Asia: continued collision tectonics

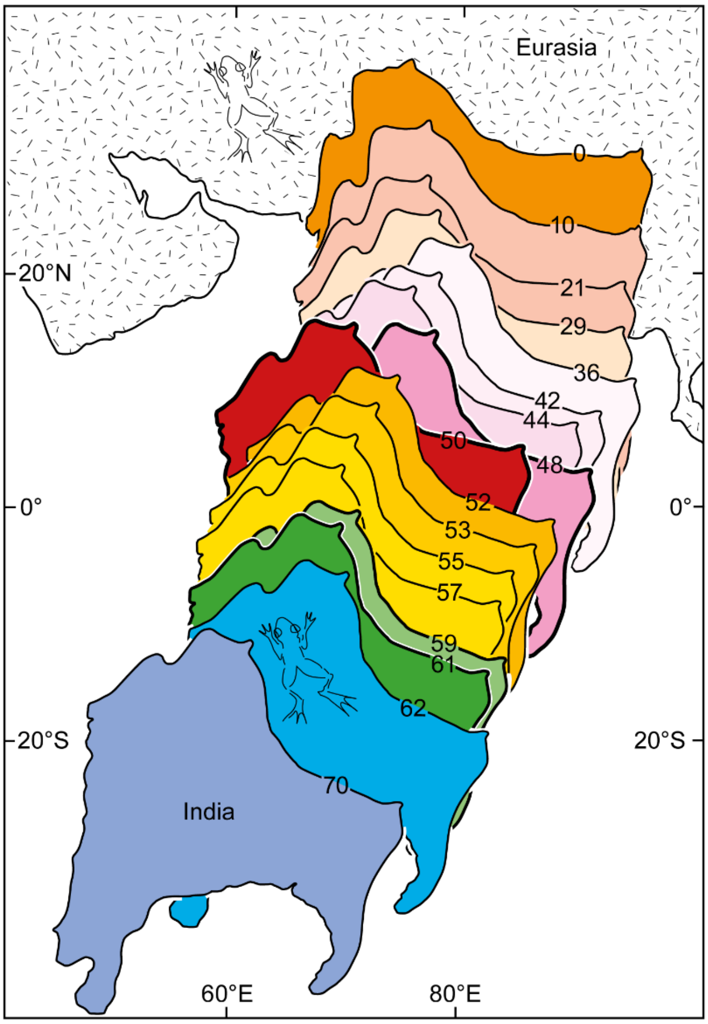
Closure of an ocean and subsequent collision of two continents result in an intricate process of thrusting and deformation and a reduction to the cessation of relative convergence between the plates when the buoyancy of the continental crust hinders subduction as a whole into the mantle. Other plates reorganize to take up the motion elsewhere. Like in Oman, the active forces responsible for collision may initiate an oceanic subduction zone at a new continental margin or intraoceanic arc system.

Tectonics of Asia shows that the behavior of continents after the collision is complex. The continuing penetration of India into Eurasia drives the growth and evolution of the Tibetan Plateau. The strain is partitioned between shortening absorbed on folds and thrusts and lateral extrusion accommodated on large strike-slip faults. Lateral heterogeneities of crustal strength determine the magnitude and distribution of deformation. Normal faulting expresses coeval east-west extension and north-south shortening in the thick continental crust of Tibet.

Plate tectonic setting

Due to continuous convergence of the Indian and Eurasian plates, the Himalaya and its adjoining region have been undergoing persistent compression since the beginning of collision 50-70 Ma ago.

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

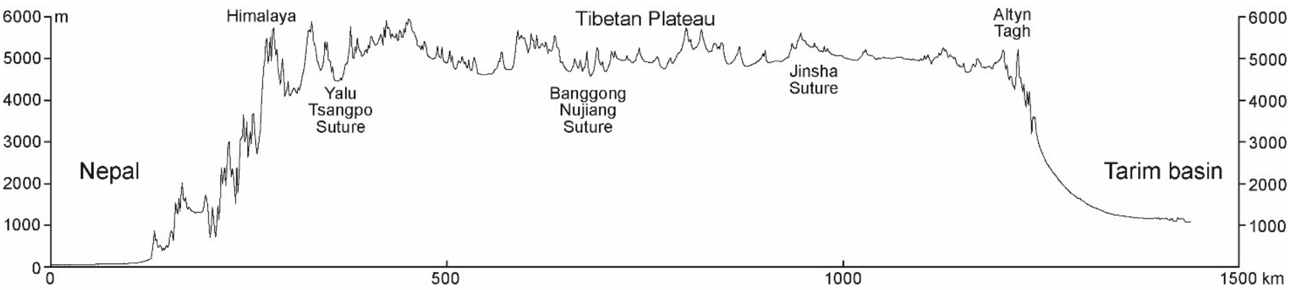


Numbered northern boundaries of India refer to ages in Ma and the corresponding position.
Frogs indicate a continental bridge at ca. 65 Ma (Jaeger *et al.* 1989 *Geology* **17(4)**, 316-319).
The smallest relative translation between 61 and 59 Ma likely points to beginning of collision.

Plate movements provided by geophysical methods (namely magnetic anomalies in the Indian Ocean and paleomagnetism, see lecture on Himalaya) indicate over 2000 km intra-continental shortening between stable India and stable Asia since the initial collision. The present-day rate of convergence is about 50 mm/yr. Seismic studies and the rate of southward advance of the foreland basin indicate that only 10 to 25 mm/yr. of shortening are currently taken up within the Himalayan thrust system. The rest of the convergence must be absorbed to the north, within and around the Tibetan Plateau. Therefore, the plateau evolution is intimately related to that of the nearby collision zone. As a corollary, any discussion of the India-Eurasia collision system cannot be complete without addressing the nature and evolution of the Asian regions around the collision zone.

Tibet

Tibet is the world's most prominent topographic effect of continental deformation. It is the largest and highest plateau on Earth, with nearly 3.10^6 km^2 at an average and uniform elevation of nearly 5000 m.



Topographic profile along 085°E longitude between latitudes N26°02' and N38°50'

The interior of the plateau is flat with internal drainage, low precipitation, and low erosion rates. It is ringed by high mountain ranges:

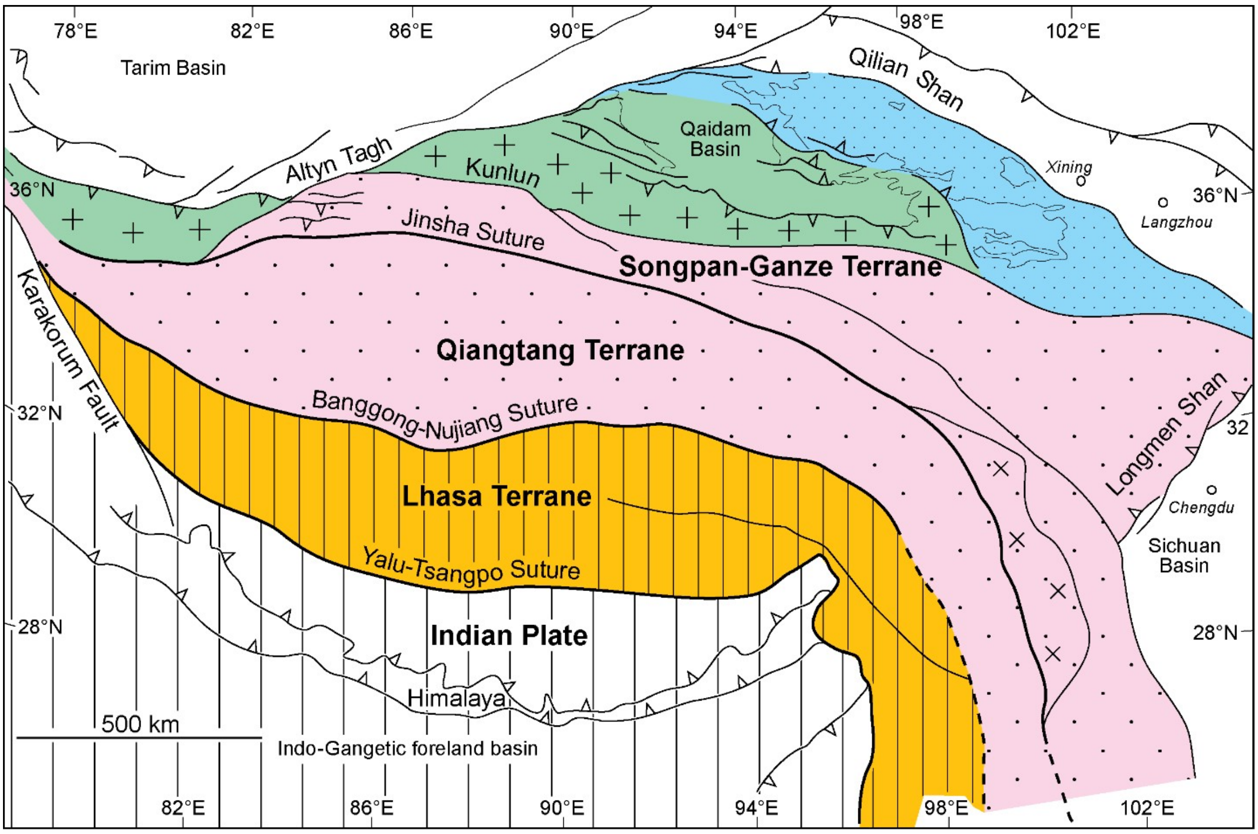
- Its northern margin follows the Kunlun - Altyn Tagh mountains, where the thin Tibetan lithosphere is thrusting the continental Asian lithosphere;
- The High Himalayas, where Tibet is thrusting the Indian continental lithosphere, are its southern border.
- The Long Men Shan, where the South China continental lithosphere is underthrusting Tibet, delineate its eastern border.
- The Karakoram-Pamir ranges define its western boundary.

These bordering mountains stand where the plateau overrides the surrounding, low-elevation sedimentary basins underlain by stable Precambrian cratons:

- The Tarim Basin to the northwest -
- The Qaidam Basin to the north
- The Sichuan Basin to the east.
- The Indo-Gangetic Basin to the south

Subsidiary mountain ranges, such as the Tien Shan and Altai exceed 4000 m in elevation.

Early investigators (18^{th} century) quickly realized and measured the gravitational attraction of large mountain ranges and concluded that a crust thicker than the average lays under mountains. Pendulum deflection smaller than expected suggested that material lighter than the mantle beneath the mountain ranges counterbalances the extra-mass of the mountain ranges above the surface of the surrounding lowlands. From this observation, the geological challenge is to know how crustal thickening has developed the mountain “roots”. Note that mountains in the ocean, on the contrary, are ranges with nearly no crust formed on the mantle, again to emphasize the large effect of different densities and buoyancy between the oceanic and continental lithospheres.



Main tectonic units of Tibet

Debates over the mode of formation of the Tibetan plateau essentially concern three fundamental questions:

(1) How 1000-2000 km of crustal shortening from collision to now are being accommodated?
(2) When did the plateau start to rise?
(3) How was its remarkably uniform elevation (ca. 5 km above sea level) attained and sustained?

These questions refer to the state of stress within the plateau, as documented by the correlation between elevation and deformation regimes: thrusting, hence horizontal compression is dominant at low elevations around Tibet, whereas N-S grabens, hence horizontal extension deforms the southern part of the Plateau, and strike-slip faulting, combining horizontal compression and extension, deforms the northern Plateau.

Shortening/Thickening: conceptual models

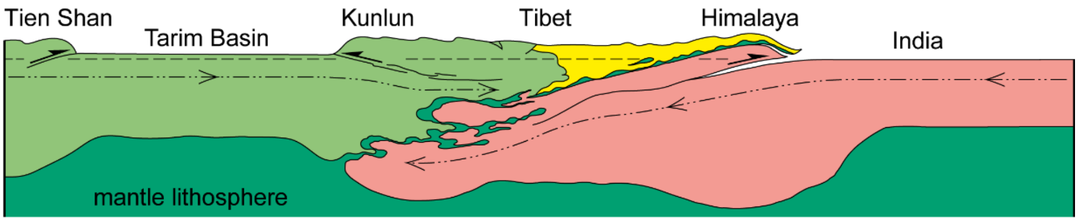
The India-Eurasia collision zone is the largest region of continental deformation on Earth. How is this non-rigid behavior of a continental plate expressed? The hypotheses advanced to explain shortening and subsequent crustal thickening fall into three major categories: crustal-scale thrusting, homogeneous pure shear, and collage.

Thrust tectonics

The large amount of thrusting derived from the structural and metamorphic geology of the Himalayas led to slightly different but consistent models:

Underthrusting of India beneath Asia

Argand suggested in 1924 that elevated areas are due to horizontal underthrusting of more than 1000 km of Indian continent beyond the modern Himalayan mountain front, beneath the entire Tibet Plateau and as far as its northern boundary in the Kunlun-Altyn Tagh fold belt. Before the collision, the surface area of the Indian block was therefore much larger than the present-day Indian Peninsula and formed ‘‘Greater India’’.



