities such as that of the olistostrome, although it is 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 kilometres further uplift and the ophiolite klippen will be eroded. Erosion will leave 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 is caused as much by tilting and movement along major thrusts as by uplift consequent on tectonic burial.

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

Calc-alkaline magmatic rocks were produced during the stage of subduction but leucogranites were forming during thrust - nappe stacking. Leucogranites are a hallmark of post-collisional crustal shortening and should be recognisable in orogenic belts that have undergone Himalayan type collision and thrusting.

**Conclusion**

The Himalaya-South Tibet suture zone was created, and continues to shape, in response to the collision of India with Eurasia. This collision was brought about by the northward migration of the Indian plate, while the intervening and previously vast Tethys Ocean was subducted beneath the southern margin of the Eurasian plate. 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 40 Ma. Continental collision, is still active, and represents the reference analogue for ancient continental collisions.

Slab-pull forces are only active while the intervening ocean is shrinking, and cease when the ocean has been fully closed by subduction. A further contributor to the continued northward movement of India seems to be the ridge-push exerted on the southern margin of the Indian plate. Therefore, the decrease of the northward drift of India from over 100 mm/a to about 50 mm/a probably marked the last stage of true continental collision and the initiation of a regime of indentation tectonics, which is studied in the next lecture on Asia.

Continued convergence at a slower rate led to deformation of the Indian continent with the successive formation of the MCT and MBT thrusts. The Himalaya mountains formed entirely within the Indian subcontinent during about the last 20 Ma. The Himalayas represent an intraplate deformation located to the south of the suture between India and Eurasia. This type of continent-continent orogen is shortened and grows vertically by the stacking of thrust sheets in the crust. The most significant thrusts are synthetic, i.e. parallel to the initial subduction zone, suggesting that the pre-existing subduction zone determines the basic polarity of thrust-driven collisional shortening.

The welding of two continents (suturing) by continent-continent collision is a long-lived and diachronous process. Structures similar to those found in the Himalaya-South-Tibet suture zone are to be expected in many places along the suture zone between Eurasia and Gondwana-derived continents and microblocks. A similar situation may have been identified in the Alps and requires splitting of the crust with major thrust zones merging towards the inner part of the belt into a unique shear zone within the crust. The driving force necessary to initiate and develop such a thrust configuration implies a crustal process. Consequently, the origin of the merging shear zones may possibly be connected with the subduction zone itself. The evolution of the thrust system leads to steepening of the inner thrust planes (and the suture) by growth of the underlying outer crystalline sheet. The vertical inner thrust zones and the suture then become rejuvenated as wrench faults, as observed in southern Tibet. This structural scheme suggests that the deep part of the crust behaved in a manner different from that of the upper parts. 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 continental collision? Which mechanisms may explain the rapid slow-down of the northward drifting India?

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

Cited and recommended literature