Crustal section of the India-Asia collision zone redrawn after figure 13 of
Argand 1924 *Comptes Rendus du 13ème Congrès géologique international*, Fascicule **1**, 171-372

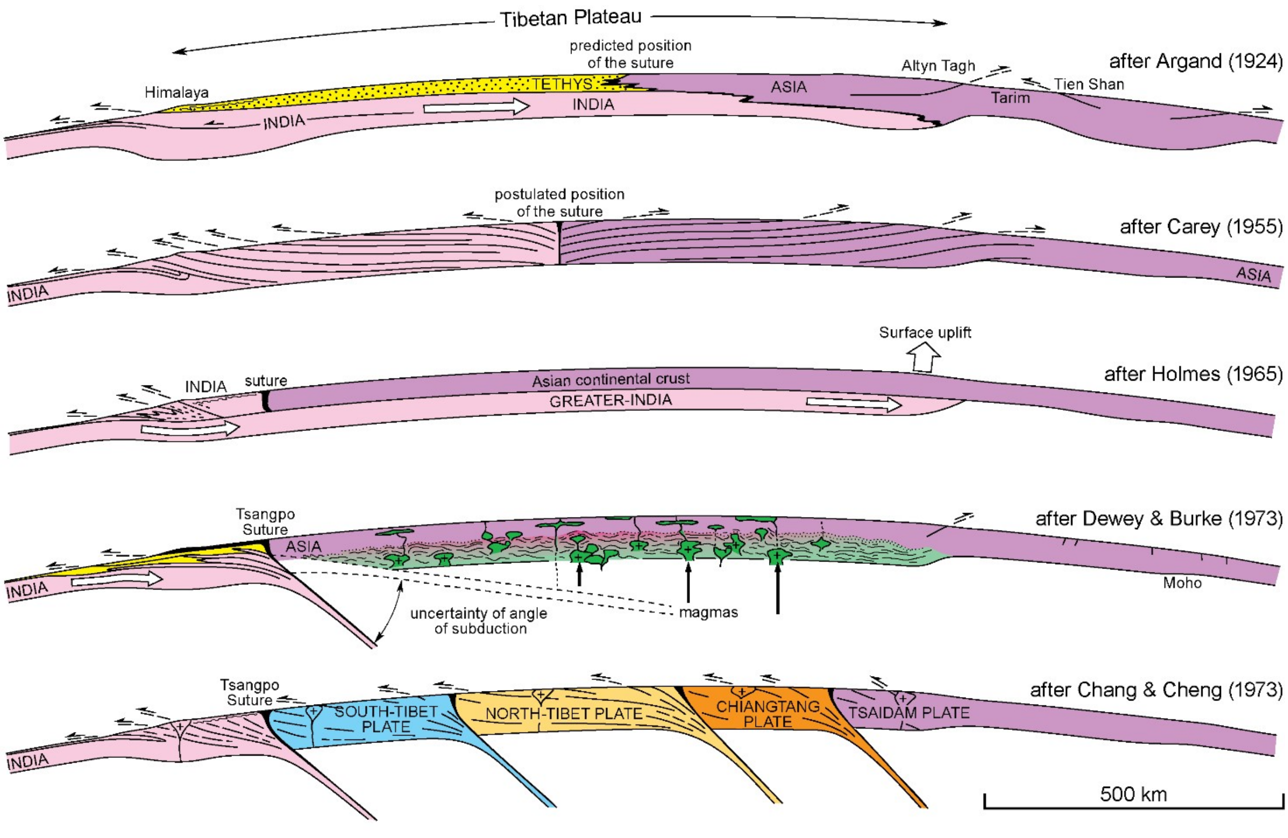
Holmes (1965) quantified the elevation of Tibet as the isostatic response of a 60 to 75 km thick crust, assuming that the density difference between crust and mantle is 400-500 kg/m^3. To explain the doubling of the continental crustal thickness compared to that of the undeformed, surrounding areas, Holmes accepted that the Indian plate underlies the Tibetan Plateau.
Two-stacked crust models inspired by Argand's interpretation involve more or less intracrustal shortening of the leading edges of the Indian and Asian continental blocks.

Crustal injection – Channel flow

An adaptation of Argand's model involves northward underthrusting (injection) of the relatively rigid Indian crust into the very weak lower crust of Asia. In some ways, the low viscosity, migmatitic crust envisioned in the "channel flow" model discussed for the Himalayas would offer the required mechanical decoupling between the upper crust of Tibet and the underthrusting Indian lithosphere.

Distributed thrusting

Intracrustal shortening and thickening result from bivergent thrusting in the leading edges of both India and Asia. Crumpling would be symmetrical about a median suture.



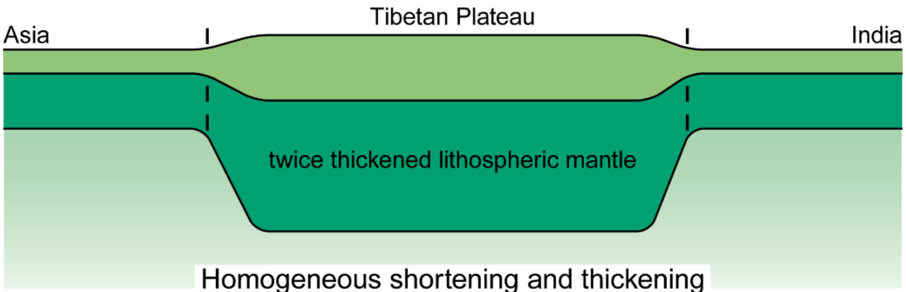
Crustal models of the Tibetan Plateau

Synthesis from Powell & Conaghan (1975) *Geology*, **3(12)**, 727-731

Homogeneous shortening and thickening

Alternatively, the Tibetan plateau has been attributed to homogeneous, twice normal thickening of the hot and weak continental lithosphere of Tibet regarded as a non-Newtonian viscous continuum. The Tibetan terranes as part of a hot ductile Asia are shortened and thickened in an accordion fashion in front of the advancing cold and rigid India subcontinent.

50% N-S contraction (ca 1000 km) of the initial area to produce today's surface of the Tibetan plateau must have been accompanied by as much ductile strain at deeper levels. It is logical, therefore, that folds in Tibet trend predominantly east-west. At shallow levels, shortening was essentially brittle.



Homogeneous shortening and thickening
after England & Houseman (1988) *Phil.Trans.Roy.Soc.London,* **A326(1589)**, 301-320

Symmetrical or asymmetrical crustal stacking wedges are variants of bulk homogeneous thickening in response to the shortening of the Asian crust.

Collage

The Tibetan plateau exposes at least three major, nearly west-east suture zones. From south to north, these are:

- The Yalu-Tsangpo Suture, which separates the Indian Plate to the south from the Lhasa Block to the north.
- The Late-Jurassic to Early Cretaceous Banggong-Nujiang suture zone, approximately 300 km north of the Yalu-Tsangpo suture, separates the Lhasa Block to the south from the Qiangtang Block to the north.
- The Triassic Jinsha suture separates the Qiangtang Block from the Songpan-Ganze terrane to the north.

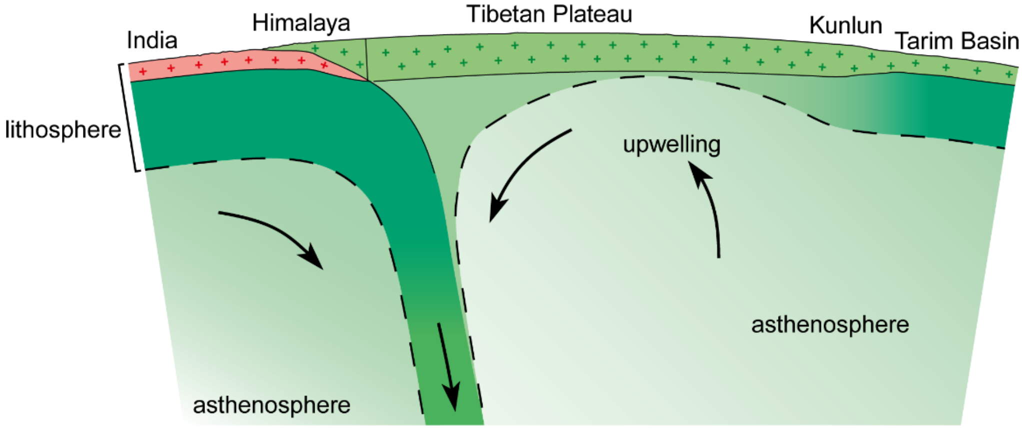
These three sutures represent relicts of the Neo, Meso, and Paleo-Tethys oceans, respectively. Accordingly, Tibet has been attributed to the successive collisions of several continental blocks, probably originating from the break-up of Gondwana, with Asia. Accretion of continental and/or island-arc-type plates thus contributed to the growth of the Asian margin southwards. Two more Paleozoic sutures exist in Asia, further north. Separate events are correlated with the five "tectonic cycles" that dominated the Phanerozoic orogenic history, namely Caledonian (early Paleozoic), Hercynian (late Paleozoic), Indo-Sinian (early Mesozoic), Yenshanian (late Mesozoic), and Himalayan (Cenozoic).

Crustal thickening and plutonism are depicted as having repetitively occurred within the underthrusting southern plates. The model highlights the relative antiquity of the penetrative deformation and metamorphism of many of the rocks of the Tibetan plateau but implies that successive collision and accretion events along the southern margin of Asia produced the plateau throughout Phanerozoic times.

Convective removal of the lithospheric mantle

Tibet as a whole is inferred to have risen significantly above its current altitude as its crust buoyantly rebounded because of the removal of part of its thickened lithospheric mantle, which triggered extension and volcanism.

However, magmatism that occurred after the collision with India was neither widespread and voluminous nor synchronous. Magmas derive from partial melting of the subcontinental lithospheric mantle and, to a lesser degree, the crust, but not from asthenospheric or mantle plume sources.



Dynamics of the convective mantle with thermal erosion of the lithospheric mantle beneath Tibet
redrawn after Molnar 1988 *Nature* **335(6186)** 131-137

The localization of Cenozoic calc-alkaline magmatism along three distinct belts of different ages, following the three principal sutures, is more consistent with melt sources related to subduction than with wholesale convective thinning of the lithospheric mantle.

Inconsistencies and shortcomings

The Yalu-Tsangpo Suture is located near the southern edge of the plateau. Thus, models of distributed thrusting symmetrical with respect to the collision site can be rejected.
Chief discrepancies between the models and the geological and geophysical data are listed as follows.
(1) In Argand's model, the underthrust Indian continent extends all over beneath Tibet as far north as the Altyn Tagh - Kunlun mountain chain portrayed in tectonic style like the Himalayas. Wide-angle seismic data are not consistent with the presence of a continuous continental slab for several hundred kilometers beneath Tibet.
(2) Geological sections across the entire Tibetan plateau do not record the surface expression of 50% crustal shortening in an accordion fashion for doubling the Asian crust thickness.
(3) Post-collision underthrusting of several hundred kilometers of continuous Indian crust beneath Tibet implies that uplift of the plateau proceeded from south to north during the Tertiary. Uplift was not produced by direct continent-continent collision, which occurred in the early Tertiary; instead, it developed rapidly at least 30 Ma later during the Miocene.
(4) Underthrusting requires "mantle peeling" (delamination) beneath the Asian continental crust which begs two serious questions:
What happens to the lithosphere below the collision (peeling or thermal erosion)?
Why does continental buoyancy not prevent significant underthrusting?
(5) Injecting the cold Indian crust into the hot Asian crust would stop heat supply from the asthenosphere and cease magmatism in the southern Lhasa Terrane, in contradiction to geological information. In any case, the high strength of the Indian continental lithosphere makes it difficult to decouple the crust from its lithospheric mantle, as required in injection models. S wave velocities seem to be inconsistent with a cold lithosphere as that of India beneath Tibet.
(6) Collages through Phanerozoic times provide no mechanism to explain why plateau uplift did not occur until the late Tertiary.

The main problem with these models concerns the mechanism of thrusting one buoyant continent under another. Underthrusting the Indian continent is less restrained if the dense Asian lithosphere is replaced by lighter material. The details of such a process are unclear. The problem can be sidestepped by ignoring the mantle part of the Asian continental lithosphere, but this begs the question as to what happens to this part of the lithosphere, or whether it does exist.

Surface uplift

Surface uplift = uplift of rock – exhumation (erosion).

The collision between the Indian and Asian plates and their continued convergence since ca. 50 Ma drive elevation changes of the Tibetan Plateau. The elevation history of the plateau from collision to the present is a major question inherently linked to research on crustal thickening. The timing of surface uplift of Tibet receives much attention because of potential links between (1) high topography and change in regional and global climate, (2) southern Asian paleo-ecology, and (3) ocean chemistry.

Uplift and initiation of the monsoonal weather system

The high-elevation Tibetan Plateau provides a broad source of heat in the lower atmosphere during the summer, which creates a vast, low-pressure system over central Asia, drawing in warm and humid air from the Indian Ocean towards Tibet. Airflow is forced upwards when it impinges on the physical barrier of the Himalaya, causing intense monsoon precipitation on the southern slopes of the plateau. Dating of loess deposits in China attests to the strength of winter monsoon winds as early as 22 Ma.

Uplift and voluminous discharge of sediments

Uplift of an area as large as Tibet has likely caused region-wide climate changes that have intensified erosion of the mountain range. The voluminous run-off due to monsoons feeds large rivers:

- the Ganges, Indus, Sutlej, and the Brahmaputra that flow south out of the Tibetan Plateau through the Himalaya;
- the Salween that descends off the eastern margin of Tibet into southeast Asia;
- the Mekong, the Yangtze, and the Huanghe that flow eastwards to debouch into the East and South China seas.

These major rivers are antecedent, meaning that Tibet has been lifted beneath them. These rivers now flow through deep gorges. Effect of uplift has been the erosion and discharge of tremendous volumes of sediments, much of which has accumulated in the vast marine fans of the Bay of Bengal and the Arabian Sea at the outlets of the Ganges and Indus rivers, respectively. Sedimentation rates deduced from seismic profiles in the South China Sea suggest an active monsoon by the early-mid Miocene (11–16 Ma). Stable-isotope studies, also from the South China Sea, indicate changes in terrestrial ecosystems that can be related to the evolution of East Asian monsoon at this time. Large masses of organic carbon are buried in sediments, hence sequestering carbon from the reservoir available for recycling between atmosphere and surface, and so forcing a cooling trend on the global climate.

Uplift and ocean chemistry

Combined mechanical erosion and chemical dissolution from the vast river system causes important chemical fluxes from the continent to the oceans. Rivers from Tibet contribute 25% of all the dissolved matter transported to the oceans by rivers worldwide. Therefore, these rivers are responsible for extremely high silicate weathering fluxes, which is a major sink for atmospheric CO_2. For this reason, some authors link uplift of Tibet enhancing silicate weathering fluxes to the global cooling during the whole Cenozoic. Although there is continuing debate on the coupling between surface uplift of Tibet and global changes, some models suggest that average temperatures on the Earth would be warmer by about 1–6 °C if there were no large and elevated plateau in Central Asia. Isotopic compositions of shells from sediments deposited in the Himalayan foreland basin suggest a strong Indian monsoon before 10.7 Ma with the climate becoming significantly arider after 7.5 Ma.

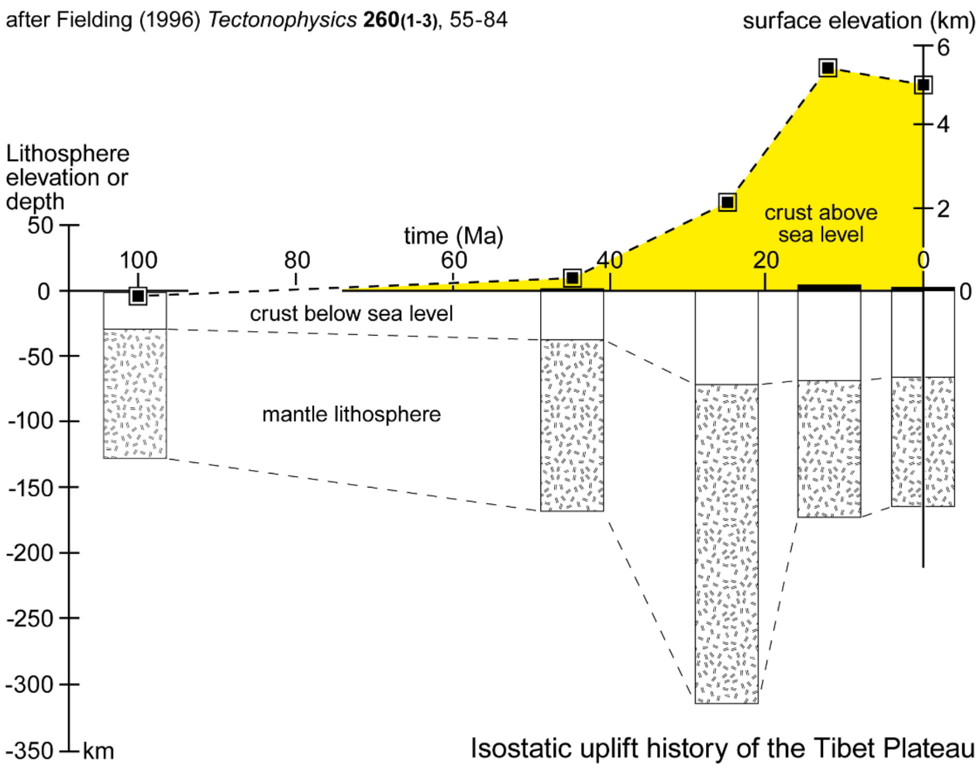
Age of the Tibet uplift

Two major pulses of Tibet uplift have been considered:

- One between 21 and 17 Ma (formation of the Himalayan relief?).

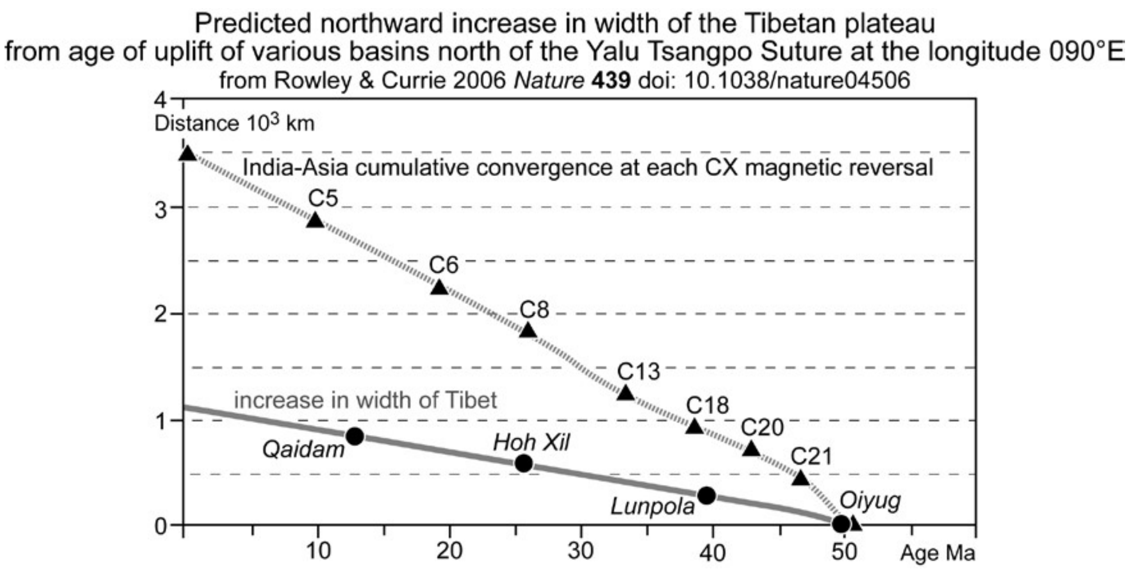
- The other between 11 and 7 Ma (Tibet itself?) assumes that the late Miocene N-S grabens are symptomatic of a collapsing thickened, high plateau, and their age thus gives the timing of the uplift. This ca. 8 Ma old event would have initiated, or at least strengthened the seasonal storm system known as the Asian monsoon that now shapes life in Southeast Asia.

Limited evidence suggests that the major uplift episode is post-Miocene. The available data, based on fossil flora and stable (along with hydrogen) isotope measurements, however, do not further resolve the details of the uplift history.



Diachronous uplift

The oxygen-isotope composition of calcareous minerals in Tibetan lake sediments has been used to infer the elevation differences between the water source in the ocean and the elevation at which the rain or snow fell.



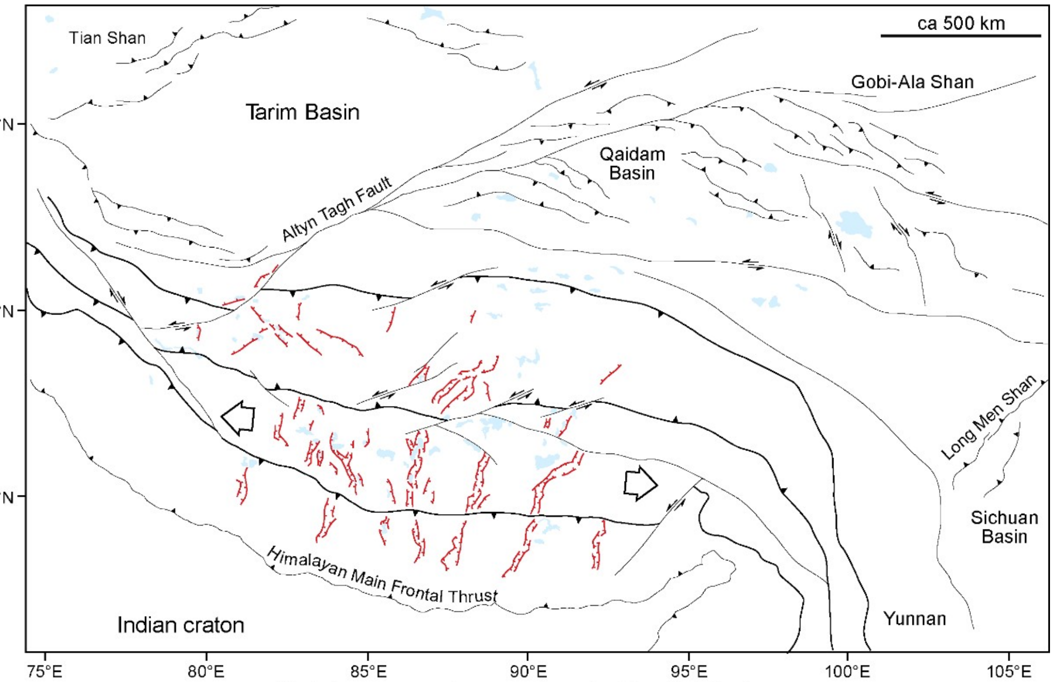
$\delta^{18}O$ paleo-altimetry suggests that surface uplift to 4000 m or more above sea level continuously grew northward across the Tibet plateau over the last 40-50 Ma. This is intimately linked to the timing of convergence between India and Asia and likely expresses the surface response to the thickening of Tibet's crust. South Tibet was elevated during the Eocene, central Tibet in the Oligo-Miocene, and northern Tibet in the Plio-Quaternary. These results support the idea that the Tibetan plateau is a long-standing topographic feature that arose from the collision between the Indian and Asian continental plates and is not the more recent product of other, deeper-seated processes.

Graben

Southern Tibet offers perhaps the most striking example of orogenic extension in the context of continental collision.

Description

A series of approximately north-south grabens and kinematically linked strike-slip faults is observed from the Himalayas in the south to the Qiangtang terrane in the north and from longitude 78°E in the west to the Namche Barwa syntaxis in the east. These grabens feature widespread, Late Cenozoic to present-day, E-W crustal extension although most of the high altitude and the thick crust of the Tibetan plateau result from N-S shortening between India and Eurasia.



Pleistocene graben system in South Tibet

open arrows = average extension direction after Armijo *et al.* 1986 *J.Geophys.Res.* **91-B14**, 13803-13872

Active normal faulting is still accommodating about 10 mm/yr E-W extension while India is still moving northwards at a rather uniform convergence rate of 40 - 50 mm/yr. relative to stable Eurasia. Supportively, focal mechanisms of the largest seismic events in Tibet show combinations of normal and strike-slip faulting with *T* axes approximately oriented east-west. GPS data showing lengthening of the baseline between Leh (Ladakh) and Lhasa (southeastern Tibet) at 17.8 ± 1 mm/yr. and between Leh and Bayi (farther to the southeast) at 18 ± 3 mm/yr. corroborate ongoing E-W extension.

Whereas Tibetan grabens are generally north-trending, their orientation fans from a northwest direction in the west to a northeast direction in the east. This pattern is explained by collisional stresses along the Himalayan arc and highlights the importance of ongoing collision in influencing the present-day state of stress in the Tibetan upper crust.

Age

Under the assumption that widespread extension in southern Tibet results from a single phenomenon, the age of graben initiation holds great significance: it marks a transition in stress regime from compression to extension. E-W extension began diachronously, at 18–14 Ma in the southern plateau (age of north-trending dikes) and at ca. 4 Ma in the north.

Interpretations

Extension of Tibet, despite on-going convergence between India and Asia, has been variably attributed to five, possibly linked processes involving lithospheric and/or local forces.

Expansion of the Himalayan arc

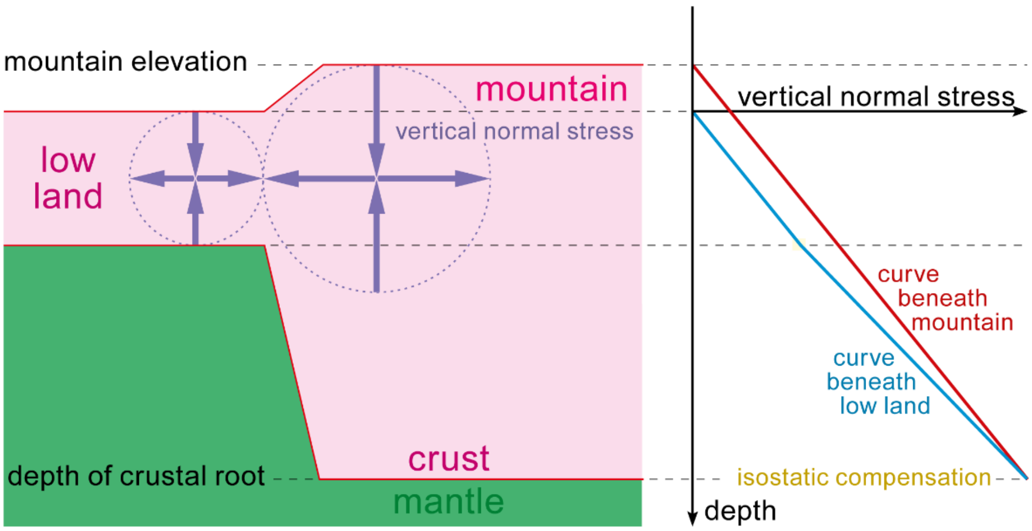
The Himalayan range is curved. The extension would express the circumferential lengthening of the initially linear Himalayas now bending between its western and eastern extremities. However, this model implies E-W compression in the core of the orogenic arc, for which there is no geological evidence.

Strain partitioning due to oblique convergence between India and Asia

The extension would accommodate local geometric and displacement conditions. Indeed, the convergence vectors of India towards stable Asia are normal to the strike of the Himalaya only in the Nepal region. There is an increasing Himalaya-parallel, wrench component towards the western and eastern extremities. Transpression can cause a range-parallel extension. Geodetic data tend to support this interpretation for present-day deformation in the Himalaya.

Radial spreading due to gravitational collapse

Tibet has a thicker crust than neighboring lowlands. Consequently, the lithostatic pressure at any depth beneath Tibet is higher than the lithostatic pressure at the same level below the lowlands, down to the compensation depth. The **gravitational potential energy** is the area beneath the lithostatic pressure curves of each region. Excess gravitational potential energy caused by the ca 5000 m elevation difference between the Tibetan plateau and the surrounding lowlands (assuming the same rock densities in both regions) can cause crustal collapse. Extension in the Tibetan Plateau would thus express the mechanical balance between the gravitational buoyancy force of the plateau and the tectonic compressive stresses. Three-dimensional viscoelastic models suggest that as long as the plateau was below 50% of its present elevation, strike-slip and reverse faults were dominant with no. The significant E-W crustal extension would have begun only when the plateau reached ~75% of its present elevation. Due to this maximum sustainable elevation, the plateau tends to spread in all directions towards its margins that expand outward.



modified after Tapponnier & Molnar 1976 *Nature* **264(5584)** 319-324
and Bird 1991 *J.Geophys.Res.* **96(B6)** 10275-10286

Delamination

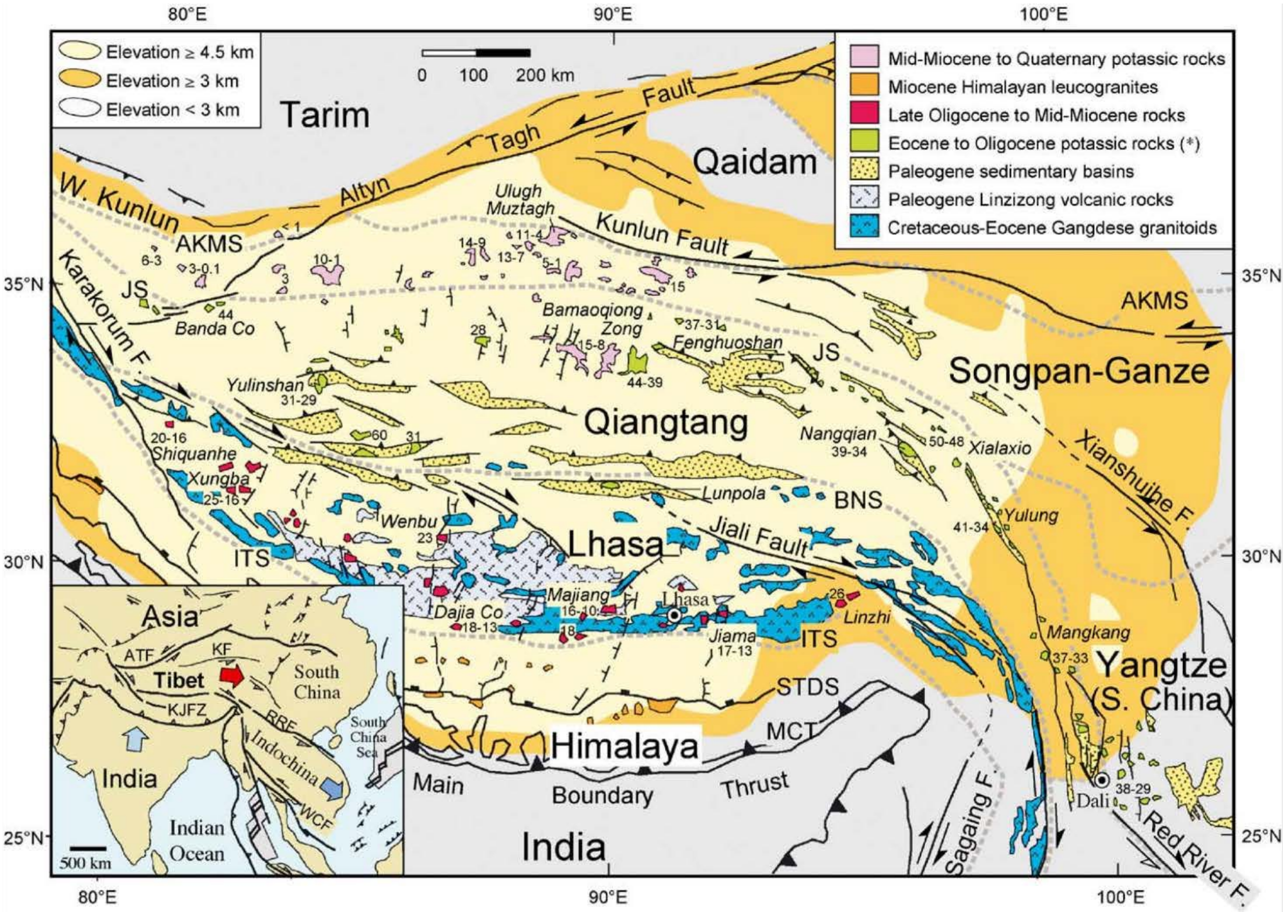
This hypothesis states that mantle convection triggers convective thinning of the lithosphere after a period of gradual thickening. Subsequent warming weakens the middle and lower crust, which would behave as a continuous, viscous fluid able to flow laterally. The weakening of the continental crust by conductive warming would require tens of millions of years unless other processes such as the removal of mantle material or frictional heating are involved. The isostatic response to this event is rapid uplift until the plateau reaches an elevation that marginal stresses cannot hold. The otherwise undocumented convective removal and sinking of the dense, lower part of the mantle lithosphere from beneath the Tibetan Plateau may thus have provided the excessive, gravity-isostasy-driven lithospheric body forces needed to cause plateau uplift and support the high topography. The resulting gravitational potential energy may have caused the Tibet lithosphere to extend horizontally and to thin out in a predominantly E-W direction. This hypothesis is now discarded since surface wave tomography shows that a continuous mantle layer underlies Tibet.

Rollback of the Pacific subductions

The rapid ESE-WNW stretching in the Tibetan Plateau results in an eastward movement of crustal material out of India's path, towards lithospheric space opened along the Pacific boundary of Asia.

Magmatism

Magmatism younger than India–Asia's early collision is widespread throughout Tibet. Spatial, geochemical, and temporal variations of this magmatism suggest that the entire plateau was unlikely caused by a single event. These variations further imply that the thermal structure of the Tibet lithosphere has also evolved.



Age distribution of magmatic rocks in Tibet; from Chung *et al.* 2005 *Earth Sc. Rev.* **68(3-4)**, 173-196

Four principal magma suites are delineated:

Cretaceous to Eocene arc magmatism in the southern Lhasa Terrane

Arc magmatism began in the Early Cretaceous (ca. 130 Ma) and lasted until the late Eocene (ca. 40 Ma), with a possible magmatic gap between 75 and 60 Ma. Post-collision magmatism ranges from basalt to rhyolite with calc-alkaline and locally sub-alkaline geochemical features and seems to be restricted to the southern part of the Lhasa Terrane. Isotopic data suggest significant involvement of a juvenile mantle component from the asthenosphere in the magma generation.

Eocene to Oligocene magmatism in the Qiangtang Terrane

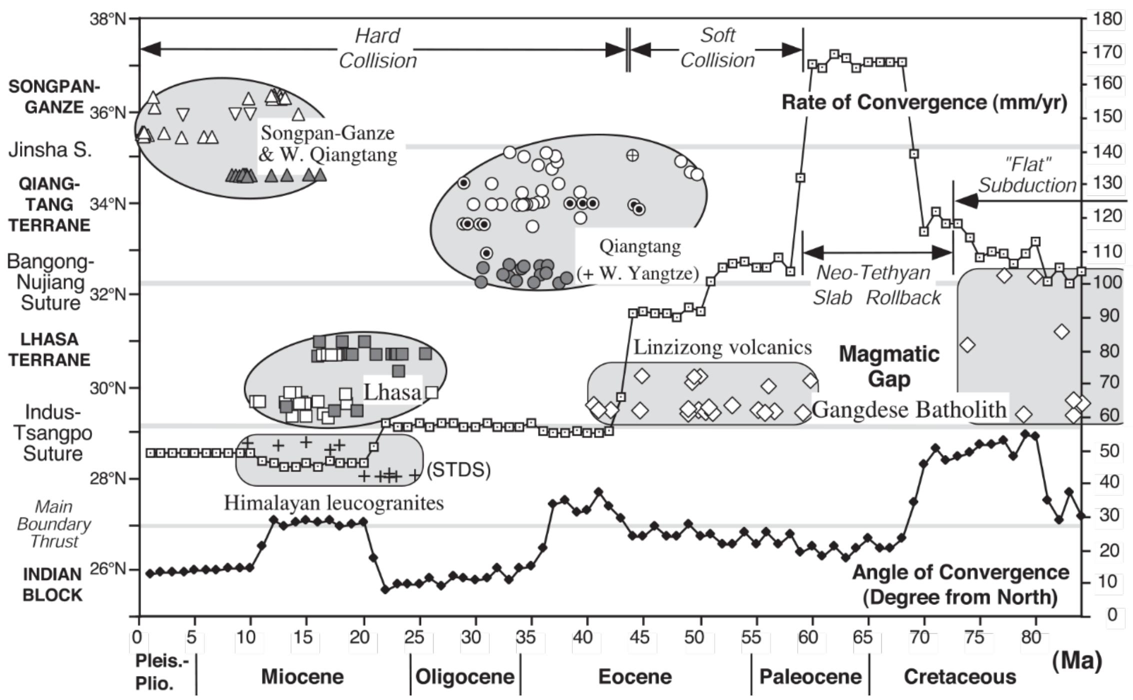
A magma suite of shoshonitic and ultrapotassic rocks characterized by high to very high alkali contents occurred over central Tibet (the entire Qiangtang Terrane) between ca. 50 and 30 Ma. Geochemistry suggests an origin by small degrees of melting of enriched lithospheric mantle.

Late Oligocene to mid-Miocene magmatism in the Lhasa terrane

In the southern Tibetan plateau, volcanic plugs and dikes associated with grabens range in age from ca. 25 to ca. 8 Ma. Therefore, there is a clear geographical relation between late tertiary volcanism and local extension. Geochemical systematics suggests that these post-collision volcanic rocks were derived from a low degree of partial melting of a metasomatized lithospheric mantle (phlogopite bearing peridotite). The calc-alkaline rocks include 'adakites' which derive from the partial melting of the eclogitized lower crust. This chemical signature is not related to the active subduction of oceanic lithosphere beneath the southern part of Tibet between ca. 25 and 8 Ma.

Mid Miocene to Quaternary volcanism

Miocene ultrapotassic, shoshonitic, and minor calc-alkaline volcanism occurred again in northern Tibet at ca. 15 Ma and became widespread and semi-continuous after ca 13 Ma or later. The most recent volcanism, reaching into the Quaternary is associated with small pull-apart basins along the northwestern boundary of the Tibetan plateau and is K-poorer than the older potassic magmatism. This young volcanism occurs only in the western part of northern Tibet, in an area that broadly corresponds to the region under which high temperatures in upper mantle have been inferred from seismic data.



Age distribution of magmatic rocks across Tibet; from Chung *et al.* 2005 *Earth Sc. Rev.* **68(3-4)**, 173-196

Three main mechanisms may explain the genesis of Cenozoic potassic volcanism in the Tibetan plateau.

- (a) It is the consequence of lithospheric delamination of a large portion of the mantle lithosphere. This mechanism is unlikely because regional variation in age and isotopic composition is not consistent with simultaneous lithosphere delamination beneath the whole of Tibet.
- (b) Slab roll back and breaking off. Rollback along the Tsangpo Suture may have been responsible for initiating the ''back-arc'' extension in the Qiangtang terrane that caused the east–west-trending sedimentary basins and associated 65-45 Ma magmatism. Generally, the hot asthenospheric mantle replaces the cold subducted slab after break-off at ca 45 Ma, producing heating of the overlying plate for several million years after the detachment.
- (c) Intracontinental subduction involving various volcanic belts with distinct ages fitting major thrusting events once the Indian collision eventually caused the Qiangtang terrane to switch from an extensional to the compressional regime in Oligocene time.

Deep structures

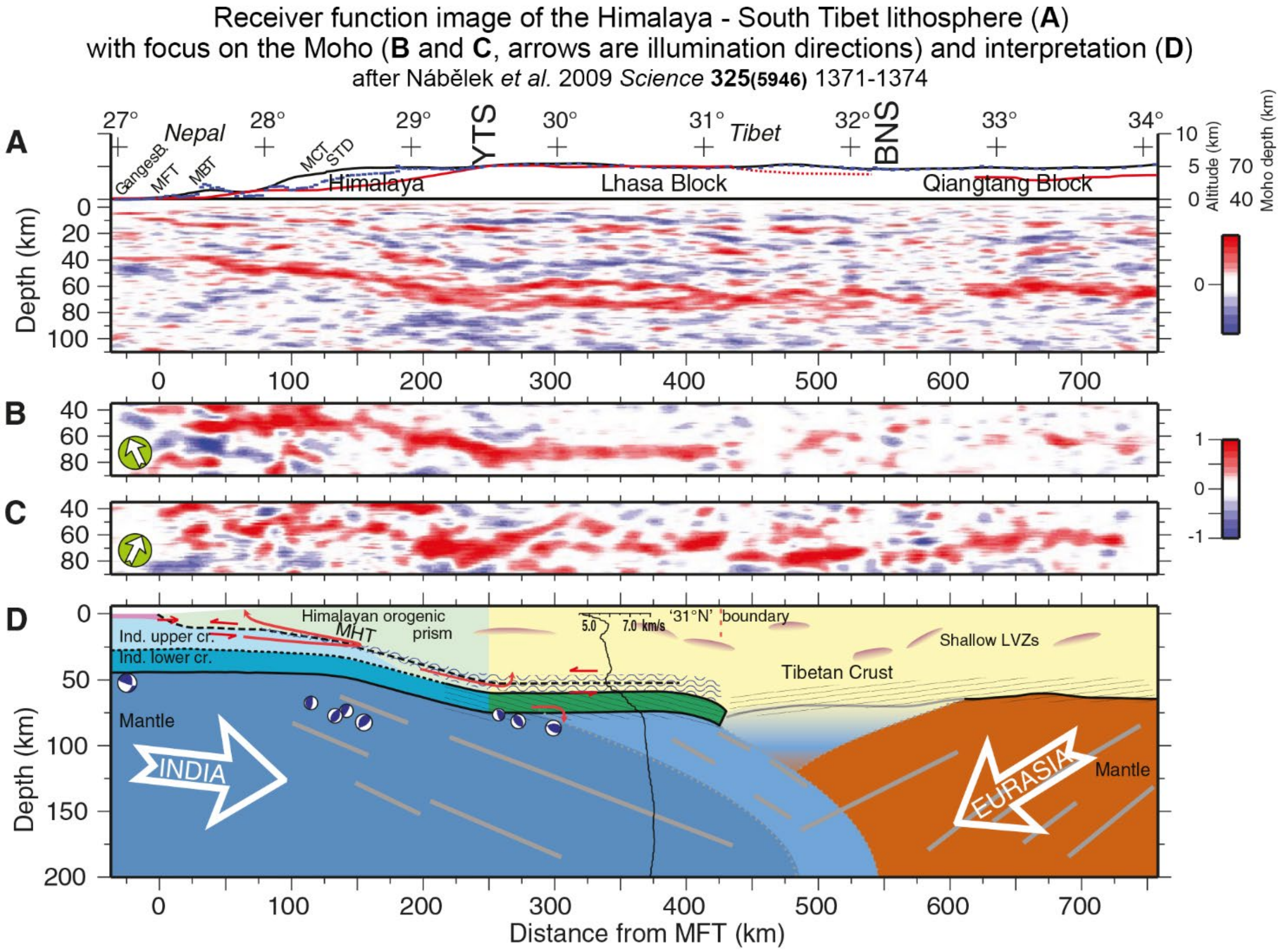
An accruing number of seismic and teleseismic data constrain the structure and the thickness of the crust and upper mantle below Tibet. They show that the uniform elevation of the Tibetan Plateau hides a heterogeneous structure in the crust and lithospheric mantle. In particular, the Banggong-Nujiang Suture is a steep, north-dipping fault zone that extends down to at least 35 km depth. It marks the major boundary between southern and northern Tibet, with contrasting crustal and mantle properties. This boundary may coincide with the northern edge of the underthrust Indian lithosphere.

Crustal structures

Geophysical studies, utilizing the body and surface waves, refraction, and gravity, show that the 60 to 70 km crustal thickness under southern Tibet becomes 10–20 km thinner in the north, in the Qiangtang and Songpan–Ganze Terranes. However, most earthquakes are shallower than 25 km everywhere. The deeper crust is likely ductile.

Southern Tibet

The crust is thickest (c. 70–80 km) under the Lhasa Terrane, where the crust-mantle transition is particularly thick. The upper boundary of a low-velocity zone at 25-40 km depth suggests a partially molten upper-to-middle crust. Yet refraction analyses do not require a large amount of melt. The high magnetotelluric conductivity of this middle crust may be due to saline fluids.



Central and northern Tibet

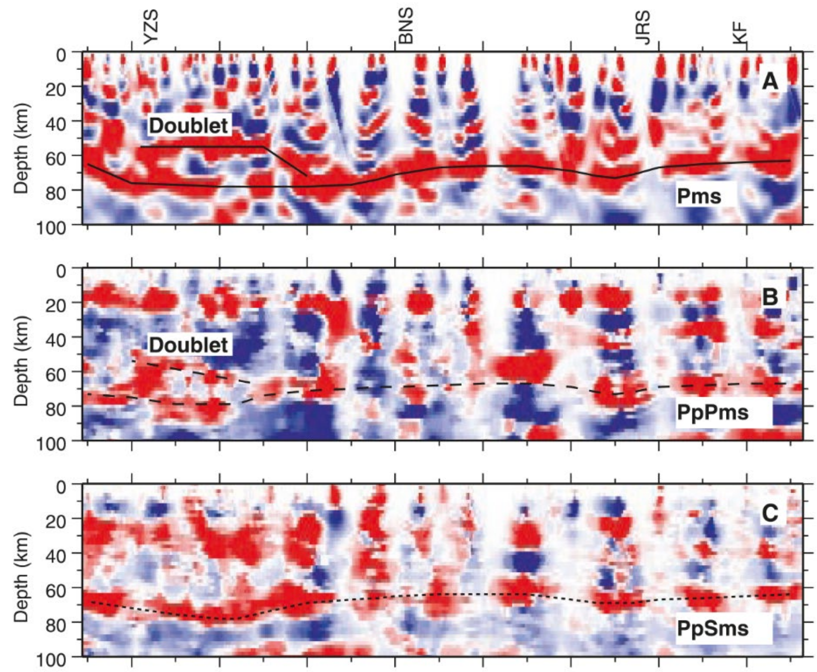
The lower crust of Central Tibet is highly reflective, in contrast with the lower crust in the Himalayas and southern Tibet. This difference may result from events that do not occur in the Indian Plate but took place during the formation of, or ongoing within the plateau.
Seismic profiles show that the plateau is thrust northward over the Tarim Basin.

Moho

Different authors using different techniques report variations of more than 20 km in the Moho depth at the same place. Combined teleseismic and variable Vp/Vs ratios define different Moho depths on both sides of the Banggong-Nujiang Suture.

Southern Tibet

Earthquakes occur beneath southern Tibet and the High Himalaya to depths of 70–80 km.
The Moho has a smooth vault shape beneath the northern Lhasa Terrane where the maximum thickness is about 78±3 km, about 100 km north of the Yalu Tsangpo Suture. The shallowest depth is 65±3 km about 100 km south of the Banggong-Nujiang Suture.



Crustal section across the Tibetan plateau with direct conversion (**A**) and two multiples (**B** and **C**) from SSE (left) to NNW (right).
after Kind *et al.* 2002 *Science* **298(5596)** 1219-1221

Wide-angle reflection data show distinct and prominent, c. 20-km offsets of the Moho associated with imbrication of the crust-mantle boundary and, consequently, a decoupling zone within the lithospheric mantle below the up to 70-80 km thick crust. If this crust-mantle topography is due to post-Miocene disruptions, as suggested by geological data, crustal thickening since the Miocene did not occur through mere underplating of several hundred kilometers of continuous Indian crust beneath Tibet (600-1000 km with a mean motion of 3-5 cm/yr. since 20 Ma).

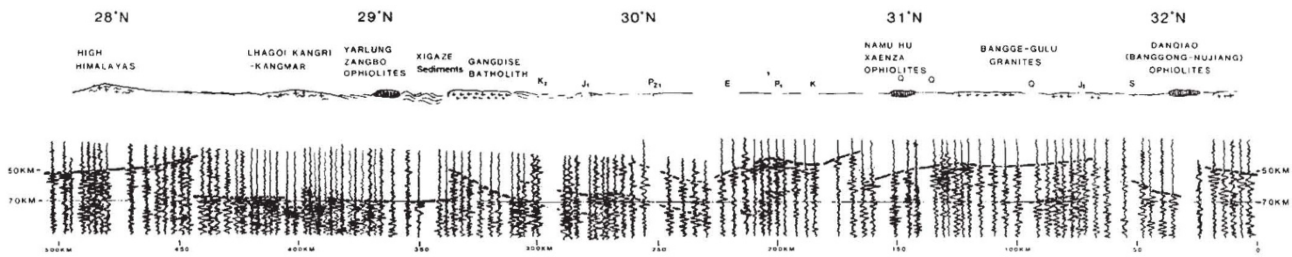
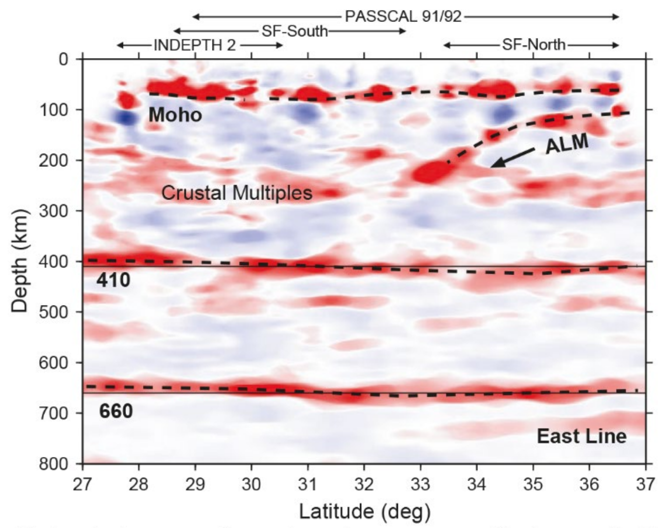


Image of Moho reflections and topography of the crust-mantle boundary beneath Tibet
from Hirn et al. 1984 Nature **307(5946)** 25-27

Central and northern Tibet

The Moho is shallower under the Qiangtang Block whose crust is about 65 km thick and displays a trough ~50 km north of the Banggong-Nujiang Suture. Further north, the Songpan-Ganze Terrane has a ca. 55 km thick crust. The Moho is bent and dips southwards below the northern front of Tibet, which reflects the underthrusting of the Tarim crust beneath the bordering Altyn-Tagh-Kunlun Mountains.



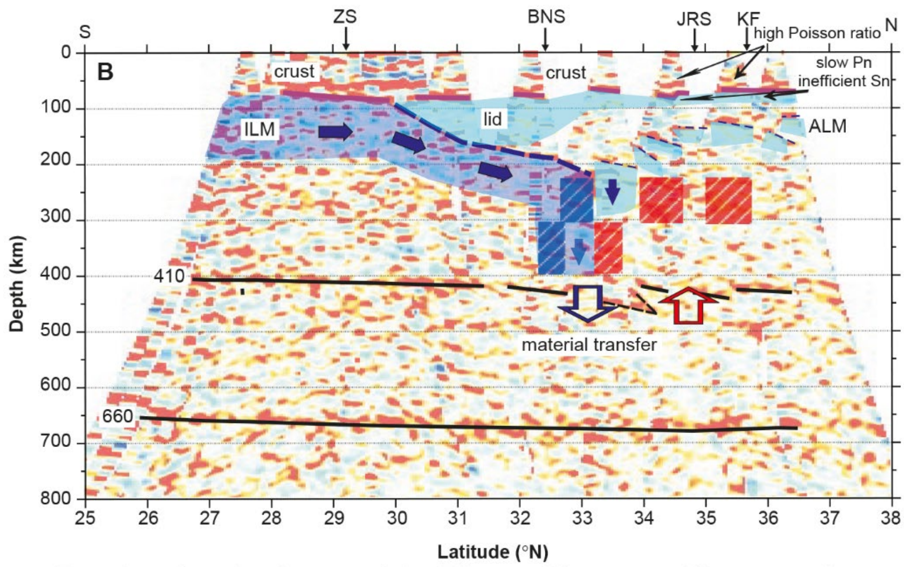
Seismic image of crust and upper mantle beneath Tibet
(ALM = Asian Lithospheric Mantle)
from Kind *et al.* 2002 *Science* **298(5596)** 1219-1221

Lithosphere

The lithosphere beneath Tibet appears thinner than beneath India, indicating that at present the Indian Plate is not underthrusting the entire Tibetan Plateau and that Tibet is not a typical shield region. P and S waves also indicate that the upper 30-40 km of the mantle is lithospheric. This precludes models in which the mantle lithosphere has been replaced with asthenospheric material to explain the anomalously thin mantle lithosphere beneath northern Tibet. There is additional evidence that the Banggong-Nujiang Suture separates different lithospheres.

Southern Tibet

P and S wave velocities show that the base of the Indian lithosphere dips northward from a depth of 160 km beneath the Himalayas to a depth of 260 km just south of the Banggong-Nujiang Suture, where the high-velocity mantle lithosphere beneath South Tibet and the Lhasa Terrane abruptly decreases. Such a presumably cold and strong mantle is consistent with the underthrusting of the Indian continental lithosphere to about the middle of the Tibetan Plateau. Tomographic images further suggest that the Indian lithosphere has an almost vertical northern edge, sinking along the Banggong-Nujiang Suture down to about 400km depth.

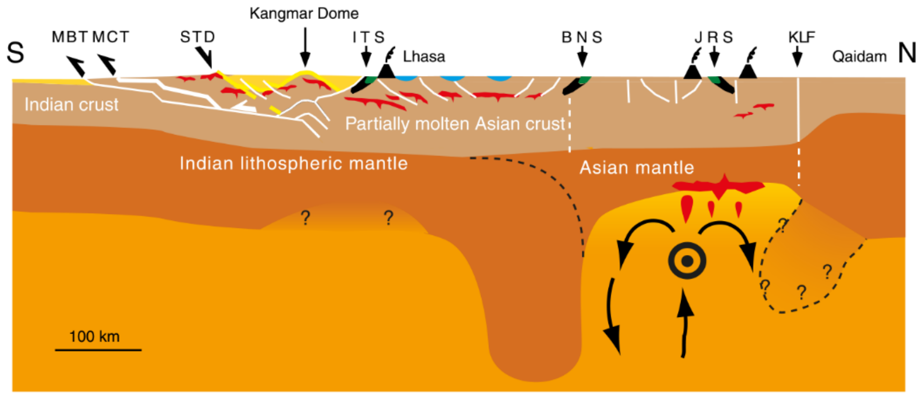


Receiver function image of the Tibetan Plateau and interpretation
from Kosarev *et al.* 1999 *Science* **283(5406)** 1306-1309

A consequence of this down-welling would be a deficit of the asthenosphere, which an up-welling counterflow should balance. This could explain the warm mantle beneath north-central Tibet.

Central Tibet

North of the Banggong-Nujiang Suture, slower P and S wave propagations point to a presumably warm and weak mantle. The base of the lithosphere is nearly horizontal at ca. 100 km depth between the Banggong-Nujiang and Jinsha sutures. The attenuation in seismic wave velocity may reveal a partially molten lithosphere. This information implies a step of about 150 km between the lower boundaries of Indian and Asian lithospheres along the Banggong-Nujiang Suture.



Interpretation of current processes in the mantle beneath Tibet
from Tilmann *et al.* 2003 *Science* **300(5624)** 1424-1427

Teleseismic P wave tomography suggests the upwelling of low-velocity material at 150-200 km of the surface. The overall northward thinning of the crust coupled with the essentially uniform surface elevation of the plateau is consistent with northern Tibet being underlain by somewhat thinner crust until the Qaidam basin, which is isostatically supported by its relatively low-density, hot upper mantle compared to that of southern Tibet.

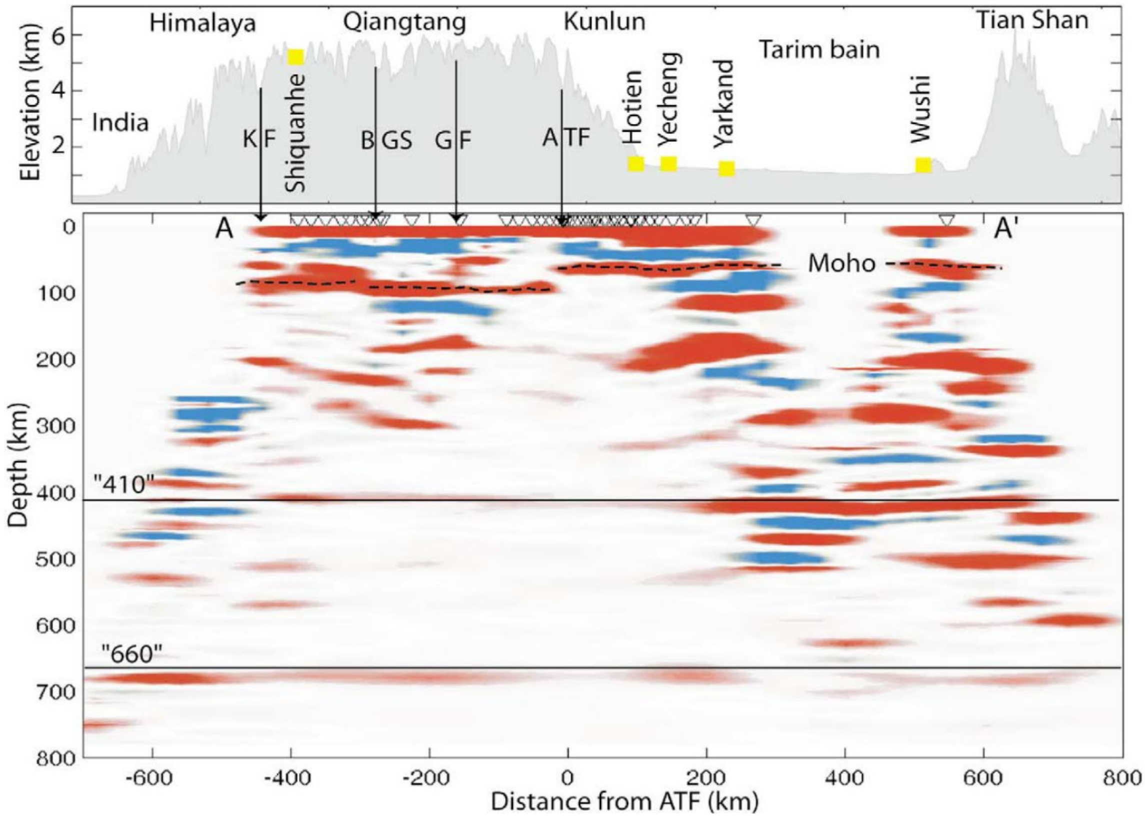
North Tibet

A south-dipping interface beneath northern Tibet is traceable southward from about 100 km depth beneath the Kunlun fault to about 250 km depth beneath the center of the Qiangtang Terrane, where multiple reflections within the crust obscure it. It might be the manifestation of the southward-dipping Eurasian plate (Qaidam Basin) mantle lithosphere underthrusting northern Tibet.
Seismic data also suggest that the lithosphere of the Tarim Basin plunges southward into the mantle, beneath the northwestern boundary of the Tibetan Plateau.

Deepest discontinuities beneath Tibet

The 410- and 660-km velocity discontinuities marking the top and bottom of the mantle transition zone are well imaged. The 410-km discontinuity would mark the transformation from olivine to α-spinel, and the 660-km discontinuity the transition from β-spinel to perovskite+magnesiowüstite. The continuity and parallelism of the 410- and 660-km interfaces implies that there is no lithospheric slab penetrating the mantle transition zone beneath Tibet.

Teleseismic image of the deep structure of western Tibet
from Wittlinger *et al.* 2004 *Earth and Planetary Science Letters* **221(1)** 117-130



In summary

The model of convective removal of a thickened Asian lithosphere is inconsistent with the lithospheric structure interpreted from seismic information.

It is unlikely that the imaged, vertical northern edge of Southern Tibet is a remnant of the oceanic lithosphere from the closure of the Banggong-Nujiang Suture because such a body of dense and cold material would not be stable over 130 million years or more and would have instead sunk into the mantle or been thermally absorbed.

Following several lines of reasoning, this "slab" is linked to the Indian plate. A convergence of 1500 to 2500 km since the collision of India with Asia is estimated from magnetic anomalies and extrapolation of the present-day ca. 15 mm/yr. shortening between India and the Yalu Tsangpo Suture. This amount requires an undeformed Indian mantle lithosphere far beyond the present-day Banggong-Nujiang Suture. Therefore, the underthrusted Indian lithosphere has either shortened since the collision, or additional lithosphere exists in the upper mantle beneath central Tibet. Alternatively, the Indian plate currently underthrusting southern Tibet is detached from the oceanic lithosphere that preceded it northward in the collision with the Eurasian plate.

The high-velocity zones identified in global seismic tomographic inversions projecting to the surface beneath peninsular India are possible Tethyan slabs. With this interpretation, the Tethys oceanic slab(s) would have detached from the northern margin of India before or early in the collision and then would have been overridden by India, which continued to drift northward.

Slip line field theory: Indentation geometry and Central Asian tectonics

Molnar and Tapponnier (1975) made a combined interpretation of satellite fault images and focal mechanism solutions of earthquakes over Asia. They noticed that active faults are widely distributed over Asia whereas India, in contrast, is relatively unaffected. Hence, the Asian lithosphere is deforming in front and around a non-deforming India.

The pattern of active faults in Asia shows that:

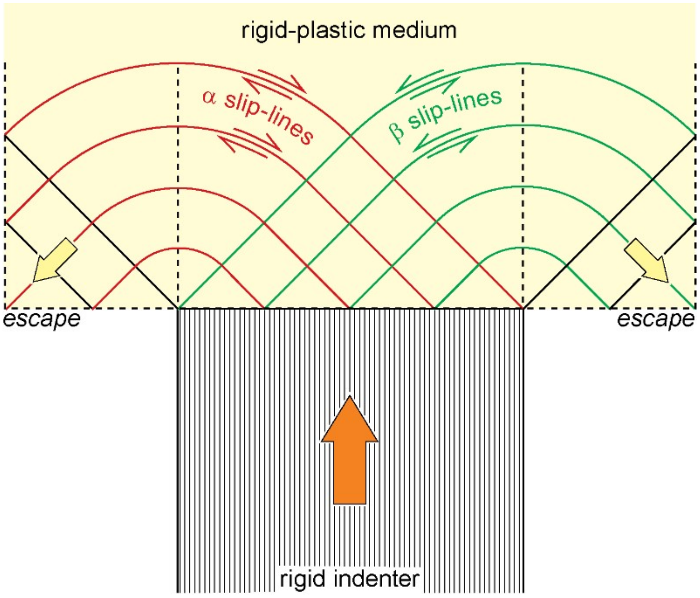
- Thrusting is restricted to a narrow belt near the Himalayas.

- Strike-slip faulting dominates an over 3000km wide region, north of the Himalayas, and extending east into Indochina.
- Crustal extension and normal faulting dominate farther north, from the Baikal region of Siberia to the northern China Sea.

Assuming that faults are planes of maximum shear stress, deformation fields in stressed, rigid-plastic materials may explain the regional changes in faulting style.

Concept

Mechanical engineers have developed the theory of **indentation**, which describes how a stiff object (the **indenter**) penetrates and deforms a weaker material. The concept considers the deforming region in a failure condition and derives potential failure surfaces, which are the **slip lines** in two-dimensions.



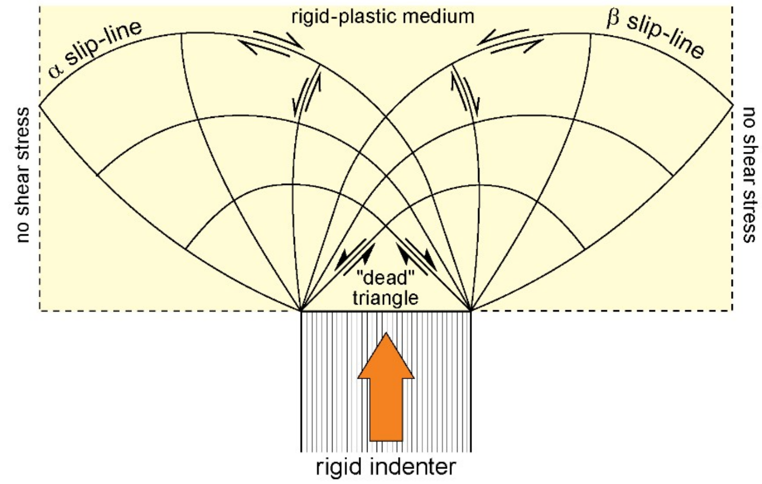
Assumptions state that:

- The ideally rigid-plastic (i.e. no strain hardening, no elasticity) material is isotropic and homogeneous,
- Temperature, body forces and strain rate play no role,
- Deformation is plane-strain, and
- Shear stresses at interfaces are constant, i.e. frictionless or stuck.

Then, the mathematical prediction defines a network of two families of lines conventionally termed α and β slip lines, which correspond to dextral and sinistral strike-slip motion, respectively. Each line is everywhere tangent to the maximum shear stress, each line is usually curved, and each line of one family is orthogonal to all lines of the other family.

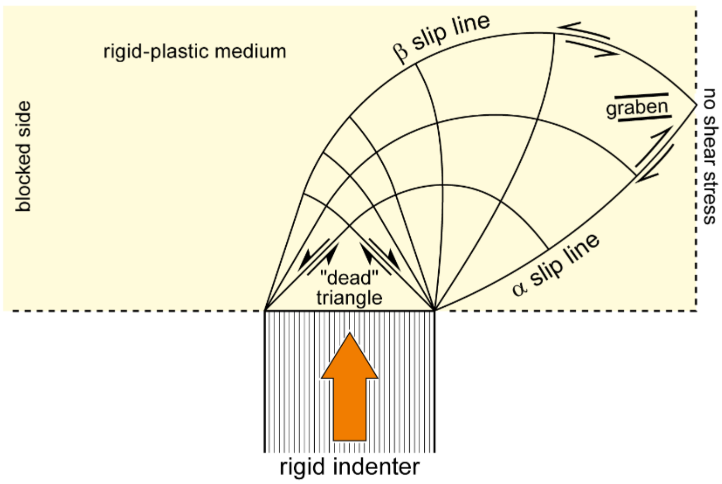
The pattern formed by the slip lines depends on the shape of the plastic medium, the boundary conditions, and the shape of the indenter.

- If the indenter is flat, deformation extends symmetrically into the semi-infinite rigid-plastic medium to a distance approximately equal to the width of the indenter. In front of the indenter, a commonly triangular region of “dead” material is bounded by two conjugate slip lines and moves with the indenter without internal deformation.



Symmetrical, far-field slip lines produced by a narrow, rigid indenter in a semi-infinite rigid-plastic body
after Molnar & Tapponnier 1977 *Geology* **5(4)** 212-216

- If the flat indenter impinges a block bounded on one side, the deformation of the softer block is asymmetric. The faults are parallel to slip lines and generate lateral block motion towards the free side. The curved shape of the slip lines additionally imposes block rotation around a vertical axis during the lateral escape.



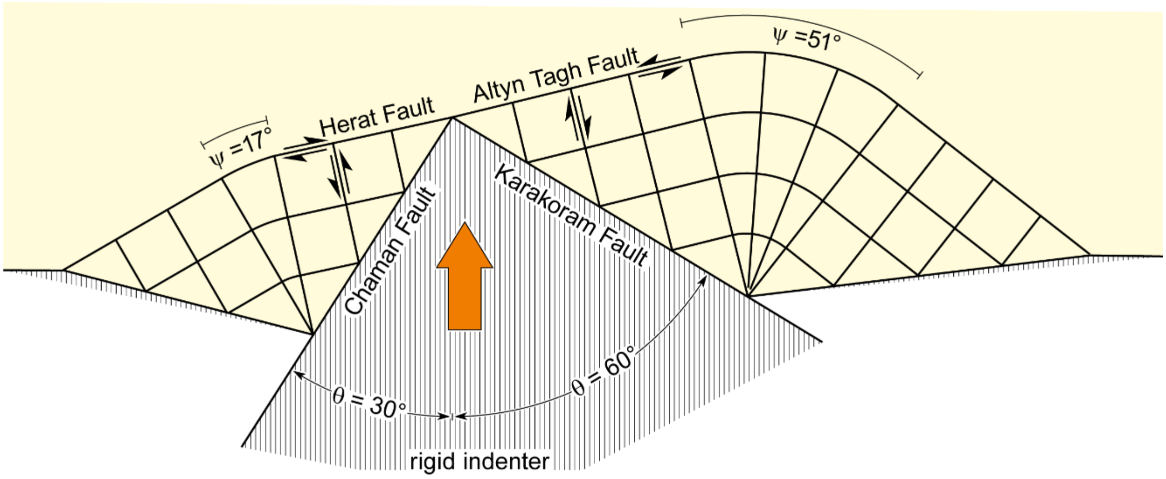
Asymmetric far-field slip lines produced by a narrow, rigid indenter in a semi-infinite rigid-plastic body with only one free side
after Molnar & Tapponnier 1977 *Geology* **5(4)** 212-216

- If the indenter is a wedge, at any given time and depending upon the angle of the wedge, deformation may or may not extend further into the medium than the wedge itself.

Application

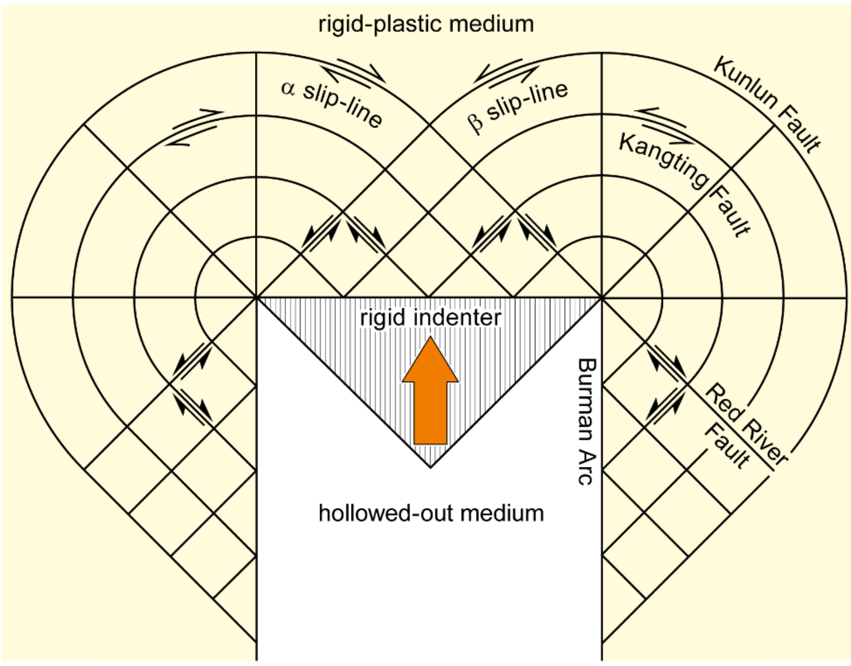
Fault tectonics of Asia is compared with slip-lines in a rigidly indented rigid-plastic (Coulomb) material. Assuming the head boundary of India to be along the Himalayan Front, and its lateral boundaries to run through the Kirthar and Sulaiman Ranges in Pakistan, parallel to the Chaman Fault in the west, and the Sittang zone in Burma, in the east, India seems to have penetrated far into (plastic) Asia. India is analogous to the rigid indenter impinging Asia.
- Thrusting in the Himalayas and South Tibet defines the southern deformation front of the collisional system. The direction of thrust faulting is approximately parallel to the orientation of the maximum compressive stress in the plastic material.
- The major strike-slip faults in Asia correspond to slip lines in front of a flat indenter.

The boundary of India in the western Himalayas and Pakistan, is similar to that of an indenting wedge that created the Herat and Altyn Tagh faults, which are indeed approximately parallel to α and β slip lines, respectively. As the direction of motion between India and Eurasia is approximately north-south, the essentially strike-slip western edge (Chaman Fault) of the Indian indenter is steeper than its eastern edge, which makes the Altyn Tagh Fault strike more northeasterly than the Herat Fault.



Model of plane indentation of semi-infinite rigid-plastic medium by a rigid wedge as analogue to the tectonic situation of Pamir (western end of the Himalayas)
from Tapponnier & Molnar 1976 *Nature* **264(5584),** 319-324

In Northeast Tibet, the Kunlun and Kangting faults are approximately parallel to β lines. The marked curvature, particularly of the Kangting Fault, is expected from the situation ahead of a flat indenter for the former and the proximity to a wedge for the latter.



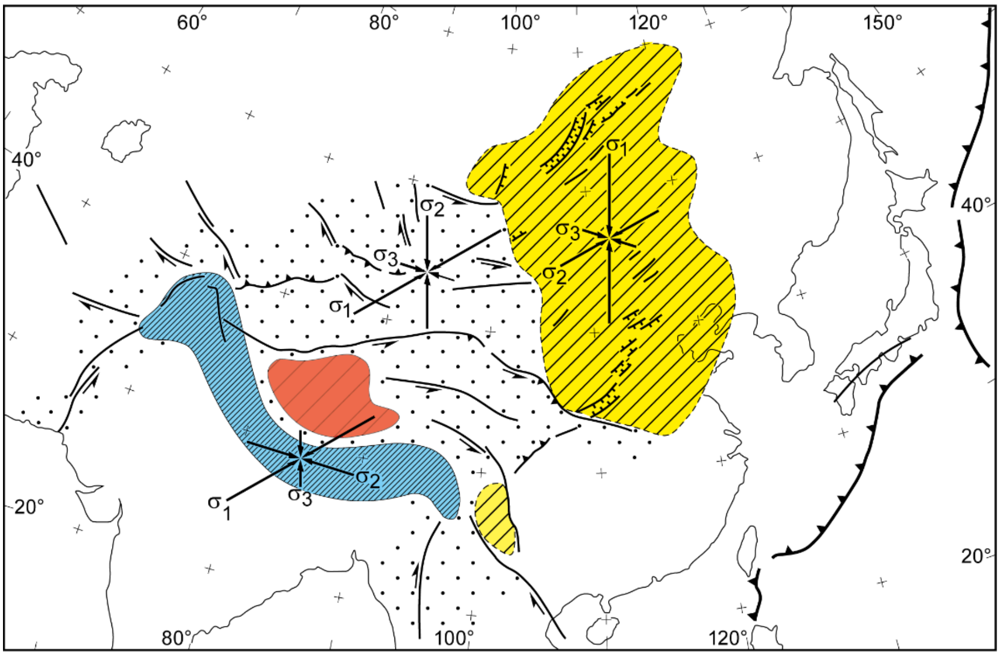
Model of plane indentation of a semi-infinite rigid-plastic medium by a flat, triangular indenter as analogue to the tectonic situation at the eastern end of the Himalayas
from Tapponnier & Molnar 1976 *Nature* **264(5584),** 319-324

Around the eastern end of the Himalayas, the slip lines continue to curve by about 180° to intersect the “north-south” plate boundaries at 45°. The dextral Red River Fault is approximately parallel to an α line.

Hundreds of kilometers of strike-slip motion on these major faults predict extrusion of continental blocks (Indochina) east and southeast of the Himalayas towards the unconstrained (subduction) margins. Lateral motion of stable blocks out of the way of the converging plates can account for 500 km and possibly 1000 km of convergence between India and Eurasia without India having been underthrusted beneath the whole of Tibet.

The analogy between large-scale geological features and the indentation of plastic materials is appealing because it predicts the curvature and sense of motion on the active faults of Asia (for example the Kangting and the Red River faults). Besides, it explains other important features:

- Eastward underthrusting can simultaneously take place at the Burma arc. Subduction results from the continental material shouldered aside to the east by the northward motion of India.
- Pull-apart basins in relay zones of strike-slip faults explain intraplate deformation affecting areas as remote as Siberia, with extension in the Baïkal and Shansi grabens, along with the oceanic ridges in the South China Sea and Burma.
- If the plane horizontal strain is the dominant mode of deformation, then the mean elevation in any given area should reflect the local value of vertical stress. The high altitude of Tibet and the general decrease in elevation away from Tibet in Asia may be a manifestation, along with the distribution of tectonic styles, of the decrease in vertical stress.



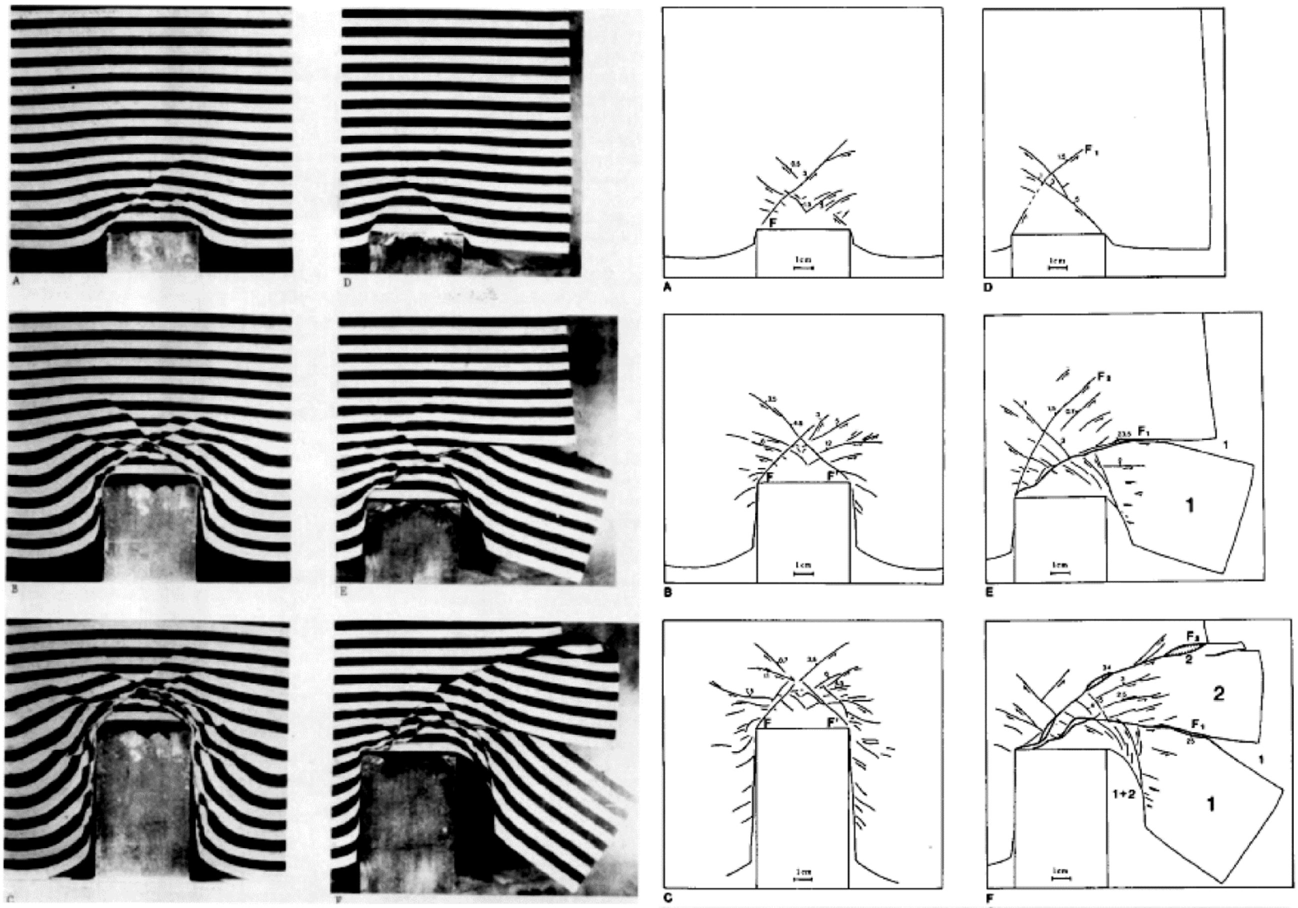
Distribution of tectonic styles in Asia
after Tapponnier & Molnar 1976 *Nature* **264(5584)**, 319-324

- As a complementary observation, the asymmetry of collisional deformation in Asia suggests that the continental lithosphere in western Eurasia offers more resistance to lateral motions than do subduction zones along the Pacific and Indonesian margins.

Escape tectonics - extrusion

The mathematical analysis of slip line fields provides an instantaneous explanation (i.e. for small increments of deformation) of orientation and sense of movements of major faults. However, it becomes complex when the problem is to simulate systems that evolve with time and over long time

intervals as in geology. The problem can be obviated to a certain extent if the mathematical model is replaced by a mechanical analog.
Tapponnier et al. (1982) have designed a mechanical device in which a block of plasticine is deformed by a rigid indenter advancing at a constant rate. In plane indentation experiments with unilaterally confined block, deformation is asymmetric and faults, eventually taking the leading role, allow displacements of blocks towards the free boundary. In particular, sinistral faults originate at the left tip (i.e. confined side) of the indenter, grow and curve out to join the free side of the model. Thereafter, it becomes predominant and guides the sideways translation and rotation of a block, close to the indenter right corner (i.e. unconfined side). The block is **extruded**. This is followed by the extrusion of a second block along another sinistral fault, while the first block continues to rotate. Many pull apart troughs develop along the sinistral faults because of their irregular geometry. As the movements progress, a gap grows between the indenter and extruded plasticine. The size of the blocks depends on the indenter width and the distance to the free side.

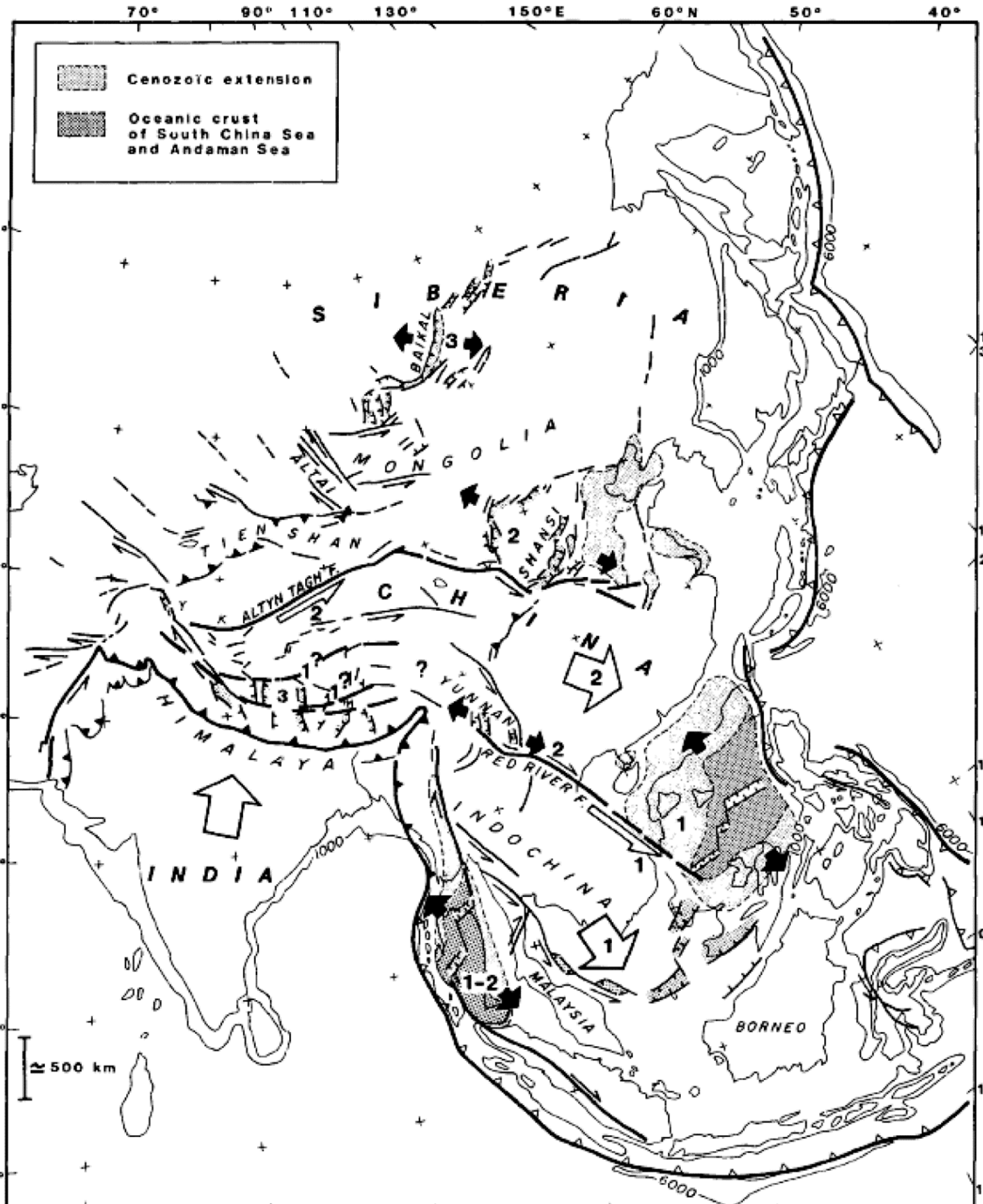


Three successive steps of two indentation experiments on plasticine (left)
and hand drawing of faults in the corresponding stages (right)
after Tapponnier *et al.* 1982 *Geology* **10(12)** 611-616

This analog model shows that crustal segments were extruded and "**escaped**" away from the advancing indenter. The **continental escape model** suggests that large portions of what is now Southeast Asia are moving eastward along strike-slip faults that emanate out of Tibet to make room for India as it advances towards the north. The model makes very specific predictions about the timing and history of the faults and block displacements:
- Left-lateral offsets along the up to 1000km long strike-slip faults of central China may reach several hundred kilometers and are much larger than dextral ones. The Red River Fault and the Altyn Tagh Fault are two successive major extrusion faults. Blocks bounded by these faults correspond to Indochina and Southeast China, respectively.

- Gaps opened up in the model are analogous to the rifts and extensional basins of northern China, Mongolia, and Siberia (Baikal), viewed as a direct consequence of the small resistance to eastward extension opposed by subduction zones along the Pacific margin of Asia. Opening due to movements along the strike-slip faults also fit the extensional tectonics observed in the Andaman Sea, the South China Sea, and the Shansi.
- The penetration of India has rotated (~25° clockwise) and extruded southeastward (800 km) Indochina in the first 20-30 Ma of collision.
- The magnetic anomalies in the South China Sea can be used to date the tectonic escape related to the India-Asia collision. The opening of the basin is marked by two distinct phases. From 32 to 27 Ma, the average spreading rate was 50 mm/yr. At the end of this opening phase, there was a ridge jump followed by a slower spreading of c. 35 mm/yr., which ceased by about 16 Ma. This chronology is consistent with the timing of movements on the main strike-slip faults. Continental escape was diminishing in the late Oligocene and had ceased by the Mid-Miocene.

Thus, tectonic escape is a convincing mechanism for accommodating intracontinental deformation on a lithospheric scale during the Cenozoic convergence between India and Asia.



Schematic map of Cenozoic extrusion in eastern Asia
after Tapponnier *et al.* 1982 *Geology* **10(12)** 611-616

However, these experiments and analogy are plane strain deformation that does not explain the thickness of the Tibetan plateau. Thrusting and strike-slip faulting might be subsequent or concurrent processes. They are not exclusive, and a possible combination of different aspects of both modes may ultimately provide the required explanation of the high elevation (average of about 5 km) and the double crustal thickness of about 70 km in Tibet.

Deformation of a viscous plate

Numerical models using continuum mechanics were inspired by the general concept of a stiff indenter deforming a viscous plate. The shortening/thickening occurs in front of the indenter, but faulting is less important than in the analog models. Simulations include the lateral escape of the continental mass towards the free lateral Pacific margin. The results suggest also that gravitational forces largely control the deformation pattern of Asia.

Present day convergence

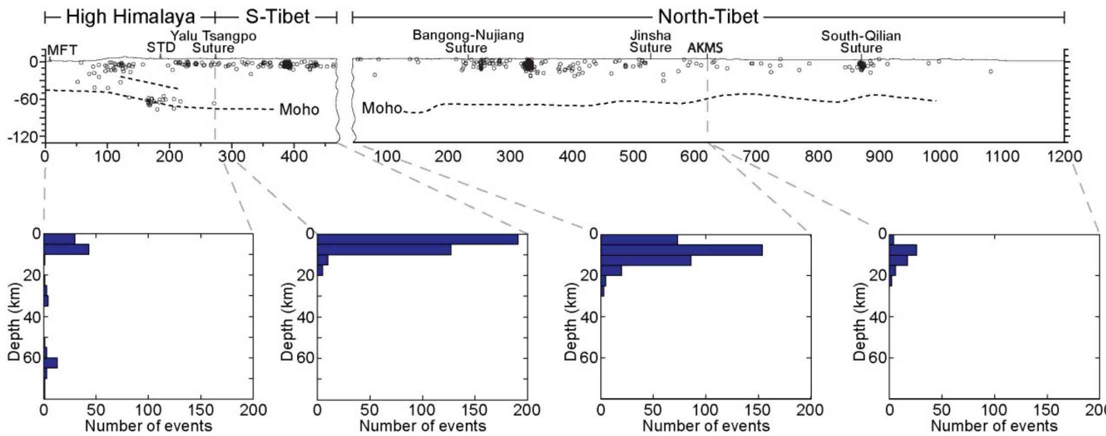
Earthquakes reveal that the high plateau is currently undergoing east-west extension, whilst the mountainous margins show compression and strike-slip faulting. An obvious feature of Asian tectonics is that deformation occurs over a vast area to the northeast of the Himalayas.

Seismic record

The Tibetan plateau is seismically very active. Magnitude 8 earthquakes are frequent.
The map distribution of earthquake epicenters exemplifies a key point: the upper continental crust is breaking over a very wide area, in contrast to the oceanic plates that deform in narrow bands (rifts) only. This means that the continental lithosphere is much weaker than the oceanic lithosphere.
Focal depths are generally less than 25 km throughout Tibet.
This distribution of earthquakes calls for two remarks:

There is a rheological layering

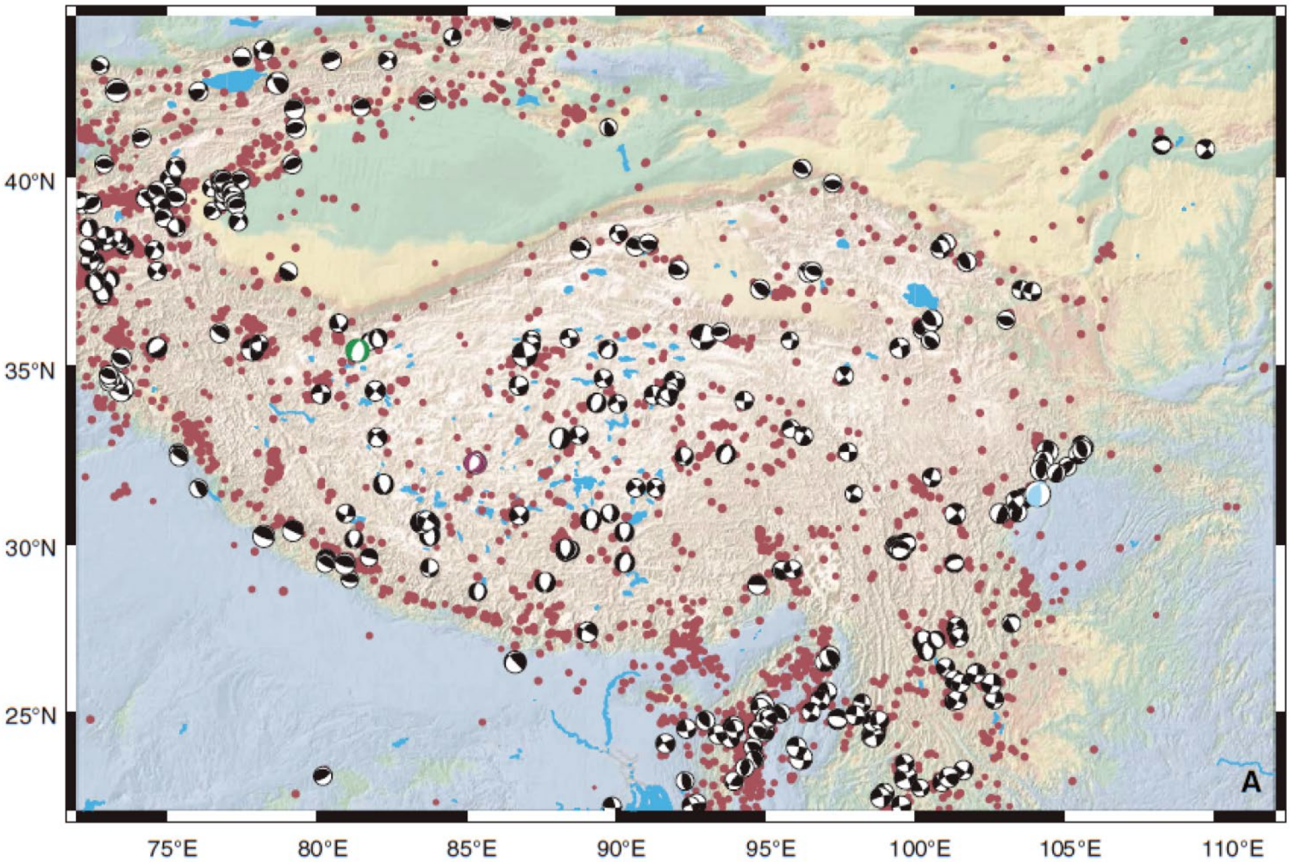
The study of earthquakes yields a clear picture of the style of deformation in at least and maybe only the upper 10 - 25 km of the lithosphere



Earthquake distribution across the Tibetan Plateau
after Wei *et al.* 2010 *Geophysical Research Letters* **37,** L19307, doi:10.1029/2010GL044800

Thrust-fault solutions along the Himalayas contrast with normal-fault solutions in the Tibetan plateau. The fault-plane solutions immediately north of the Main Frontal Thrust, within the Himalaya, document thrust faulting. The north-dipping nodal planes, assumed to be the thrust planes, dip at less than 10° in the east but increase to 20° in the west. The focal depths of these earthquakes are about 15 km, which is consistent with the earthquakes occurring at the top of the Indian Plate subducted beneath South Tibet. However, less than half (i.e. ca 15 mm/yr.) of the estimated convergence between India and Eurasia is taking place in the Himalayas proper. The remaining convergence is believed to be taking place over the very large area north of the Himalayas.

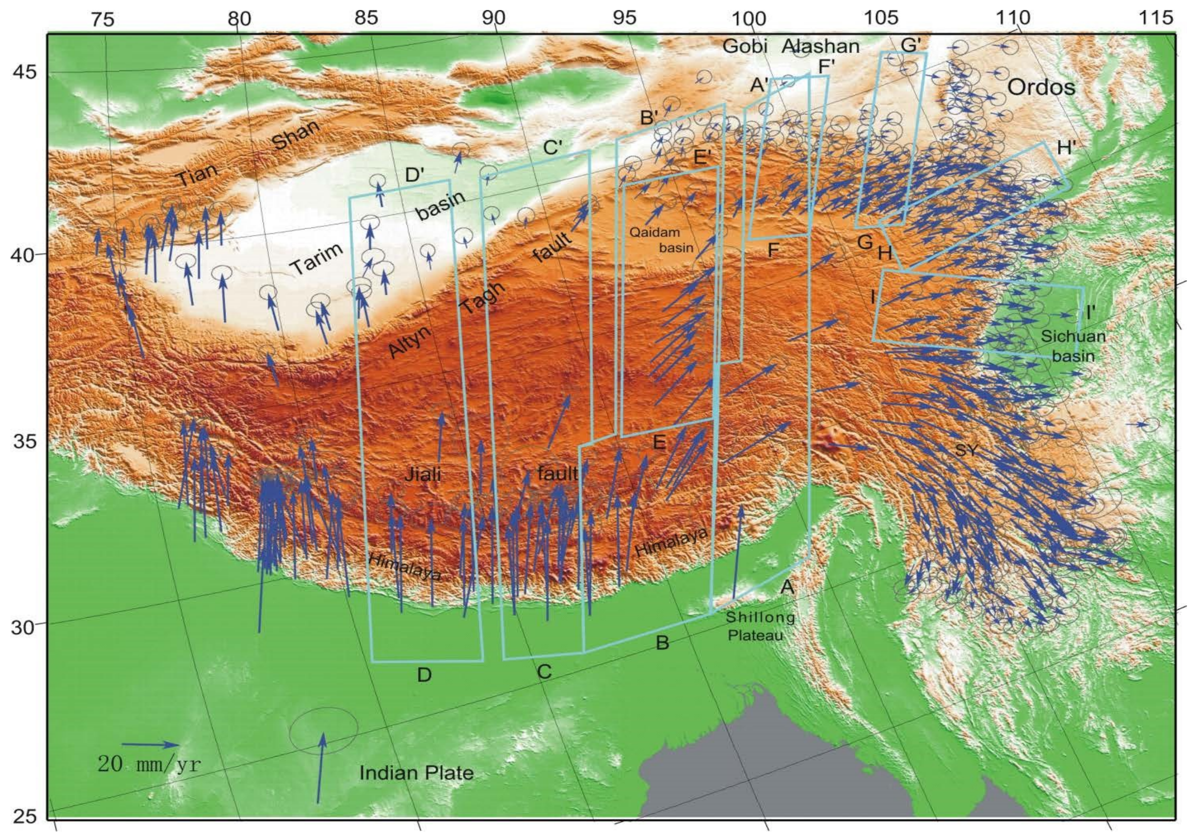
North of the Himalayan thrust-faulting earthquakes, the deformation style changes: the focal mechanisms indicate that normal faulting and east-west extension is taking place, which is consistent with the grabens described on the Tibetan Plateau. Extension implies increasing in surface area and decreasing in the thickness of the crust of Tibet, although it is part of the largest active zone of continental collision. Extensional faulting dies out northwards to be replaced by thrust faulting on the northern and eastern margins of the plateau. Extensional earthquakes make it clear that the forces acting today within Asia are not simply those due to the relative motion of the Indian and Eurasian plates.



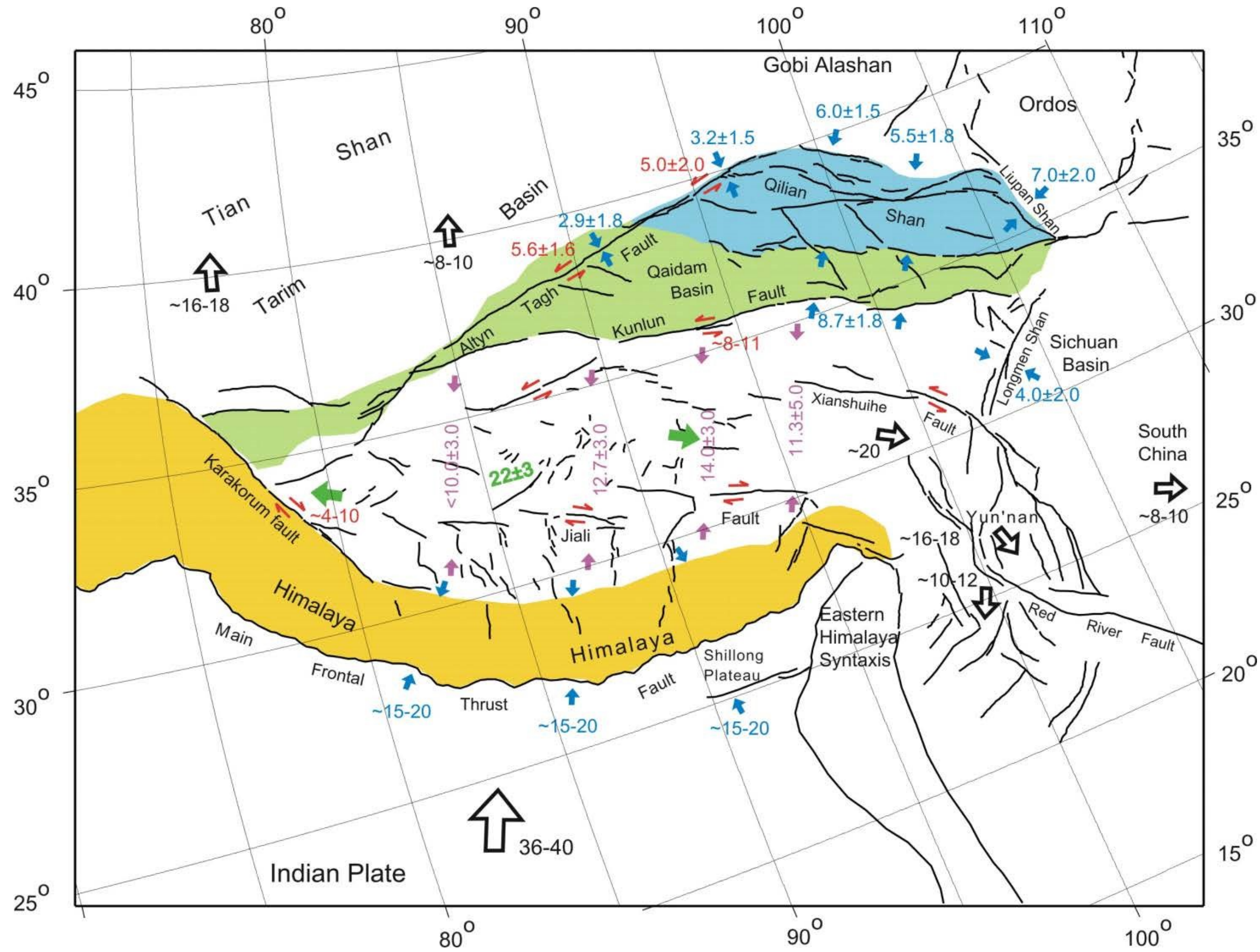
Focal mechanisms over Tibet after Taylor & Yin 2009 *Geosphere* **5(3)** 199-214

Global Positioning System measurements

GPS measurements of crustal motions show a bulk eastward movement of the Tibet Plateau together with its northern and eastern forelands. Within the interior of the plateau, distributed NNW-SSE short-term shortening occurs at a rate of 10 to 15 mm/yr. GPS velocities decrease along the northern margin of the Tibetan plateau from about 20 mm/yr. at the western end to zero at the eastern end. The northern foreland moves northeastward at about 10 mm/yr., indicating that the northern boundary of the deformation zone lies north of the plateau. Other movements around the eastern boundary of Tibet display radially divergent movements with south China moving almost 10 mm/yr east-southeast, while the eastern boundary of the Tibetan Plateau moves at about 15 mm/yr.



GPS velocities in and around the Tibetan Plateau with respect to stable Eurasia
From Zhang *et al.* 2004, *Geology*, **32(9)**, 809-812



Active movements of the Tibetan Plateau in mm/yr
From Zhang *et al.* 2004, *Geology*, **32(9)**, 809-812

Conclusion

The spread of earthquakes over Asia demonstrates that the continental parts of lithospheric plates do not behave as rigidly as the oceanic parts. Continental deformation affects regions of hundreds to thousands of kilometers wide whereas deformation in the oceans is concentrated in narrows fault systems along plate boundaries. Overall post-collisional convergence between India and Asia of the order of 2000–3000 km seems to have been accommodated by a combination of:

- (a) northward underthrusting of parts of India and thrust imbrication of Indian crust
- (b) pervasive shortening and thickening of the Asian lithosphere, and
- (c) eastward escape of continental blocks along strike-slip faults.

The concept of indentation tectonics is successful in explaining the spatial distribution and relationship of the various styles of faulting and deformation in a deforming continent as Asia. However, it does not account for crustal thickening in Tibet.

The introduction to the course on tectonics invited to investigate how geographic features (map distribution and topography) and deformation histories result from both horizontal movements (that may reach 100-200 mm/yr) and vertical components (up to 10-20 mm/yr). Another goal was to describe some fundamental differences between the continental and oceanic lithospheres. Differences in their behavior are due to important mechanical differences.

Convergence in continents and oceans differs in character. The oceanic lithosphere moves as rigid plates pushed into the mantle along a collection of subduction zones. The continental lithosphere floats on the mantle whereas the oceanic lithosphere tends to sink as it ages. The distribution of surface heights, earthquakes, and faulting over Asia shows that the deformation of the continental lithosphere is diffuse. A zone of continental compression like Tibet is a region in which the crust is shortened and thickened. The coeval decrease in surface area and an increase in the thickness of the continents produces mountain belts and collisional plateaus.
Consequently, the material of the continental crust is approximately conserved; it is redistributed by the deformation, but is not substantially added to by plate creation, or substracted by subduction.

The style of deformation observed at least in some parts of the continents suggests that the theory of plate tectonics does not directly explain some forces acting in the continental lithosphere. For example, widely distributed extension in Tibet does not take place by the creation of lithosphere at spreading centers, but by the widespread thinning of the crust and probably the lower lithosphere as well.
The final stage in the tectonics of many mountain belts may be their extensional collapse. The nature, magnitude, and source of the forces that affect continental deformation are a challenge to present-day research in geodynamics. Tectonics in continents is not mere plate tectonics.

Question

Why in the Alps is there no continental plateau and correspondingly thickened crust equivalent to Tibet?

Recommended Literature

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